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The Influence of Soil Surface Conditions and Rainfall Intensity on Runoff Generation Potential in Semiarid Botswana

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Authors' contributions

This work was carried out in collaboration between all authors. Author KB managed the experimental process and analyzed data. Author BK designed the study and wrote the first draft of the manuscript. Author CP prepared the study protocol and managed the literature searches. Author GG assisted in data analysis and edited the first draft of the manuscript. All authors read and approved the final manuscript.

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ABSTRACT

The study analyzed an investigation of soil surface conditions and their runoff generation potential by means of field experiment and model predictions. The field experiment was carried out during the period January 2012 – September 2013 at the Botswana University of Agriculture & Natural Resources (BUAN) Farm, located at Sebele (24°33'S, 25°54'E) and 994m above mean sea level.
The specific objectives of the study were (1) to determine the proportion of rainwater that went off as runoff from common tillage systems, and (2) to determine the rainfall intensity for runoff initiation under the bare soil surface condition.
In order to achieve the above specific objectives a field experiment was carried out. For specific objective one, a Completely Randomized Block Design comprising of three blocks of runoff/catchment plots measuring 25 m^2, 50 m^2 and 100 m^2 were laid out. Within same

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plots/catchment, the following soil surface conditions were imposed: Mouldboard Ploughed Surface (PS), Poorly Managed Surface (PM), Harrowed Surface (HS) and Natural Vegetation (NV). At the bottom of the catchment area, a runoff collection system was laid out and runoff was measured after every storm event.
The rainfall intensity data collected from the recording float-and-syphon type rain gauge by the Botswana Dryland Farming Scheme (1985-1994) at Sebele was compiled and used to complement the rainfall intensity data recorded during the experimental period (2012/13).
The analysis of the field experimental results showed that a 5 x 5 m PM (un-weeded surface) yielded significantly more runoff than NV, PS and HS by 39%, 61% and 56% respectively. Thus, to build-up moisture conservation on farmland for crop growth, farmers should choose a tillage system that promotes good rainfall infiltration into the soil, such as ploughing and harrowing once.
The power regression curve analysis to test if measured rainfall intensity could initiate runoff on bare soil surface showed that a rainfall intensity of 1.0 mm/h initiated runoff of 1.3 mm at R^2 = 60%, which was relatively lower. This could be attributed to the only 22 observations made due to the limited number of rainfall events during the period under review.

Keywords: Botswana; infiltration; rainfall intensity; runoff; surface conditions.

1. INTRODUCTION

When rain falls onto the earth's surface it moves according to the law of gravity; a portion of the precipitation seeps into the ground to replenish soil water or ground water but most of it flows downhill as runoff. Runoff occurs only when the precipitation rate exceeds the rate at which water infiltrates into the soil and when surface storage is exceeded. Runoff studies are carried out with either a model or statistical design based on runoff measurements from plots or with catchment observation, and sometimes with a combination of both. One major interest in the study of runoff process at field level has been determining discharge or yield over a specified period of time in relation to the total rainfall. Results from most of the studies have shown a good relationship between discharge and plot or catchment area subject to the translocation factors. The effect of some translocation factors which include slope degree, length and orientation on the runoff process and discharge has also been a major area of interest in several field studies. An increasing slope length induces a corresponding increase in runoff volume from plots [1,2]. This is contrary to the conclusion that runoff volume decreases with increasing slope length [3].

Hard-setting soils, widely prevalent in semi-arid Botswana, are caused by acidity, low fertility and low organic matter content, and inappropriate tillage operations. Textural properties of hard-setting soils range from loamy sand to sandy clay with a low shrink – swell capacity which results in high bulk density values on drying [4]. The combination of relatively compacted surface soil layers with low infiltration capacity, low vegetation cover and high intensity rainfall patterns results in high runoff potential particularly in eastern Botswana.

