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Improving soil surface conditions for enhanced rainwater harvesting on highly permeable soils

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The harnessing of runoff water from rainfall over land rather than allowing these waters to run into streams and rivers and eventually lost into the sea is attaining some popularity due to the increasing demand for scarce water resources. Sandy soils, especially in arid and semi-arid regions and along some coastal areas of Ghana (from Aflao to Tema New Town) do not generate sufficient rainwater runoff for storage because of their high permeability. This is important, as groundwater in these areas is mostly saline. To make such lands productive in terms of their ability to harvest rainwater, an experiment under laboratory conditions was conducted to apply top dressing on these land surfaces using less permeable soils on slopes of 20 and 30°. These adverse soil conditions were ameliorated with good results even though the conditions as pertains in the real world could not be completely simulated. Rather than have low or non-existent runoff from such lands from rainfall events, the application of a top dressing using a less permeable soil presented possibilities for harvesting and storing rainwater for agriculture and other uses. Harvested runoff water from rainfall of between 6 and 80 m^3/ha was obtained on the treated soils under laboratory conditions from a previous situation of zero runoff from the untreated soil. The time taken to generate runoff was drastically reduced from 4,783 min (when no runoff was generated) to less than 70 min with the treatment. This presents a hopeful mechanism for developing water resources in areas of water scarcity to improve upon poverty and livelihoods of the communities affected.

Key *w*ords: Ghana, rainwater harvest, Overland flow, Deep percolation losses, Soil amelioration, Tottori dune sand, Koyama mash clay, Isahaya polder clay.

INTRODUCTION

Runoff from highly permeable soils is difficult to generate because of their high infiltration rates. Due to the high permeability of sandy soils, heavy rainfall conditions in the order of 38.5 mm/h applied continuously for over four days on these soils may not generate any runoff (Amu-Mensah et al., 2013).

The rainfall regime in the Accra Plains of Ghana is the lowest in the country and rarely exceeds 850 mm/yr whereas evapotranspiration rates exceed 2,000 mm/yr. Similar conditions exist in arid and semi-arid areas of the world. Under such conditions as pertains in the Ada area of the Greater Accra Region, where local shallot cultivation is undertaken, frequent irrigation is needed to sustain crop yields because the soils lose considerable water through deep percolation and from evaporation ((Ben-Asher et al., 1978). The Ada area has a shallow water table that enables farmers to use tube wells to irrigate their farms. The efficiency of rainfall is low and without the tube wells, there would be no farming in this area. Where such water resources are not available, storage of rainwater offers a good source of water for irrigation and for other uses. When the runoff characteristics

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of the soils are poor, only appropriate soil amelioration measures will ensure sufficient water harvested from rainfall to meet demand.

This paper discusses an experiment conducted on a sloped field in a large glasshouse at the Arid Land Research Center of Tottori University, Japan. The purpose was to understand the process of runoff generation as influenced by the surface treatment of highly permeable sandy soils using less permeable clay and loamy sands, and the consequences to erosion as they affect the successful harvesting and collection of rainwater for storage to meet various water needs. It was also to find simple solutions to harvesting water from rainfall in the conditions mentioned, to meet especially domestic water needs. Since rainfall in the tropics is mostly relief in origin, field slopes of 20 and 30°, which represent mountain slopes where rainwater-harvesting potential exists, were used (Buah, 1998).

METHODOLOGY

In an attempt to enhance the runoff from dune sand (a highly porous soil very much like beach sand and similar to the delta soils (Wikipedia, 2013) of the coastal areas around Ada in Ghana) rainfall-runoff experiment was undertaken with treatments of Tottori Masa soil (loamy sand), Koyama Mash clay and Isahaya Polder clay. The treatments involved spreading uniformly and compacting over the dune sand soil, a 7 to 10 cm layer of the treatment soil. The properties of the soils used are given Figure 1.

