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Investigating rainwater harvesting on highly permeable soils - baseline conditions

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Dune sand was subjected to varying rainfall intensities in order to generate runoff under laboratory conditions on slopes of 20 and 30°. Soil moisture probes were inserted into the soil at varying depths to investigate the movement of water through the profile. Results indicate that in spite of continuous simulated rainfall administered for over 4,000 min, no runoff could be generated over the sand surfaces and across the different slopes. It was deduced that for this to occur, rainfall intensities in excess of 6,000 mmh^{-1} would be required. The results also indicated that to generate runoff from such sandy soils, treatment of the upper 0 to 10 cm of the soil profile would be required to reduce significantly the infiltration rate of the soil profile, which then will translate into runoff generation.

Key words: Ghana, rainwater harvest, overland flow, deep percolation losses, soil amelioration, sand

INTRODUCTION

Rainwater harvesting is becoming increasingly important as a means of securing water for various uses. Though Ghana has sufficient water resources, it is becoming increasingly evident that the quantity and quality of the surface water resources of Ghana is decreasing (WARM Study, 1998).

Rainwater harvesting is very crucial to the sustainable development of water resources for domestic, agricultural, industrial, aquaculture and ecosystem protection water needs. Since rainfall incidence and amount is limited and unpredictable in many areas of its occurrence, any process that maximises the retention and collection of rainwater through minimising of the losses incurred is beneficial to the success of such resource development process (Amu-Mensah et al., 2006). Not all soil types aid water harvesting from rainfall due to a number of factors including slope, permeability and vegetative cover. This paper discusses an experiment conducted on a sloped field in a large glasshouse, at the Arid Land Research Center of Tottori University, Japan for the purposes of understanding the process of runoff as they affect the successful harvesting and collection of rainwater for storage to meet various water needs. Since rainfall in the tropics is mostly relief in origin, field slopes of 20º and 30º that represent mountain slopes typical of Ghana where rainwater-harvesting potential exist, were used.

RAINFALL RUNOFF PROCESS

Rainwater runoff is that part of precipitation, as well as any other flow contributions, which appears as surface streams of either perennial or intermittent form. This is the flow collected from a drainage catchment or watershed, and it emerges at an outlet of the catchment.

It occurs when rain falls with intensity greater than the rate at which it is able to infiltrate the soil and penetrate into the water table. It may also occur when low intensity rainfall occurs over extended time as to saturate the soil

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profile and therefore generate excess water that runs off the land. The rate at which water seeps into the soil is known as the infiltration rate ($f(t)$; function of time, t) of the soil. It depends on the permeability of the surface of the soil and on the antecedent rainfall, which is important because of its effect on the moisture level of the soil profile. Initially, when the soil is dry, infiltration rate is high (fo) and the soil absorbs virtually all the rainfall. As the upper layers of the soil fill up with water, the infiltration rate reduces exponentially until it reaches a constant rate (fc).This relation, developed by Horton is expressed in Equation.

$$f(t) = fc + (fo - fc)e^{-kt}$$

$$\text{k is a decay constant}\,[\text{t}^{-1}]$$

Equation 1 Horton's infiltration relation

Horton's infiltration model is one of several models including Philip, Swartzendruber, Kostiakov (with its variants) and the SCS models, developed to describe the infiltration of water through various soils. Each has its strengths and weaknesses, however the Horton model represents well, the soil infiltration process as compared to other models (Zolfaghari et al., 2012). The Horton's infiltration model is assumed in this adopted for this work.

Total runoff from a catchment comprises direct and indirect runoff, which together end up at the outlet of the catchment. Direct runoff consists of surface flow and infiltrated rainfall moving laterally through the upper horizons of the soil and latter reappearing at the surface of the soil. Surface or overland flow arises from excess rainfall that is not able to infiltrate into the soil but flows over the land surface in channels. It travels over the ground surface and through channels to reach the outlet of the catchment. Indirect runoff on the other hand is formed by delayed subsurface and groundwater flow formed from seepage of rainwater into deeper layers of the soil profile. This accumulates and flows laterally in deeper horizons and latter emerges as springs in riverbeds and other low elevations to contribute to stream flow. During dry seasons, most of the flow in rivers and streams are a result of this indirect flow and is referred to as the base flow of the river or stream.

