SOIL EROSION STUDIES UNDER SIMULATED RAINFALL CONDITIONS IN A LATERITIC TERRAIN

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PRAVEENA K K

(2012 – 18 – 104)

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KELAPPAJI COLLEGE OF AGRICULTURAL ENGINEERING AND TECHNOLOGY

TAVANUR - 679573, MALAPPURAM

KERALA

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DECLARATION

I hereby declare that this thesis entitled "**SOIL EROSION STUDIES UNDER SIMULATED RAINFALL CONDITIONS IN A LATERITIC TERRAIN"** is a bonafide record of research done by me during the course of research and that the thesis has not previously formed the basis for the award to me of any degree, diploma , associateship, fellowship or other similar title of any other University or Society.

Tavanur, **PraveenaK.K**

Date: **(2012 - 18 - 104)**

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Certified that this thesis, entitled **"SOIL EROSION STUDIES UNDER SIMULATED RAINFALL CONDITIONS IN A LATERITIC TERRAIN"** is a record of research work done independently by **Miss. Praveena K.K. (2012 – 18 – 104)** under my guidance and supervision and that it has not previously formed the basis for the award of any degree, diploma, fellowship or associateship to her.

Dr. Kurien E. K
(Chairman, Advisory Committee)
Associate Professor
Department of Land & Water Resources
and Conservation Engineering
KCAET. Tavanur

Tavanur
Date:

CERTIFICATE

We the undersigned members of the Advisory Committee of **Miss. Praveena K.K., (2012-18-104)** a candidate for the degree of **Master of Technology in Agricultural Engineering**, agree that the thesis entitled **“SOIL EROSION STUDIES UNDER SIMULATED RAINFALL CONDITIONS IN A LATERITIC TERRAIN”** may be submitted by **Miss. Praveena K.K.,** in partial fulfilment of the requirement for the degree.

Dr. Kurien E. K
(Chairman, Advisory Committee)
Associate Professor, Department of Land & Water Resources and Conservation Engineering, KCAET, Tavanur

Dr.Abdul Hakkim. V.M
(Member, Advisory Committee)
Associate Professor and Head,

Department of Land & Water
Resources and Conservation
Engineering

K.C.A.E.T, Tavanur.

Dr.Leven. K .V
(Member, Advisory Committee)
Associate Professor
Department of Irrigation and
Drainage Engineering
KCAET, Tavanur

Dr Habeeburrahman P. V
(Member, Advisory Committee)
Professor and Head
KVK, Malappuram
(Member)

EXTERNAL EXAMINER

(Name and Address)

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Dedicated to
My loving family
And
Profession

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SYMBOLS AND ABBREVIATIONS

Af	African
Agric.	Agricultural
Am.	America/American
ASAE	American Society of Agricultural Engineers
A	Ampere
Bull.	Bulletin
ºC	Degree Celsius
chap.	Chapter
Cir	Circular
Cons.	Conservation
Contd.	Continued
Dept.	Department
Eng.	Engineering
et al.	and other people
Fig.	Figure
ha	hectare
hp	horse power
G.I	Galvanized Iron
G.V.	Gate valve
ha	hectare(s)
J.	Journal
KAU	Kerala Agricultural University

KCAE T	Kelappaji College of Agricultural Engineering and Technology
L W R C E	Land & Water Resources and Conservation Engineering
L/min	Litre per minute
manag.	Management
MTA	Male threaded adaptor
No.	Number
PAM	Polyacrylamide
pp.	Pages
proc.	Proceedings
PVC	Poly Vinyl Chloride
Res.	Research
Resour	Resources
rpm	revolutions per minutes
s	second(s)
Sci	Science
Soc.	Society
t	tonne(s)
t/ha	tonne per hectare
Tech.	Technical
Tr.	Transactions
TNAU	Tamil Nadu Agricultural University
Univ.	University
USDA	United States Department of Agriculture
Vol.	volume

INTRODUCTION

CHAPTER 1

INTRODUCTION

Human intervention and manipulation of soil has lead to an increased amount of erosion, known as accelerated erosion. Soil erosion is one form of soil degradation similar to soil compaction, low organic matter, loss of soil structure, poor internal drainage, salinisation and soil acidity problems. Soil erosion is a naturally occurring process on all lands. The agents of soil erosion are water and wind, each contributing a significant amount of soil loss. Soil erosion may be a slow process that continues relatively unnoticed or it may occur at an alarming rate causing serious loss of topsoil. The loss of soil from cultivated land may be reflected in reduced crop production, lower surface water quality and damaged drainage networks.

