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Quantifying rainfall–runoff relationships on the Dera Calcic Fluvic Regosol ecotope in Ethiopia

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ABSTRACT

Droughts, resulting in low crop yields, are common in the semi-arid areas of Ethiopia and adversely influence the well-being of many people. The objective of this study was to assess the benefit that in-field rainwater harvesting (IRWH) would have, compared to conventional tillage, on maize yields on a semi-arid ecotope at Dera situated on the eastern part of the Rift Valley. Rainfall–runoff measurements were made during 2003 and 2004 on 2 m × 2 m plots provided with a runoff measuring system and replicated three times for each treatment. There were two treatments: conventional tillage (CT) and no-till (NT), the latter with a flat surface that promotes runoff and therefore IRWH. Rainfall intensity was measured at 1 min intervals with an automatic tipping bucket instrument, and runoff was measured after each rain event. Measured runoff as a function of rainfall intensity and duration from half the rainfall–runoff events was used to determine the critical parameters of a appropriate runoff model. The calibrated model was found to be capable of predicting runoff in a satisfactory way.

Rainfall–runoff measurements were made during the rain seasons in 2003 and 2004 during which there were 25 rain events with >9 mm of rain. There was no statistical difference between the runoff on the two treatments. The measured runoff (*R*) for the two rain seasons, expressed as a fraction of the rainfall during the measuring period (*P*), i.e. *R*/*P*, gave values of 0.46 and 0.39 for the NT and CT treatments, respectively.

Results from 7 years of field experiments with IRWH at Glen in South Africa were used to estimate the yield benefit of NT for Dera compared to CT. The results were 696 and 494 kg ha^{-1} for 2003 and 2004, respectively. Based on the estimated average long-term maize yield of 2000 kg ha^{-1} at Dera, this was an estimated yield increase ranging from 25% to 35%.

1. Introduction

More than 80% of Ethiopia's population is involved in agriculture, the backbone of the country's economy. Crop production is mostly under rainfed conditions, most of which is marginalized by water stress (Ministry of Agriculture (MoA), 2000). This, and the frequent droughts, is a serious threat to those engaged in agriculture. The optimum utilization of rainwater is therefore of utmost importance, requiring diligent adherence to the principle of "more crop per drop", as appropriately stated recently by the UN President Kofi Annan. In scientific terms this means improving rain water productivity (RWP) recently defined by Botha (2007) as the total long-term grain yield divided by total long-term rainfall.

One way of improving RWP is through the use of rain water harvesting. Many types of water conservation techniques that

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show significant crop yield increases have been tested worldwide (Berry and Mallett, 1988; Mwakalila and Hatibu, 1993; Kronen, 1994; Gicheru et al., 1998; Ojasvi et al., 1999). A technique that has given good results in semi-arid South Africa is in-field rain water harvesting (IRWH) (Hensley et al., 2000). This technique is also known as mini-catchment runoff farming (Oweis et al., 1999). The technique is illustrated in Fig. 1. It combines the advantages of water harvesting from the no-till, flat, crusted runoff strip, and decreased evaporation from the deeply infiltrating runoff water which accumulates in the mulched basin area. The technique led to maize yield increases of between 25% and 50% compared to conventional tillage practices, and resulted in significant increases in RWP. It was shown that the technique is suited to semi-arid areas with crusting soils that have a high water storage capacity (Botha et al., 2003).

Rainfall in semi-arid areas with fine textured soils is mainly lost through evaporation from the soil surface (E_s) and runoff (R). Under these conditions E_s can be 60–70% of the annual rainfall (Bennie and Hensley, 2001), and R can vary between 8% and 49% of the annual rainfall depending on the prevailing conditions (Haylett, 1960; Du Plessis and Mostert, 1965; Bennie et al., 1994; Hensley et al., 2000; Botha et al., 2003). Studies by Morin and Benyamini (1977) and Morin and Cluff (1980) showed that the most important factors influencing runoff in semi-arid areas were: rainfall intensity (P_i); the final infiltration rate of the soil (I_f), which is greatly decreased by crusting; the extent to which the soil surface can store water before runoff starts which is described by a parameter termed surface detention (SD); a crusting parameter (γ). Their studies resulted in the formulation of a runoff model that satisfactorily predicted runoff from crusted soils of Arizona (Morin and Cluff, 1980) and Israel (Morin et al., 1983). In South Africa the model has been successfully used by Zere et al. (2005) for predicting the runoff measured by Du Plessis and Mostert (1965) over 18 years on a Tukulu form soil (Soil Classification Working Group, 1991) (Haplic Luvisol FAO, 1998b) at Glen.