Rainwater harvesting assumes that there is no flowing water resource and therefore all water harvested is mainly from surface flows, principally direct runoff. This means that for the target soil fc must be low and k must be high. The result of this is that the terminal or steady infiltration rate of the soil is low enough to generate sufficient direct runoff and the decay is rapid enough to ensure the attainment of the steady state infiltration in the shortest time. This is illustrated in Figure. Soil compaction, chemical additives, bitumen coating and covering with plastic sheeting are a few ways to attain this state. This paper examines the baseline conditions of rainfall runoff existing in dune sand subjected to varying intensities of rainfall under different slope conditions.

The dynamics of water movement and storage in the soil, evaporation of moisture from the soil surface, infiltration rate of moisture in the soil as well as rainfall intensity and duration, affect the amount of water to be harvested from a land surface (Bouwer, 1990). The soil amelioration proposed in this study is therefore not a panacea for improving the rainwater harvesting properties of any land surface.

RUNOFF FROM A SLOPED FIELD UNDER DUNE SAND CONDITIONS

In order to understand the rainfall-runoff process for improving rainwater harvesting, experiments were conducted on a sloped field inside a glasshouse at the Arid Land Research Center of Tottori University, Japan. Two pairs 20º and 30º slopes, each pair facing north and south, were used in the experiment. Each 20º field measured 2.7 m × 1.8 m on the surface, while each 30º slope measured 2.9 m × 1.8 m and had Tottori dune sand packed to a bulk density of 1.6 gcm^{-3}. Amplitude Domain Reflectometer (ADR) Theta soil moisture sensors (Cambridge Delta-T™ ML-1® probes) were inserted into the soil at depths of 10, 50 and 100 cm for each field. These sensors measure the dielectric constant of the soil matrix through the amplitude difference between a 100 MHz incident sinusoidal wave transmitted into the soil, and a reflected wave received by the sensor. This is output through internal circuitry as voltage within a range of 0-1000 mV. The moisture content of the soil is directly related to the output voltage recorded by the ADR. An initial plot of sets moisture content against measured dielectric constant provides calibration for converting the measured dielectric constants to equivalent moisture content in the soil. A schematic of the experimental layout is shown in Figure 2. Overhead sprinkler nozzles placed 2.5 m above the slope provided a spray of "rain" water at an average intensity of 38.5 mmhr^{-1}. The measured distribution properties of the rainfall system and the layout of the process for measuring uniformity index are shown in Figure 3. The measured characteristics of the rain system are presented in Table 1.

The ADR theta probes, temperature and humidity sensors, wind speed sensor and solar radiation sensor (Epply Pyranometer, EKO™ MS-62) were then connected to a Campbell Scientific™ CR23X® datalogger. This were used to log soil moisture information and all other datasets at 1 s intervals and the average in a 1 min interval was output to final storage.

Since the ADR sensor readings are dependent on moisture variation as well as on soil type, they were calibrated for Tottori dune sand. The process involved adding known quantities of water to a mass of initially dry soil sample. Several samples, from dry to saturated conditions were prepared and thoroughly mixed. The probes