Laterite is highly weathered material, rich in secondary oxides of iron, aluminum or both. It is nearly void of bases and primary silicates but it may contain large amount of quartz and kaolinite. It is either hard or capable of hardening on exposure to wetting and drying. The term ‘laterite’ was originally used for highly ferruginous deposits first observed in Malabar Region of coastal Kerala and parts of Karnataka. In Kerala, laterite soils are the most important soil group covering the largest area. The lateritic terrain of Kerala occupies the midland region and the economy of the state depends upon this terrain which produces most of its cash crops.

The measurement of soil erosion could be done either in the field or in the laboratory. The use of these two techniques depends upon the objectives of data collection on soil erosion. In laboratory experiment, the measurement can be carried out under simulated conditions, *i.e.* to assess the influence of one or more related parameters on the rate of soil erosion. The study is carried out by repeating the experiment for different slope steepness. In brief, the experimental techniques are employed for studying the mechanics of erosion, where the effect of related factors can be controlled.

Rainfall simulators are used in most of the laboratory studies, which is designed to produce a storm of energy, intensity and drop size characteristics that can be repeated on demand. Rainfall simulators allow generating rainfall with a known intensity and duration on an erosion plot in a controlled manner and thus make it possible to quantify runoff and soil loss. It allows very detailed erosion predictions. Thus simulators have widely contributed to the understanding of soil erosion process. It is possible to find good correlations between the values of soil loss measured in an erosion plot under simulated rainfall.

Rainfall simulators are classified according to the drop formers used. The most common are hanging yarn type, tubing tips, with either hypodermic needles or capillary tubes and nozzles. None of the simulators accurately recreates all the properties of natural rain. But rainfall simulators using sprinkler nozzles are capable of recreating the desired characters of natural rainfall.

Field measurements may be classified into two groups as those designed to determine soil loss from relatively small areas or erosion plots and those designed to assess erosion over a larger area, such as a drainage basin. Runoff plots are isolated areas of known size used to measure the losses of soil and water due to erosion. The rainfall simulators used for such kind of rainfall simulation should be capable of achieving fairly uniform, continuous rainfall intensity application over the study area. The simulators should also be capable of applying almost vertical impacts for most raindrops and applying repeatable simulated rainstorms.

Runoff is generated by rainstorms and its occurrence and quantity are dependent on the characteristics of the rainfall event like intensity, duration and distribution. When rain falls, the first drops of water are intercepted by the leaves and stems of the vegetation. This is usually referred to as interception storage. As the rain continues, water reaching the ground surface infiltrates into the soil until it reaches a stage where the rate of rainfall intensity exceeds the infiltration capacity of the soil. Thereafter, surface puddles, ditches, and other depressions are filled, after which runoff is generated.

Soil erosion models are used to predict soil erosion risk or rates of erosion for a specified area. There are many erosion prediction models in existence but some notable ones include the Universal Soil Loss Equation (USLE), Water Erosion Prediction Project (WEPP), European Soil Erosion Model (EUROSEM) and the Morgan-Morgan-Finney model (MMF). All erosion models require input data which may include rainfall erosivity, volume and intensity, soil parameters of erodibility, properties such as moisture content, bulk density, cohesion strength, depth and surface depression storage, slope steepness and length, cropping regimes, land management, and land cover. With any model it is important that it should be validated using measured data.

Field size plots and relatively small rectangular plots are commonly used in erosion studies. The runoff plots could be utilized to study the effects of rainfall on runoff and soil erosion from bare soils and the surfaces with mulches. The data which are obtained can be used to construct or validate a model or can be used to develop equations to predict runoff and soil loss.