Time Domain Reflectometer (TDR) soil moisture probes were inserted into the soil profile at depths of 10, 50 and 100 cm respectively in each of the soil profiles. These were connected to a Campbell Scientific CR23X data logger to log soil moisture data at the respective depths. Overhead rainfall from full-circle jet nozzles (Spraying Systems Co., Japan) provided rainfall onto the slopes for a period of 157 min. Average intensity of the spray system was 40.3 mm/h at a mean pressure of 2.75 kg/cm^3.

Data collected included rainfall intensities, rainfall amounts, runoff amounts, runoff rates, visual (photographic) changes in soil surface resulting from erosion and soil moisture variability at the various depths. The experiment was conducted in a glasshouse, on a sloped bed as shown in the schematic representation in Figure 2.

A cross-section of the soil profile showing the arrangement of the TDR probes, spraying nozzles, runoff collection bottles and soil layers is shown in Figure 3.

RESULTS AND DISCUSSION

Results show remarkable improvement in runoff generation over the layered soil surface as opposed to the bare sand runoff experiment (Table 1). Runoff from the slopes was first observed 28 min from the start of the experiment. This occurred on the 20% slope with Masa top layer dressing. It was followed by runoff from the 20% slope having as top layer, the Isahaya polder clay after 45 min of continuous rainfall. A little runoff was observed on the 30% slope with Isahaya as topsoil. This started 69 min into the experiment. The 30% Masa-topped slope did not produce any runoff however, a pool of water collected at the base of the slope 54 min into the experiment. Since this pool of water was persistent, it is probable that some runoff was generated but seeped into the soil at the base of the slope, preventing runoff to be collected into the bottles.

In all the runoff events, surface flow was enough to dislodge some soil particles. Runoff water collected was coloured in all the events however very little rill formation was observed. It is possible that the colouring of the runoff water was due mostly to silt particles suspended in the runoff flow. This is most probably due to the ramming of the slopes, which was done to compact and stabilise the soil as the top layer dressing was being applied. A more stabilised slope may not have produced any colouration in the runoff water. It is likely that heavier rainfall intensities would dislodge some soil and cause significant erosion. The Koyama clay-topped slopes did not produce any noticeable runoff. Figure 4 shows a graph of the progression rate of runoff with time for the three-runoff events that occurred.

The experimental setup showing the rainfall-runoff process in progress is shown in Figure 5. The low distribution coefficient (41 to 49%) of the overhead sprinkler system may also have contributed to the low runoff generated.

Observed runoff ratios needed for rainfall harvesting are low because of a number of factors. Firstly, the treatment soils as well as the underlying dune sand were initially dry and required a significant amount of wetting to generate some runoff. Much of the rainwater was thus used to wet the soil profile especially as the soil mass was not as stabilised as exists in real life. In spite of this, runoff was observed to occur early in the experiment as opposed to the non-treated condition when no runoff was observed from the dune sand slopes. The layer of treatment soil may be too thin and therefore does not effectively reduce the infiltration rate of the soil. If this occurred, a significant amount of the rainwater will still infiltrate into the soil profile. The fact that some runoff was generated in spite of the thin layer of treatment soil, when previously no runoff was generated, shows how effective this method can be. Additional treatment to improve the structure of the treatment material through mulching for example, could further improve runoff.

It is probable, though not confirmed that the “fingering phenomenon” (Dong et al., 2010), which is responsible for high infiltration in sandy soils overlain with a less permeable soil, is the reason for the low runoff generated. Another reason for the low runoff ratio is the short duration of the experiment. Since a significant fraction of the rainwater as well as time was required for the initial wetting of the soil, enough time was not available for the generation of actual runoff. This is especially the case for the Isahaya-treated soil on the 30° slope. In order to reduce errors, plastic rain shields were placed to prevent direct rain into the collecting gutters.