Tillage practices also can affect runoff generation. Deep tillage (>20 cm soil depth) is often needed on poorly drained or hard-setting soils to improve water infiltration and seedbed conditions for plant growth [5,6]. Non-inversion tillage operations such as chisel ploughing or ripping can decrease soil strength while causing little damage to soil structure of fragile soils [4]. In deep ripping of silt loam textured soils, infiltration can be increased and has been shown to be directly related to structural stability [7], bulk density and pore structure [8]. Thus, tillage alters soil pore size and geometry and consequently influences soil water transmission and storage on silt loam soils [9].

In Botswana, agriculture plays a very important role in the economy as more than 80% of the population is involved in agriculture. The government considers arable and livestock farming as key areas for employment creation and income generation for the majority of rural families [10]. Climate is a key factor in determining the level to which both crop production and livestock rearing succeed in any particular year. Rainfall and temperatures are the main elements which influence whether a season has adequate moisture for plant growth or is dry leading to drought. Rainfall is seasonal, unreliable and varies from year to year [10]. It is therefore very crucial that every effort is made to conserve and efficiently utilize the scarce rainwater. For arable crop production, this requires improved soil management techniques that maximize the holding of rainwater into the soil, coupled with cultural and agronomic practices which ensure the most optimum use of the available soil-water by plants. To mitigate the effects of water shortage smallholder farmers are, therefore, turning to yield improving measures such as water harvesting [11].

Rain Water Harvesting (RWH) is defined as a process of collecting, concentrating and storing various forms of runoff for various purposes [12]. The collected runoff can be used for several purposes such as to improve soil-moisture for plants, to supply water for livestock and domestic needs and to recharge the groundwater [13]. In order to improve the productivity of rainwater in semi-arid areas, it is often necessary to concentrate it into a small area of use through some form of tillage.

Common tillage systems and soil surface conditions prevalent in Botswana include:

- Mouldboard ploughed, row planted and weeded soil surface
- Mouldboard ploughed, disc harrowed, row planted and weeded soil surface
- Mouldboard ploughed and un-weeded soil surface.

The objective of this study was two-fold: (1) to determine the proportion of rainwater that went off as runoff from common tillage systems, and (2) to determine the rainfall intensity for runoff initiation under the bare soil surface condition.

2. MATERIALS AND METHODS

The study was conducted at the BUAN Farm situated at Notwane, Sebele (24°35′ S: 25°58′ E; 998 m), about 15 km North-East of Gaborone. The climate of Sebele is semi-arid with an average annual rainfall of 538 mm. Most rainfall occurs in summer (late October to March/April). Prolonged dry spells during the rainy season are common and rainfall tends to be localized [14]. The soils are shallow, ferruginous tropical soils, mainly consisting of medium to coarse grain sands and loams with a low water holding capacity and subject to crusting after heavy rains. The soils in the area are sandy loam and classified as heplic lixisols [15]. The fertility status is medium and the farm was initially used for vegetable production.

For objective 1, the study involved a complete randomized block design comprising four soil surface treatments and three micro-catchment sizes. Blocking was done to take account of variability of soil and slope distance. The soil surface condition treatments were Mouldboard Ploughed Surface (PS), Harrowed Surface (HS), Poorly Managed Surface (PM), which are commonly used in the country and Natural Vegetation (NV) as a control. The micro-catchment sizes were 5 x 5m, 5 x 10m and 5 x 20 m as shown in Fig. 1.

To obtain different soil surface conditions as outlined previously, the PS surface was effected first and thereafter a disc harrow was either used or not depending on the treatment. For PM, mouldboard ploughing followed by disc harrowing was initially carried out after which the plot was not weeded for the entire period of experimentation. This was to distinguish this treatment from NV. Ridges were then made with spades and rakes to ensure that the rainwater was directed into the runoff collection system downslope. As part of characterization of soil surface conditions, soil parameters namely, soil bulk density, field hydraulic conductivity, cumulative infiltration and soil moisture content were measured, whilst soil porosity was calculated. Soil bulk density was measured on undisturbed cores (5 cm in diameter and 5 cm high) down to 10 cm depth prior to experimental commencement and during the rainy season. Total porosity was calculated from the relationship between bulk density and particle density (i.e. the density of the solid material viz. 2.65 gcm^{-3} for most mineral soils) [16]. Soil moisture was measured gravimetrically in the 0-10 cm layer before experimental commencement, during the rainy season and after the rainy season. Cumulative infiltration was measured by a double ring infiltrometer before experimental commencement. Field saturated conductivity of the soil was determined by the variable head permeameter [17] before experimental commencement of the rainy season by sampling to a depth of 30 cm.