The present study has been taken on a lateritic terrain at Tavanur, Malappuram District of Kerala State. The soils in the area were identified as belonging to the Naduvattom series. A rainfall simulation study was taken on natural soil demarcated in to micro soil erosion study plots of size 2 x1.5 m.

The objectives of the thesis work are listed as,

1. To develop a rainfall simulator.
2. To study the performance of the developed rainfall simulator.
3. To study the effect of rainfall on soil loss.
4. To study the effect of rainfall on runoff.
5. To develop a soil erosion model.

REVIEW OF LITERATURE

CHAPER 2

REVIEW OF LITERATURE

The use of artificial rainfall is a common method to study the runoff and soil loss. Micro soil erosion plots demarcated by borders under simulated rainfall were made use in several erosion studies. Experiments under natural rainfall had drawbacks such as variation in intensity and duration of rainfall, initial soil water status, too long observations for several years. Attempts to reproduce the rain under controlled conditions, both in field and laboratory, were therefore designed to overcome these disadvantages. The previous studies relevant to the topics of soil erosion, runoff and rainfall simulators are briefly reviewed in following sections.

2.1 Laterite soil

The term 'laterite' was introduced by Buchanan (1807) as a name for a soft ferruginous rock that was quarried in southern India for building blocks and has close genetic association with bauxite. The term 'laterite' was originally used for highly ferruginous deposits first observed in Malabar region of coastal Kerala and Dakshin Kannad and other parts of Karnataka.

Lake (1980) used the following simple descriptive classification for the laterites in Malabar, India.

Groups	**Nature of the laterite**	**Origin**
Plateau laterite	Vesicular	Nondetrital
Terrace Laterite	Pellety	Detrital
Valley Laterite	Partly vesicular	Partly nondetrital
Valley Laterite	Partly pellety	Partly detrital

Bayewu *et al*. (2012) studied the petrographic and geotechnical properties of lateritic soils developed over different parent rocks. A total of five bulk samples of laterite soils developed over five different parent rock materials were collected. These rock types are porphyroblastic gneiss, banded gneiss, quartz schist, gneiss and biotite gneiss. He concluded that biotite gneiss and granite gneiss have the highest feldspar content and are likely to weather into soils with higher percentage of clay minerals which controls the geotechnical properties. The differences in the engineering properties of the soils is related to the variation in mineralogy of the parent rock from which the soils were derived, resulting in differences in plastic index, grain size distribution, CBR (California Bearing Ratio) characteristics, liquid limit, plastic limit and unconfined compressive strength.

From the distribution of the laterite soil it can be seen that this vast region have a large portion of favourable topography for agriculture and adequate temperature for the plant growth. The physical constraints for laterite soils in crop production include susceptibility to erosion, low water holding capacity and drought stress. In Kerala, laterite soils are grouped into different series according to their locality and profile features (Soil Survey Department, Kerala).

2.2 Soil erosion

Soil erosion may be defined as the detachment and removal of soil material from the soil surface of the ground, either by water or by wind. Several distinctive processes are involved in erosion of surface materials by water. They are raindrop splash, unconcentrated wash including sheet flow erosion, concentrated wash including rill, gully, stream bank, and channel erosion, and a mixed process in which erosion takes place by raindrop splash and transport (Finkel, 1986).

Onyando *et al*. (2000) reported that soil erosion and surface runoff was higher in the deforested, agriculture and grazing lands than in the forested lands. He also suggested that soil erosion and surface runoff depend on rainfall and several watershed characteristics and management practices.

Soil erosion describes the detachment, transport and deposition of soil particles by wind or water. It is a biophysical process that also occurs naturally, but is highly accelerated by human interferences that are linked to social, economic, political and institutional factors (Lal, 2001).

Bernard and Eric (2002) reported that the evaluation of soil susceptibility to runoff and water erosion is often expensive and time consuming. Soil susceptibility is linked to aggregate stability whose determination is far easier.

Soil erosion plots of different types and sizes are widely used to investigate the geo morphological processes related to soil erosion. The relation between soil loss at land surface and the values obtained by field plots depends on how good the methodology performs over a set of ecosystem properties, such as those related with temporal and spatial scale issues, disturbance and representation of natural conditions, and the ability to account for the complexity of ecosystem interactions (Boix *et al*., 2006).