It is however significant that the experiment produced

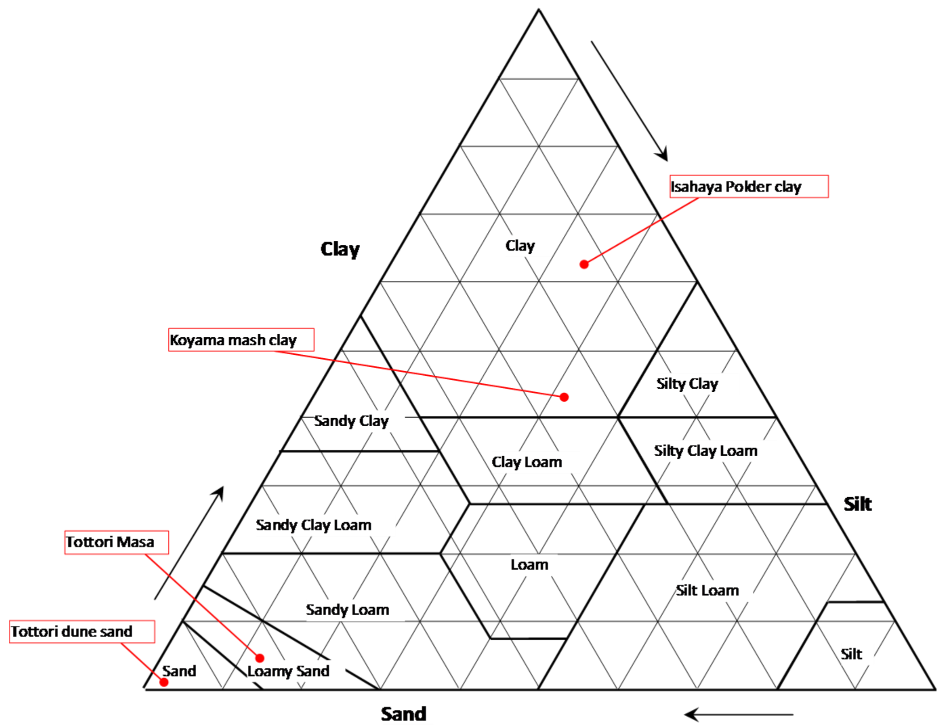

Figure 1. USDA textural classification of soils used for rainfall-runoff experiment.