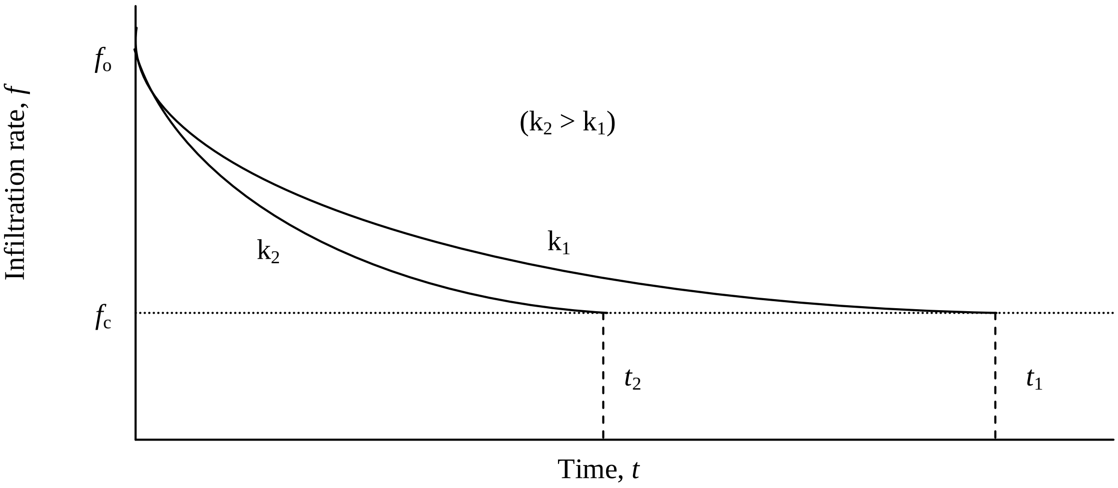

Figure 1. Effect of decay constant k, on time of runoff incidence (as k increases, t decreases).

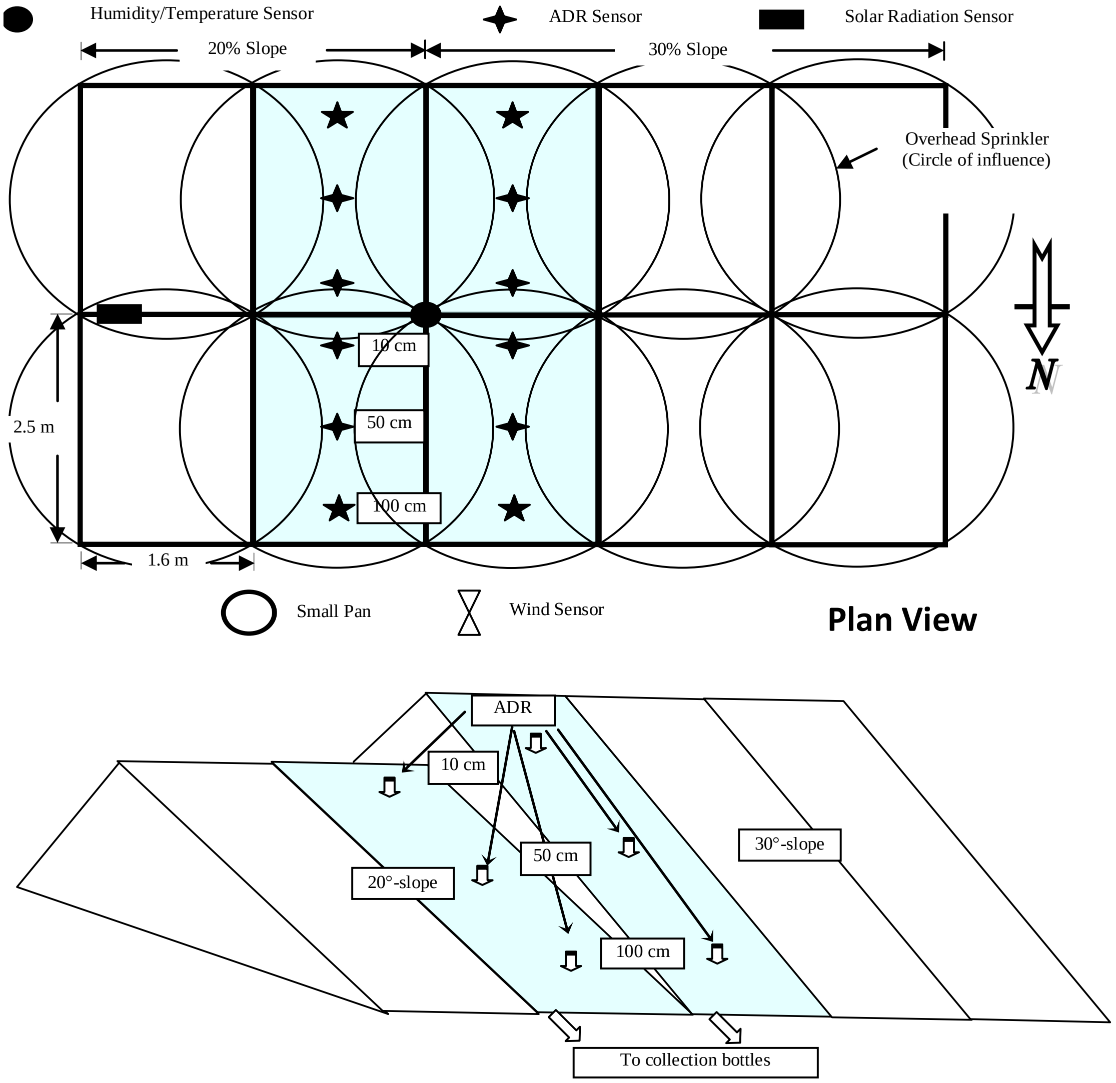

Figure 2. Schematic of sloped rainfall-runoff experimental layout showing location of ADR probes.