Geologic and accelerated are the two main types of erosion. Geologic erosion is a normal process of weathering that generally occurs at low rates in all soil as part of the natural soil forming processes. In contrast soil erosion becomes a major concern when the rate of erosion exceeds a certain threshold level and becomes rapid, known as accelerated erosion (Blanco *et al*., 2010)

2.2.1 Soil erosion process

There are four primary types of erosion that occur as a direct result of rainfall such as splash erosion, sheet erosion, rill erosion and gully erosion. Splash erosion is generally seen as the first and least severe stage in the soil erosion process, which is followed by sheet erosion, then rill erosion and finally gully erosion (Zachar and Dusan, 1982).

Erosion is a three step process involving the detachment, transportation, and deposition of soil particles. Detachment occurs when the erosive forces of rainfall drop impact or when flowing water exceeds the soil's resistance to erosion. Detached particles are transported by the splash and flow of raindrop. Deposition occurs when the sediment load of eroded particles exceeds its corresponding transport capacity. The relative importance of these fundamental processes depends on whether the processes are occurring on inter-rill or rill areas and in the levels of the controlling variables (Foster, 1985).

All the erosion processes take place through a medium, which may be water, wind, snowmelt etc. The most commonly however, soil erosion is driven by rainfall erosivity i.e. the potential of rainfall to cause erosion (Mark, 2005).

Rill erosion refers to the development of small, ephemeral concentrated flow paths which function as both sediment source and sediment delivery systems for erosion on hill slopes. Generally, where water erosion rates on disturbed upland areas are greatest, rills are active. Flow depths in rills are typically of the order of a few centimetres or less and slopes may be quite steep. This means that rills exhibit hydraulic physics very different from water flowing through the deeper, wider channels of streams and rivers (Jean *et al.*, 2007).

Gully erosion occurs when runoff water accumulates and rapidly flows in narrow channels during or immediately after heavy rains or melting snow, removing soil to a considerable depth (Deva *et al.*, 2008).

In splash erosion, the impact of a falling raindrop creates a small crater in the soil, ejecting soil particles. The ejected soil particles can travel in as much as 0.6 m vertically and 1.5 m horizontally on level ground (Obreschkow, 2011).

A field experiment using rare earth elements as tracers was conducted to investigate soil erosion processes on slope surfaces during rainfall events. A plot of 10 m × 2 m × 0.16 m with a gradient of 36.4% was established and the plot was divided into two layers and four segments. Various rare earth element tracers were applied to the different layers and segments to determine sediment dynamics under natural rainfall. Results indicated that sheet erosion accounted for more than 90% of total erosion when the rainfall amount and density was not large enough to generate concentrated flows. Sediment source changed in different sections on the slope surface, and the primary sediment source area tended to move upslope as erosion progressed. In rill erosion, sediment discharge mainly originated from the down slope and moved upwards as erosion intensified. The results obtained from this study suggest that multi rare earth tracer technique is valuable in understanding the erosion processes and determining sediment sources (Mingyong *et al.*, 2012).

2.2.2 Erosion measurement

Agriculture can result in soil erosion when improper management is applied on arable land. The frequent use of heavy machinery which is often not adapted to the land favours soil compaction. Different tillage methods disturb the soil, alter the bulk density and hydraulic conductivity of the soil and damage its physical and chemical properties (Oldeman, 1997).

The near to complete removal of natural vegetation from large stretches of land or by "converting forest into agricultural land, large scale commercial forestry, road construction or urban development" (Oldeman,1997) might be the most severe cause of soil erosion. The study of different models by Kirschke *et al.* (1999) confirms that deforestation, especially in combination with population pressure, is clearly very relevant for erosion.

Toy *et al.* (2002) described the benefits of erosion measurements as,

1. Determination of the environmental impact of erosion and conservation practices
2. Scientific erosion research
3. Development and evaluation of erosion control technology
4. Development of erosion prediction technology
5. Allocation of conservation resources and development of conservation regulations, policies and programs.