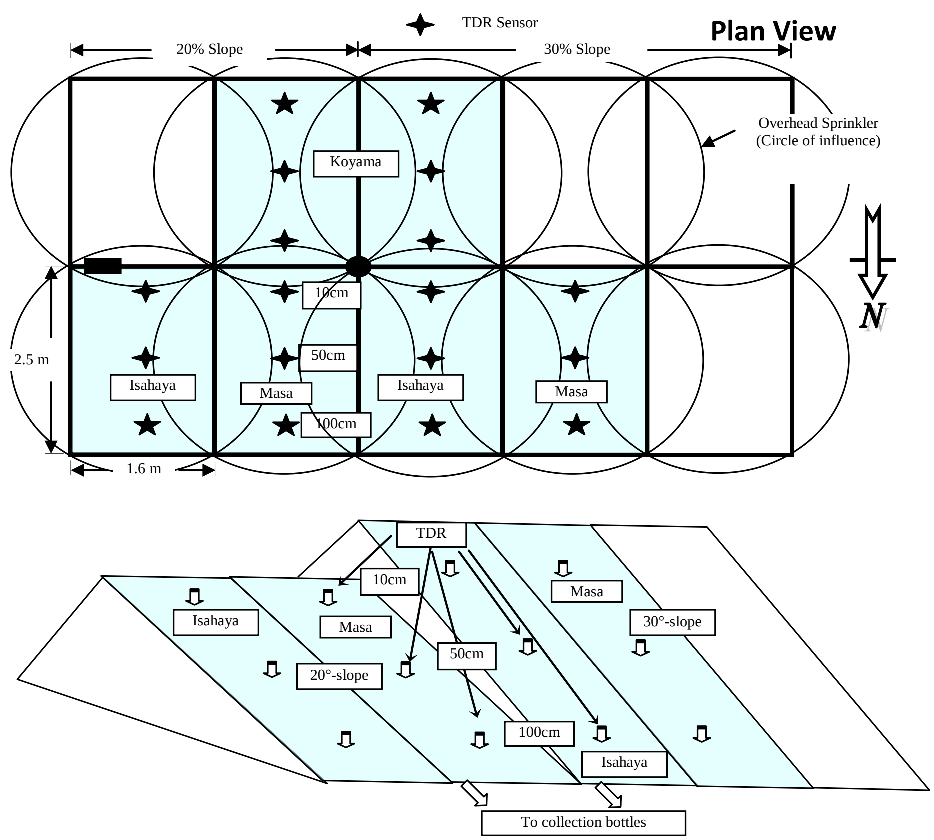

Figure 2. Arrangement of TDR probes, rainfall nozzles, runoff collection bottles and treatment soil layer.

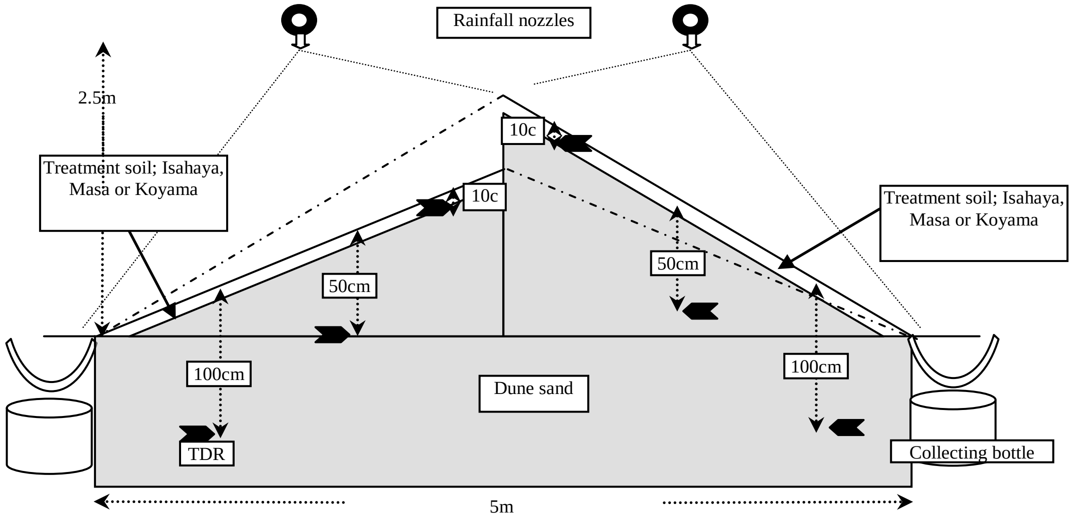

Figure 3. Cross sectional layout of layered rainfall-runoff experiment showing positions of equipment used.

Table 1. Results of runoff events on treated sand slopes.

Runoff events	Dune sand	Top layer treatment material (on dune sand) and slope		
	No treatment	Isahaya clay 20° slope	Masa 20° slope	Isahaya 30° slope
Start of runoff (from start of rainfall)	No runoff*	45 min	28 min	69 min
Total runoff (l)	0	7.95 (17,408 m^3/ha)	36.8 (80,580 m^3/ha)	2.77 (6,127 m^3/ha)
Mean runoff rate (l/h)	0	5.25	19.74	0.0006
Maximum recorded runoff rate (l/h)	0	7.16	30.6	0.0006
Runoff ratio (%)	0	1.68	7.75	0.58

*No generated runoff after 4,783 min (Amu-Mensah et al., 2013).