Figure 3. Setup for measuring uniformity and spray characteristics of overhead rainfall system (cups collect rain water.

Table 1. Characteristics of rainfall system for sloped rainfall-runoff experiment.

Mean sprinkler intensity = 38.5 mmh^{-1}	20° N slope	30° N slope	20°S slope	30° S slope
Christiansen's uniformity index (%)	50.2	56.8	53.3	54.7
Distribution coefficient (%)	41.9	40.3	47.4	49.8

were then successively inserted into the moist soil and readings were logged onto the CR23X datalogger for 5 s. A sample each of the moist soils was weighed and placed in a constant temperature oven (105°C) for 24 h until the sample was oven dry. Analysis of the gravimetric moisture content was done and converted to volumetric moisture content using the dry bulk density of the soil. The 5n s average ADR readings stored on the datalogger were then plotted against the volumetric moisture content. Regression analyses of the lines of best fit were obtained and the results are represented in Figure 4. Correlation coefficients of more than 0.99 were obtained using a third order polynomial equation as shown in the figure. With this data, it was possible to monitor the moisture variation in the slope experiment by applying the regression equation of each sensor. The experiment was carried out for 79 h and 43 min and the data collected were analysed.

Though the overhead sprinkler system was continuously operated for almost five days, there was no runoff from either the 20º or 30º sand plots in both north and south inclinations. This may be attributed to the high infiltration rate of sandy soils though some runoff might have occurred if higher rain intensities had been applied. Figure 5. illustrates these observations.

Immediately after the start of rain, soil moisture is seen to rapidly rise at all the depths starting at the surface and moving downwards. The rise in moisture content is steep indicating a rapid movement of water through the dry soil profile. Moisture content distribution through the profile is not uniform but the movement of the waterfront is identified from the sudden change in the moisture content at subsequent depths. In all the fields, the sequence of moisture content change is from the 10 cm-depth to 50 cm and finally to 100 cm. The probes were not placed in the same vertical plane but were horizontally displaced to cover the field as shown in Figure 2. It is therefore difficult to attribute the increase in moisture content at the lower depths only to vertical movement of water alone. It is probable that lateral movement of water contributes to this