Leo (2005) reported that erosion measurement techniques for scientific erosion research are more accurate and aim at causes and effects of erosion. When expressed in an equation this implies a dependent variable which can be estimated from values of one or more independent variables. An erosion inventory often uses a mix of two technologies: direct measurements and the use of erosion prediction technology. Characteristics of measurement techniques for erosion inventory are,

1. They are not so accurate.
2. They are cheap and fast so that many spots (e.g. along transects) can be measured.

The choice of tillage practice also influences the roughness of the surface, thus the resistance to soil detachment and transport, and the direction of the runoff channels (Morgan, 2005).

Schindler (2008) reported that the suitability of crops “to the capacity of the soil and wider environment” is crucial in maintaining the conditions of the soil, preventing degradation and minimising the risk of productivity losses. Especially mono cropping can harm soils but also the introduction of less suitable cash crops can eventually lead to a decline of soil fertility.

2.2.3 Factors affecting soil erosion

The major factors affecting the soil erosion are climate, soil, vegetation and topography. Climatic factors affecting erosion are rainfall, temperature, and wind. The plant cover can be regarded as protection against erosion since it reduces the force of the rainfall and the velocity of the runoff (Morgan, 2005).

2.2.3.1 Precipitation and wind speed

Climatic factors include the amount and intensity of precipitation, the average temperature, as well as the typical temperature range, seasonality, wind speed, and storm frequency. Generally in similar vegetation and ecosystems, areas with high-intensity precipitation, more frequent rainfall, more wind, or more storms are expected to have more erosion.

Since erosion starts with the process of soil detachment by raindrop impact, the basic unit of raindrop erosivity can be represented by the stress, momentum or kinetic energy of a single raindrop (Sharma, 1996), which are all functions of the drop size, drop shape and the terminal velocity.

Jayawardena (2000) introduced a relatively inexpensive device that uses a piezoelectric force transducer for sensing raindrop impact response which is used to find the drop size distribution, momentum and kinetic energy of rainfall. The instrument continuously and automatically records, on a time-scale, the amplitude of electrical pulses produced by the impact of raindrops on the surface of the transducer. The size distribution of the raindrops and their respective kinetic energy are calculated by analysing the number and amplitude of pulses recorded, and from the measured volume of total rainfall using a calibration curve.

Simultaneous measurements of the instrument, a rain gauge and a dye-stain method were used to assess the performance of the instrument.

The impact of rainfall and its related parameters is best described as erosivity, which is determined by the raindrop size, rainfall intensity, amount and frequency of the rain as well as runoff amount and velocity. The erosivity is further influenced by the terrain characteristics such as slope gradient, length, aspect, shape and ground cover (Lal, 2001).

The quantity of soil lost during a rainfall event is a function of the kinetic energy of the rain that impacts the soil. Larger rain drops have both greater mass and vertical terminal velocity such that a disproportionate amount of erosion results from the action of a small number of large drops (Neil, 2004).

The soil loss is related to the rainfall through the detachment of soil particles by the power of raindrops hitting the soil surface and through the contribution of rain to the runoff which determines the transport of the material (Morgan, 2005).

2.2.3.2 Soil structure and composition

Soil containing high levels of organic materials are often more resistant to erosion, because the organic materials coagulate soil colloids and create a stronger and more stable soil structure. Chow and Rees (1994) studied the effect of content and size of soil coarse fragments on soil erosion. He reported that the runoff and soil loss were found to decrease with increasing size and content of coarse fragments. Bradford and Foster (1996) reported that sediment size will influence on sediment yield and the splash process.

The amount of water present in the soil before the precipitation also plays an important role, because it sets limits on the amount of water that can be absorbed by the soil. Wet, saturated soils will not be able to absorb as much rain water, leading to higher levels of surface runoff and thus higher erosivity for a given volume of rainfall (Torri, 1996).

The term soil structure means the grouping or arrangement of soil particles. Over cultivation and compaction cause the soil to lose its structure and cohesion and it erodes more easily (National Department of Agriculture, 1999).

Very small and coarse particles results in the greatest resistance to detachment, due to strong adhesive or chemical bonding in small particles and the affect of increased weight of coarser particles (Morgan 2005).