A conventional method of measuring runoff from the various sized plots involved employing a number of collecting tanks (drums) with a divisor between any two of them [18]. This consisted of the divider drum with 15 outlet pipes of diameter 2 cm. The central pipe was connected to the collector drum by a hose pipe. The overflow pipes of the divider drum were adjusted such that the overflow volume draining into the collector drum was 1/15 of the total overflow. The runoff collection system is shown in Fig. 2. After each

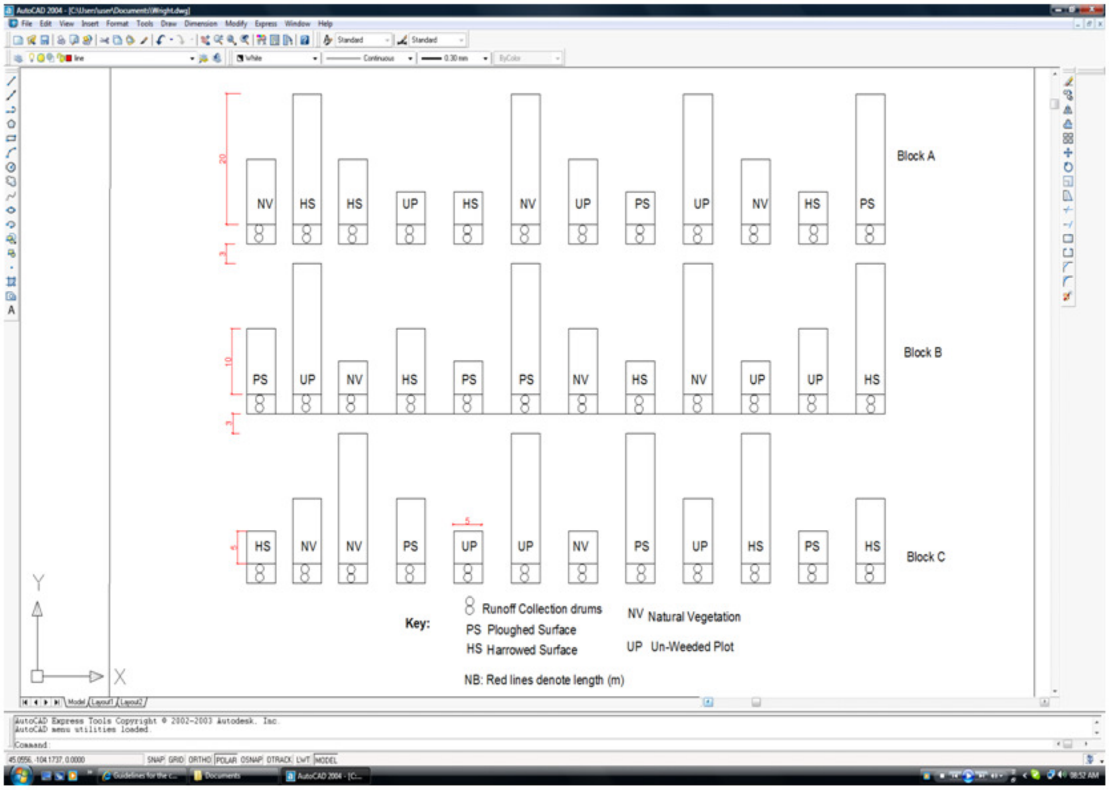

Fig. 1. Experimental layout for objective 1

rainfall event the depth of runoff collected into the 210 litre drums (of the runoff collection system) was measured by a metre rule (mm). Then the conversions, from millimetre (mm) to litres (l), were obtained from a developed calibration curve.