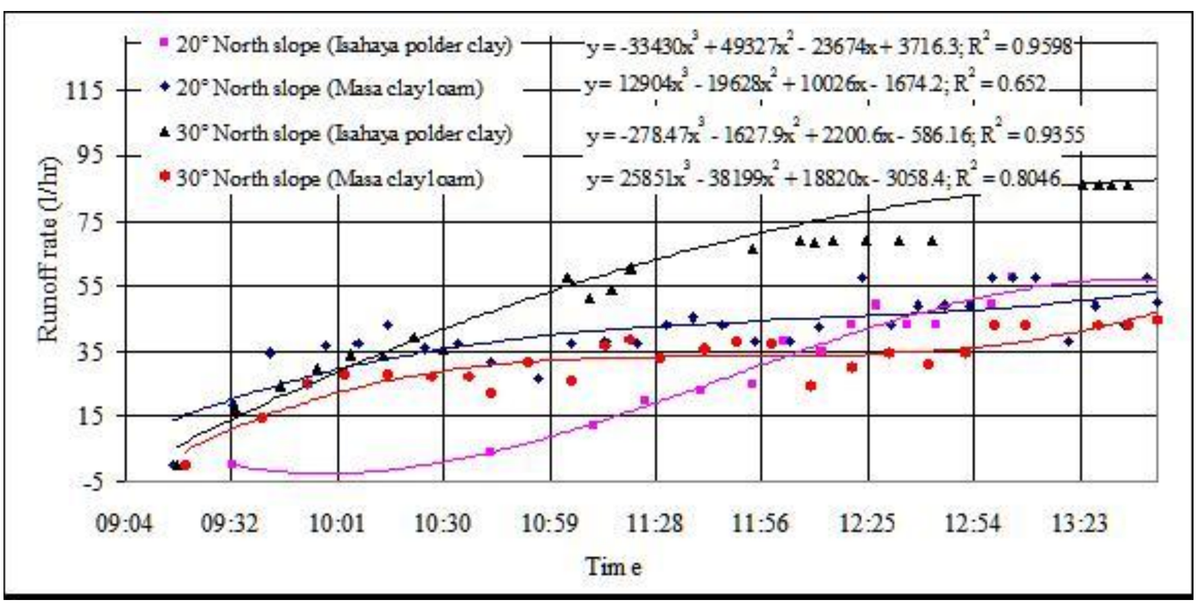

Figure 4. Runoff progression rate as measured for constant rainfall intensity of 40.3 mm/h.

Figure 5. Rainfall-runoff experimental layout showing slopes with different top layer soil treatments.

some level of runoff and therefore presents some options for improving the runoff characteristics of soils with poor rainwater harvesting potential. Based on the initial condition of the experimental plot, with its clear disparities to real land situations, which over time have established a firm and stabilised regime, it is reasonable to assume that the runoff characteristics of the experimental plot will improve with time as the plot stabilises through the wetting and drying cycles characteristics of natural lands.

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 of the soils particles. These methods are quite expensive and usually interfere with the natural environment and deprive the land from being used for other activities. The use of less permeable soils as a top layer dressing to reduce infiltration and enhance runoff has been shown to be a viable option with appreciable results obtained.

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, which currently infiltrate into the soil and is lost, could be harvested from the treated lands and made available for development of the riparian communities.

Sandy soils are characterised by high infiltration rates in excess of 6,000 mm/h that makes them unable to generate any sufficient runoff even when rainfall with average intensity of 38.5 mm/h are continuously administered to them. This was in spite of continuous rainfall being administered for a period of 4,783 min. Upon the treatment on these soils however, runoff generation started in as little as 28 min and in as much as 69 min after rainfall with average intensity of 40.3 mm/h was administered.

Runoff ratios observed are low and the thin layer of top dressing employed could have been the reason for the observation. This could have enabled significant amounts of the rainfall to seep into the soil profile because of the thickness of the layer. The low intensity of the rainfall event, which under tropical conditions could reach as high as 140 mm/h could also have caused these low ratios.

Considering that the rate of runoff continued to increase as the experiment progressed, it is to be expected that a well compacted top dressing which has stabilised over time, will offer better runoff generation capabilities. It is also reasonable to suppose that a thicker top dressing on the sand would yield higher runoffs as they would further reduce the permeability of the soil.

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