The composition, moisture, and compaction of soil are all major factors in determining the erosivity of rainfall. Sediments containing more clay tend to be more resistant to erosion than those with sand or silt, because the clay helps bind soil particles together (Mirsal *et al*., 2008).

Soil compaction also affects the permeability of the soil to water, and hence the amount of water that flows away as runoff. More compacted soils will have a larger amount of surface runoff than less compacted soil (Blanco *et al*., 2010).

2.2.3.3 Slope

Some studies looked into the effects of different slope or rainfall intensities on the dynamics of erosion (Huang, (1998); Fox and Bryan, (1999) and Romkens *et al*., (2001)).

Fox and Bryan (1999) found that for a constant runoff rate, erosion by rain-impacted flow increased roughly with the square root of slope gradient, as for the runoff velocity.

Kinnell (2000) reported that sediment concentration in flow from side slopes increased with slope gradient, particularly if this exceeded 10 per cent. After studying erosion from small plots with slope gradients of four per cent and eight per cent in tilled fields, Chaplot and Bissonnais (2003) reported that sediment concentration in runoff was not correlated with slope gradient.

The velocity and volume of the surface runoff increase with the slope steepness and its slope length. The soil loss is proportional to the product of the slope length and the tangent of the slope angle (Kumar, 2004).

Tony *et al.* (2005) conducted a full scale field study to investigate the effects of rainfall infiltration on a natural grassed expansive slope. A 16 m wide x 20 m long area was selected for instrumentation. The instrumentation included jet-filled tensiometers, moisture probes, a tipping bucket rain gauges and a v-notch flow meter. An artificial rainfall of 370 mm was applied to the slope. The results showed that the depth of influence of rainfall depending upon the elevation of the slope ranged from 2.8 to 3.5 m. Positive pore pressure were measured within the influence depth, and there existed a significant subsurface down water flow at the end of the simulated rainfall, particularly near the lower part of the slope.

For the mild slopes of five per cent and nine per cent, the sediment concentration is stable, which could characterize either a transport limited or a detachment limited process. For the intermediate slope of 15 per cent, the concentration continued to increase mildly, as if the transport limiting situation of the first stage was still occurring. Finally, for the steeper slopes 20 per cent and 25 per cent, the sediment concentration reached a peak value before declining, indicating that erosion shifted from transport limited to detachment limited regime (Ben-Hur, 2006).

The topography of the land determines the velocity at which surface runoff will flow, which in turn determines the erosivity of the runoff (Whisenant, 2008).

Suhua Fu (2009) conducted a study to investigate the effect of slope gradient on soil erosion. Simulated rainfall was conducted above a series of soil trays with nine different slopes on sandy loam soils. The results revealed that the total soil loss was increased with slope, and then decreased after a maximum value was reached. He also indicated that the slope gradient has greatest effect on down slope soil erosion and least impact on lateral erosion.

Longer, steeper slopes especially those without adequate vegetative cover are more susceptible to very high rates of erosion during heavy rains than shorter, less steep slopes. Steeper terrain is also more prone to mudslides, landslides, and other forms of gravitational erosion processes (Blanco *et al.,* 2010; Wainwright, 2011).

2.2.3.4 Vegetative cover

Vegetation acts as an interface between the atmosphere and the soil. It increases the permeability of the soil to rainwater thus decreasing runoff. It shelters the soil from winds, which results in decreased wind erosion, as well as advantageous changes in microclimate. The roots of the plants bind the soil together, and interweave with other roots forming a more solid mass that is less susceptible to both water and wind erosion. The removal of vegetation increases the rate of surface erosion (Styczen and Morgan, 1995).

Siepel *et al.* (2002) expanded use of Manning's roughness in determining erosion rates under grass vegetated surface conditions and show that a certain minimal cover is required to trap suspended sediment.