Fig. 2. Runoff collection system

For objective 2, rainfall intensity data from the Botswana Dryland Farming Scheme [19] at Sebele was compiled and used to complement the rainfall intensity data recorded during the experimental period (2012/13). The Botswana Dryland Farming Scheme rainfall intensity data was recorded using the recording type rain gauge. The rain gauge chart representing rainfall for 24 hours was collected from a float and syphon type rain gauge. The rainfall intensity data recorded during the experimental period (2012/13) was collected in a similar way.

The data from the complete randomized block design field experiment was analyzed using ANOVA procedure [20] and means were separated by least significant difference (LSD) at 5% level. The interaction between rainfall intensity and corresponding runoff using historical and collected data was analyzed by a power regression curve to determine the rainfall intensity threshold that initiated runoff under a bare soil surface condition.

3. RESULTS AND DISCUSSION

3.1 Characterization of Soil Surface Conditions

Generally the range of infiltration varied from 12mmh^{-1} to 14mmh^{-1}, while hydraulic conductivity varied from 3.6 x 10^{-4} mmh^{-1} to 3.7 x 10^{-4} mmh^{-1} between soil surface conditions. These results are shown in Table 1. Soil bulk density was lowest under NV but highest under PM soil surface condition. Natural vegetation had a pronounced effect on porosity, infiltration and interception, and enhanced both soil infiltration and soil water storage capacity. As a result, NV's physical soil characteristics were comparable to those of mechanically-disturbed treatments such as HS and PS. These results were consistent with those obtained by other researchers from a similar semi-arid environment [21].

3.2 Effects of Soil Surface Conditions on Runoff

When making a comparison between soil surface conditions, it was found that runoff collected from PM, over the season, was significantly higher (Table 2) than runoff from HS, NV and PS by 39%, 61% and 56%, respectively. These could also be explained by the point that PM in the experiment had an increased bulk density (1.67 g/cm^3) and reduced infiltration (12.0 mm/h) whilst PS, HS and NV had infiltration rates of 13.0 mm/h, 12.5 mm/h and 12 mm/h and bulk densities of (1.48, 1.53, 1.41) g/cm^3 respectively. Field observations from similar semi-arid environments have shown that increasing cover (canopy and litter) increased infiltration and reduced both runoff and soil loss [22]. This is indicated for NV (Table 2), though not significant, had the 2nd highest runoff value behind PM. Elsewhere, a simple empirically based model to explore the effect of soil properties on runoff generation found runoff to be negatively affected by soil porosity [23]. This explains the significant runoff generating potential of PM with high bulk density but low soil porosity/ permeability (Table 2). These findings were consistent with those obtained by other researchers, who observed that as soil bulk density increased, soil porosity decreased which limited depth of water flowing through the soil thereby increasing the depth of water flowing on the surface as runoff [24].

3.3 Effect of Catchment Size on Runoff

A comparison between the catchment sizes (Table 3) revealed that a 5 m x 5 m catchment significantly recorded 80% and 87% more runoff than a 10 x 5 m and 20 m x 5 m respectively.

These results suggested that it was possible to generate significant runoff from a small piece of land ($25m^2$). This is supported by other researchers, who reported that small plots tended to have 30% higher runoff compared to larger plots [25]. It was also argued that the runoff efficiency (volume of runoff per unit area) increased with the decreasing size of the catchment i.e. the larger the size of the catchment the longer the time of concentration and the smaller the runoff efficiency [26]. This implied that runoff generated from a small area such as $25m^2$ could have adverse effects leading to degradation on the land provided soil properties were similar.

3.4 Effect of Rainfall Intensity on Runoff under Bare Soil Surface

The results of the power regression curve analysis to test if the measured rainfall intensity could initiate runoff are shown in Fig. 3. A small rainfall intensity of 1.0 mm/h initiated runoff of 1.3 mm on bare soil surface. These results are based on a low correlation coefficient of R^2 = 60% which could be attributed to only 22 observations made due to the limited number of rainfall events during the period under review.