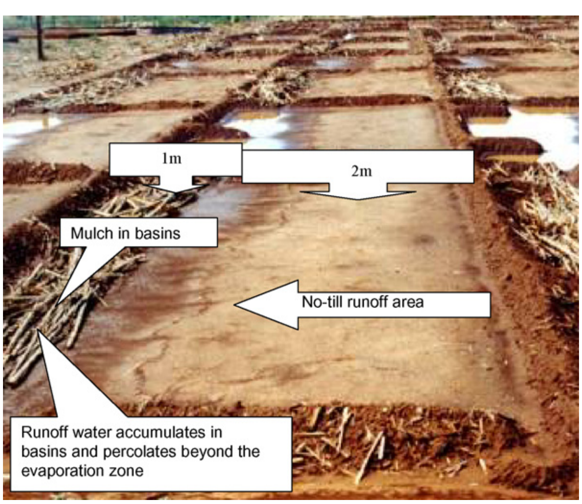

Fig. 1 – A diagrammatic description of the no-till, mulching, basin tillage, in-field rain water harvesting (IRWH) production technique (Hensley et al., 2000).

The basis for the Morin and Cluff (1980) runoff model is provided by the following infiltration equation for crusted soils developed by Morin and Benyamini (1977):

$$I_t = I_f + (I_i - I_f)e^{-\gamma pt} \quad (1)$$

where I_t = infiltration rate as a function of time (mm h^{-1}), I_f = final infiltration rate of the soil (mm h^{-1}), I_i = initial infiltration rate of the soil (mm h^{-1}), p = rain intensity (mm h^{-1}), t = time from the beginning of the rainfall event (h), and γ = crusting parameter (mm^{-1}).

Morin and Cluff (1980) showed that by integrating Eq. (1) with regard to time, and introducing changes in P_i over time segments of a rain event (Δt_i), the following expression was valid:

$$F\,\Delta t_i = I_f\,\Delta t_i + \left(\frac{I_i - I_f}{-\gamma P_i}\right)[\exp(-\gamma D_i) - \exp(-\gamma D_{i-1})] \quad (2)$$

where $F\Delta t_i$ = total infiltration during time segment Δt_i with rainfall intensity P_i (mm), D_i = accumulated rain depth during time segment i (mm), and P_i = rainfall intensity during time segment i (mm).

If the soil surface was such that it did not store any water before runoff occurred, then for any time segment during which $P_i > I_f$, the runoff for each time segment Δt_i of a rain event, i.e. R_i, could be calculated as:

$$R_i = P_i\,\Delta t_i - F\,\Delta t_i \quad (3)$$

This is however not the case in practice as a soil surface always has some degree of surface roughness accumulating rainwater to an extent. It is dependant on the degree and configuration of the roughness before runoff commences. Morin and Cluff (1980) deal with this factor by combining the D_i of Eq. (2) and 'a surface detention' parameter, SD_m, termed 'maximum storage and detention'. By introducing this term into Eq. (3) they showed that it was possible to compute the runoff of any rain event, segment by segment, using the following equation:

$$R_i = P_i\,\Delta t_i - F\,\Delta t_i(SD_m - SD_{i-1}) \quad (4)$$

where R_i = runoff for time segment i (mm), $F\Delta t_i$ = total infiltration during time segment Δt_i with rainfall intensity P_i (mm), P_i = rainfall intensity during the time segment i (mm h^{-1}), SD_{i-1} = storage and detention during the previous time segment (mm), and SD_m = maximum storage and detention (mm).

Substitution of the right hand side of Eq. (2) into the $F\Delta t_i$ term of Eq. (4) provides the complete Morin and Cluff (1980) runoff equation. Now consider the importance of the flat, crusted, no-till runoff strip in Fig. 1 in relation to Eq. (4). The parameters SD_m and I_f are minimized, and R_i into the basin area is therefore maximized. Values for I_i and I_f are relatively easily measured for a particular soil. Therefore if P_i and R are measured on an experimental plot (rainfall–runoff relationships), γ and SD_m can be determined by iteration. The Morin and Cluff (1980) runoff model (MC model) is thus clearly well suited for predicting the benefits of IRWH for crop production in semi-arid areas with crusted soils. It was therefore concluded that if rainfall–runoff relationships on a benchmark ecotope in Ethiopia could be determined, it would enable researchers to quantify the extent to which the IRWH technique would result in increased yields on similar ecotopes