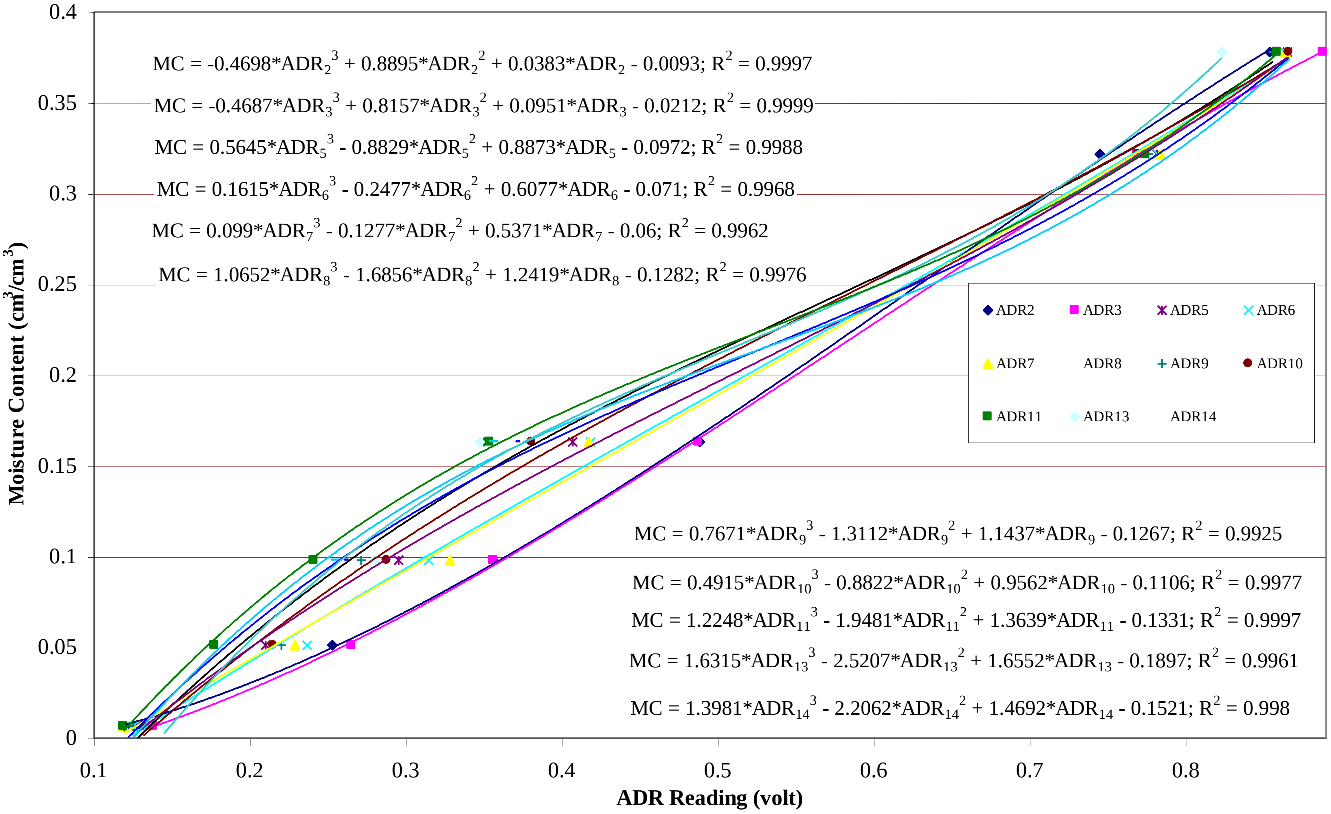

Figure 4. Calibration curves for ADR sensors used in rainfall-runoff experiment.

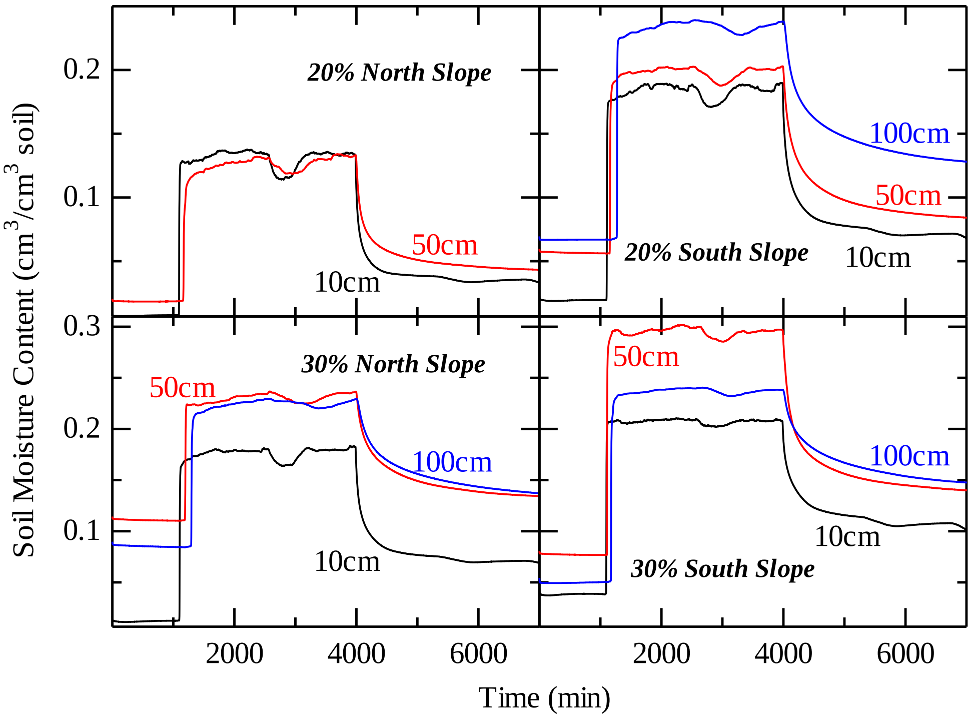

Figure 5. Soil moisture variations in sloped sand fields at different depths, before, during and after rainfall.