This is explained by the fact that the soil infiltration ability on cultivated or bare fields was commonly limited by surface crusting rather than by deeper profile conditions [27]. As a result, rainwater falling on bare ground could not penetrate, and ran off sideways, even on very gentle slopes. The rapid drop in infiltration rate (IR) of most of the bare soils during rainstorms is due mainly to the surface seal. The seal is less permeable, by a few orders of magnitude, than the subsurface horizon. This justifies the 60% correlation coefficient value found by the study.

Table 1. Summary of the physical characteristics of the experimental field for objective 1

Soil surface	Bulk density (x 10^3 kgm^{-3})	Porosity	Infiltration rate (mmh^{-1})	Hydraulic conductivity (mmh^{-1})
HS	1.53	0.41	12.5	$3.5x10^{-3}$
NV	1.41	0.46	12.0	$3.6x10^{-3}$
PM	1.67	0.37	12.0	$3.6x10^{-3}$
PS	1.48	0.44	13.0	$3.7x10^{-3}$

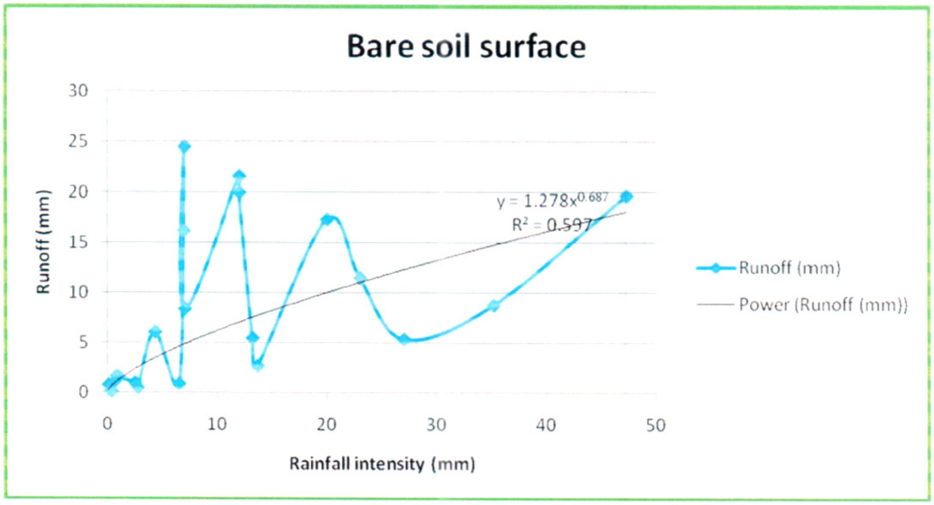

Fig. 3. Rainfall intensity vs runoff on a bare soil surface

Table 2. Effects of soil surface condition on runoff

Soil surface	Runoff (mm)	Bulk density (gcm^{-3})
PM	1.197a	1.67
NV	0.725b	1.41
PS	0.467b	1.48
HS	0.522b	1. 53

Means with same letters are not significantly different at P<0.05, using Duncan Least Square

Table 3. Effects of catchment size on runoff

Catchment size	Mean runoff (mm)
5m x 5m	1.782a
10m x 5m	0.347b
20m x 5m	0.169b

Means with same letters are not significantly different at P<0.05, using Duncan Least Square

4. CONCLUSIONS

A field experiment was conducted during the period January 2012 – September 2013 at the BUAN Farm, Botswana, with the objective of, firstly, determining the proportion of rainwater that went off as runoff from common tillage systems, and secondly, determining the rainfall intensity for runoff initiation under the bare soil surface condition. The study concluded that:

- A PM (un-weeded surface) produced higher runoff than NV, PS, and HS by 39%, 61% and 56% respectively;
- The rainfall intensity of 1.0 mm/h initiated runoff of 1.3 mm on the bare soil surface.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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