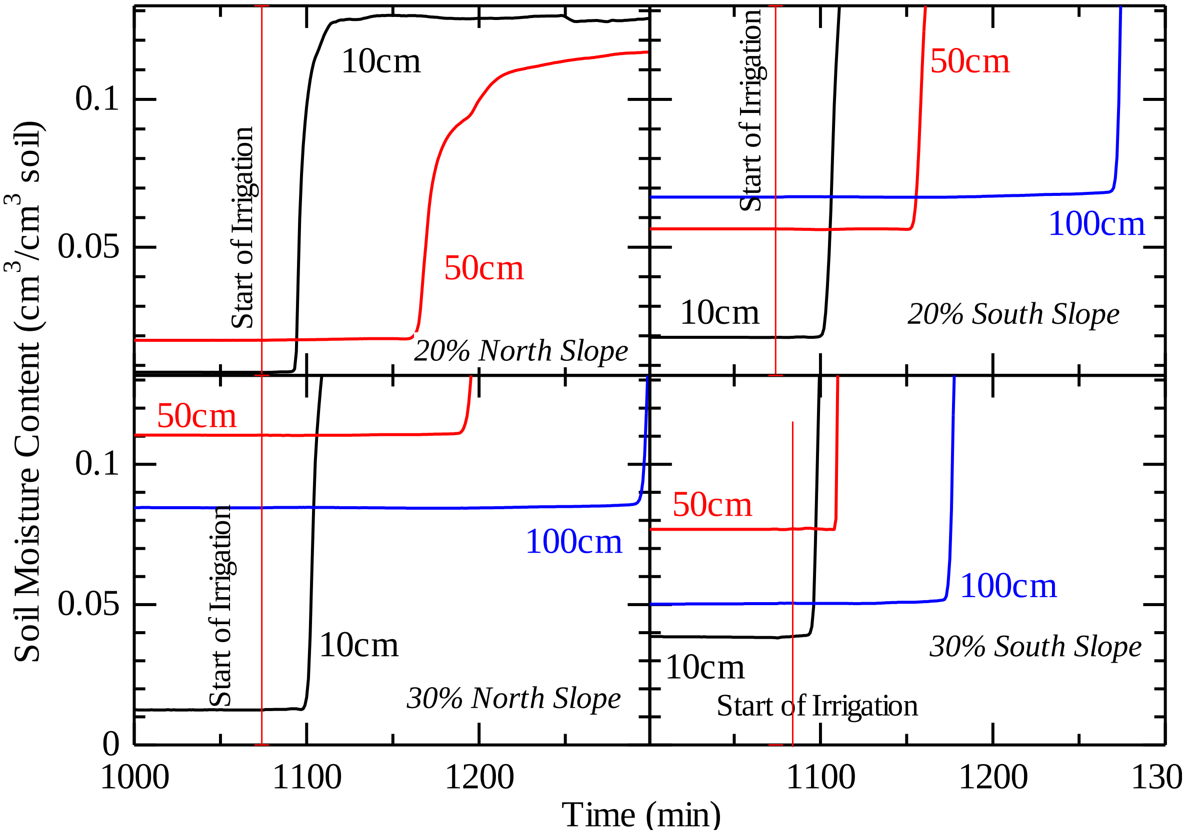

Figure 6. Rapid increases in moisture content of soil profile due to high infiltration rate.

phenomenon. Water entering the soil accumulates until its weight is more than the attractive forces between the soil and water. The water then moves to lower layers as a result of the pull of gravity, wetting the soil profile in the process. The time taken for the waterfront to move from one depth to another is used to determine the rate of movement of the water when the soil is being wetted. Infiltration rate is approximated to the rate of movement of the wetting waterfront. The infiltration rate for each layer of soil is obtained from Equation 2, which approximates the slope of the wetting front curve, n

$$If = \frac{\Delta d}{\Delta t}$$

where If is Infiltration rate (mm/h)

Δd *and* Δ are depth of water movement (mm) and time taken (h) respectively.

When the rainfall system is switched off, moisture content in the soil profile is seen to decrease rapidly. This shows that the soil is very permeable and infiltration rate is high. The rate of water movement is approximate to the rate at which moisture content at the different depths, change. In order to estimate the rate at which water infiltrates in the soil, the time taken for moisture content change from one depth to the next is calculated. Since the depth between the reference points are known, the rate in terms of distance per unit time can be deduced. Figures 6 and 7 respectively show enlarged portions of the wetting and drying phases of the moisture content curves at the three depths.

The infiltration rates calculated during the initial wetting are presented for the three depths in Table 2. Infiltration rates calculated soon after rainfall is stopped are also presented in Table 3.The high infiltration capacity of Tottori dune sand means that runoff is only possible with rainfall intensities in excess of 6,000 mmh^{-1}.

Runoff are also achieved when an impermeable surface exist at a shallow depth beneath the soil profile. This is the case in the rice plains of the Oda River basin of Ghana where sandy soils are underlain at average depths of 1 to 1.5 m by heavier clay and loam soils (Opoku-Duah et al., 1999). Though most of the soil profile is sandy in nature, runoff occurs at the slightest rain event enabling the fields to be irrigated.

Water harvesting from sand slopes may be achieved when the entire soil depth is saturated because of the presence of a high water table. This is the case at the Aframso rice plains of Ghana where the main problem is flooding during the rainy season (Opoku-Duah et al., 2000).

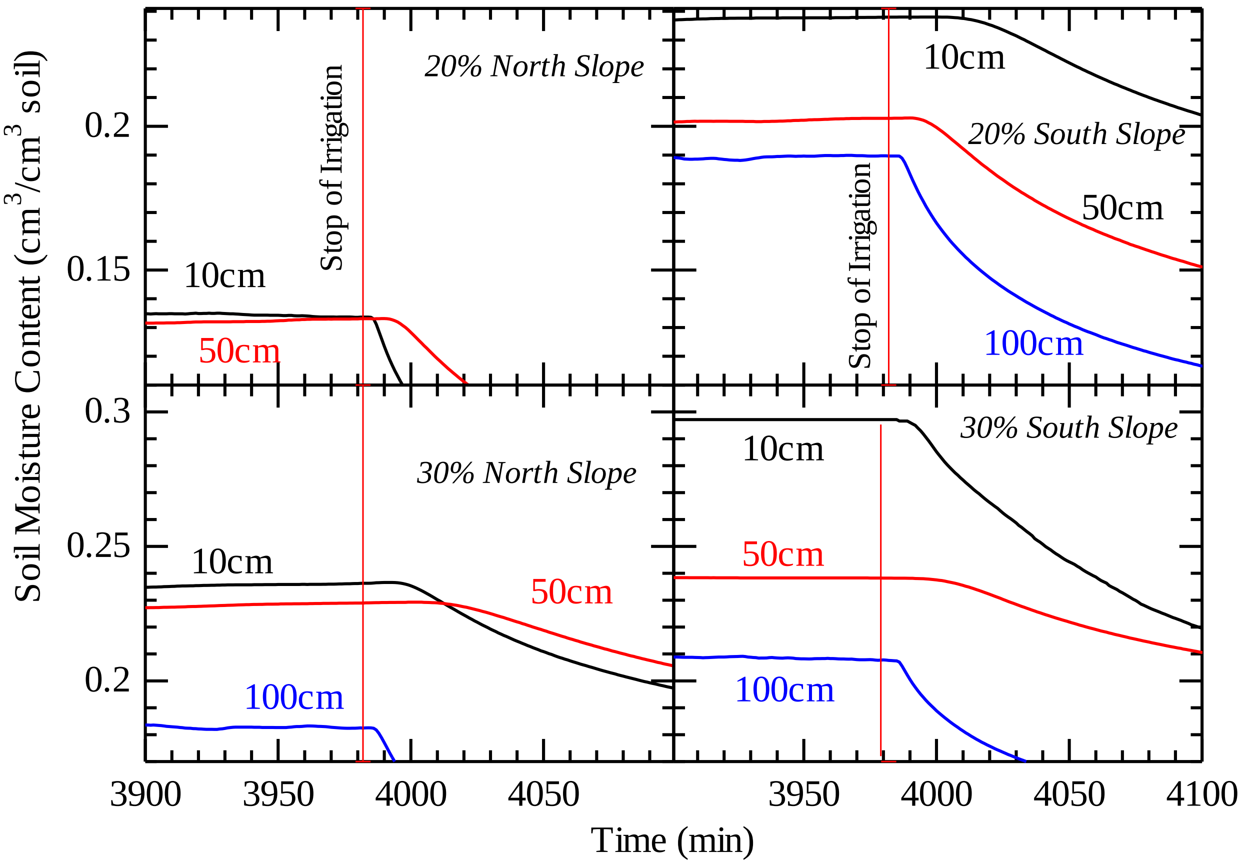

Figure 7. Rapid depletion in moisture content of soil profile due to high percolation rate.

Table 2. Initial infiltration rates calculated at start of rainfall.

Profile range (cm)	Δ*d* (cm)	20° North slope		20° South slope		30° North slope		30° South slope	
		Δ*t* (min)	*If* (mmh^{-1})	Δ*t* (min)	*If* (mmh^{-1})	Δ*t* (min)	*If* (mmh^{-1})	Δ*t* (min)	*If* (mmh^{-1})
0-10	10	16	375	22	273	23	261	17	353
10-50	40	69	348	55	436	88	273	16	1500
50-100	50	N/A	N/A	116	259	104	288	60	500
0-50	50	86	353	77	390	111	270	33	909
0-100	100	N/A	N/A	193	311	192	313	93	645

N/A – data not available.

Table 3. Terminal infiltration rates calculated after rainfall is stopped.

Profile range (cm)	Δ*d* (cm)	20° North slope		20° South slope		30° North slope		30° South slope	
		Δ*t* (min)	*If* (mmh^{-1})	Δ*t* (min)	*If* (mmh^{-1})	Δ*t* (min)	*If* (mmh^{-1})	Δ*t* (min)	*If* (mmh^{-1})
0-10	10	3	2000	3	3333	3	2000	3	2000
10-50	40	6	4000	6	4000	8	3000	4	6000
50-100	50	N/A	N/A	13	2308	20	1500	11	2727
0-50	50	9	3333	9	3333	11	2727	7	4286
0-100	100	N/A	N/A	22	2727	31	1935	18	3333

N/A – data not available.

During the rainy season, runoff from higher slopes flow into the plains, which are sandy and form a reservoir storing and releasing water by lateral flow into the river. At the Gbi-Godenu rice plains of Ghana, runoff is obtained through seepage flow at the base of the slope caused by lateral flow as a result of reduced infiltration caused by iron-pans. Alternatively, the sand slopes can be lined with cheep rubber sheeting, clay or loamy soils or planted with Vertiver grass having dense root network. This would also likely generate some runoff for agricultural use.

CONCLUSIONS

Soil amelioration techniques for improving runoff characteristics of soils for better water harvesting are available and include using plastic sheets, bitumen spreads, concrete layers and chemical additives mixed into the top soils to improve bonding to the soils (Prinz et al., 1997). These methods are quite expensive and usually interfere with the natural environment and deprive the land of other possible uses. The use of less permeable soils as a top layer dressing to reduce infiltration and enhance runoff presents an interesting and viable option that could give appreciable results.

This will especially be useful in areas with sand, sandy loam and loamy sand soils having high infiltration rates. Various locations in Ghana especially along the coastal stretch of the country and in some inland valley alluvial plains could benefit from this process if these areas are consciously lined with laterite and clay soils. When carefully designed and constructed, these rainwater harvesting fields could concentrate and channel rainwater into dugouts and reservoirs for storage and used for agricultural and other uses to improve the livelihoods of the people. Water that currently infiltrate into the soil and is not available for use could be harvested from the treated lands and made available for development of the riparian communities.

The water harvesting options presented are for agricultural water uses only as quality issues need to be addressed to enable such water to be potable. Currently serious perceptions and norms exist in the minds of most users that make the deployment of roof rainwater harvesting a problem (Hans et al., 1999, 1999a).

Soils with infiltration rates in excess of 6,000 mmh^{-1} did not generate any runoff when simulated rainfall with average intensity of 38.5 mmh^{-1} was continuously administered on them. This was in spite of continuous rainfall being administered for a period of 4,783 min. It is recommended to investigate the effect of soil surface treatment on runoff occurrence using less permeable soils for top dressing of dune sand under similar conditions.

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