Xinxiao *et al.* (2006) conducted a study on the effects of vegetation cover and precipitation on the process of sediment produced by erosion in a small watershed of Loess region. The conclusions showed that with the increase of precipitation indexes and the decrease of plant indexes and the amount of sediment produced by erosion in the study area would become larger. In order to distinguish the influences of erosion due to human activity and natural factors, the paper introduced multi-variable regression method by standardization data to determine the relative contributing ratio to soil erosions in the study area. The conclusions showed that the contributing ratio of vegetation cover and precipitation changes were 45.7 per cent and 54.3 per cent. It was obvious that the influences of precipitation were larger than those of vegetation for the soil erosion in the study area.

Veena and Devidas (2010) conducted an experiment on six selected experimental fields of 2 × 2m within the catchment with distinct variations in surface characteristics such as grass-covered area with gentle slope, recently ploughed gently sloping area, area covered by crop residue, bare badland with steep slope, gravelly surface with near flat slope and steep slope with grass cover. The results indicated that each variation among the plots depend on their slope angle and surface characteristics. An important finding that emerged from the study was that the grass cover is the most effective measure in inducing infiltration and in turn minimizing runoff and sediment yield. Sediment yields were lowest in gently sloping grass covered surfaces and highest in bare badlands surfaces with steep slopes.

2.3 Rainfall simulators

The most important design requirements of a simulator are that it should reproduce the drop size distribution, drop velocity at impact and intensity of natural rainfall with a uniform spatial distribution and that these conditions should be repeatable. The need to reproduce the energy of the natural rainfall for the intensity being simulated is generally regarded as less important (Bubenzer, 1979).

The major accessories related to the rainfall simulator is pipe work, windshield, frame, wheels, guttering for collection of sediment and runoff generated, pump, electrical generator, water tanks and so on add significant costs over and above that spent on the drop forming device. In addition to the material costs and maintenance requirements, operating the equipment needs human labour. Meyer and Harmon (1979) stated that three people are needed to assemble and dissemble a fairly straightforward rainfall simulator, plus all its accessories.

One of the biggest problems in soil erosion research is the need to rely on natural rainfall to observe soil erosion. It is virtually impossible to predict where and when rainfall events are going to take place. Rainfall simulators are used in most of the laboratory studies, which is designed to produce a storm of energy, intensity and drop size characteristics that can be repeated on demand. Rainfall simulators have been used to accelerate research in soil erosion and runoff from agricultural lands, high ways etc (Meyer, 1980).

Meyer (1988) suggested that the goal of rainfall simulator research is to collect accurate and useful data, not optimize a simulator. Generally, one square meter and smaller plots may be sufficient for studying raindrop impact erosion. The rainfall simulators used for such kind of rainfall simulation should be capable of achieving fairly uniform, continuous rainfall intensity application over the study area. The simulators should also be capable of applying almost vertical impacts for most raindrops, and applying repeatable simulated rainstorms.

Simanton and Emmerich (1994) developed a rotating boom rainfall simulator for doing experiment on a 3 × 10 m plot at the USDA-ARS Walnut

Gulch Experimental Watershed in South eastern Arizona. The plot has a gravely sandy loam surface texture and a grass-dominated vegetation community, and the data are for very wet initial soil moisture conditions. The rainfall rates were 60 and 126 mm h^{-1}. The observed steady-state infiltration rates were computed as the difference between the rainfall rate and the observed steady-state runoff rate. The predicted infiltration and runoff rates were computed using the IRS model (Stone et al., 1992), which couples the Green-Ampt Mein Larsen model equation (Mein and Larsen, 1973) with a method of characteristics solution of the kinematic wave model. Finally he noted that the observed infiltration rate is larger for the higher rainfall rate.

Kim and Miller (1996) concluded that the presence of salts in water used for rainfall simulator studies may cause serious errors where the intent is to simulate rainwater of low electrical conductivity.

Valmis *et al.* (2001) conducted a soil loss experiment in the laboratory using a rain simulator where soil loss was measured and the soils attitude was studied under the conditions of simulated rainfall. It was found that the instability of aggregates is negatively correlated with cation exchange capacity and the total specific surface of soils. Also the calcium carbonate content affects positively the aggregates instability.

Shekl *et al.* (2003) used a portable rainfall simulator and 1 m^2 plots to determine the relative soil erodibility of geological formations and to find its relation with physical and chemical characteristics of soils in the Golabad basin, Isfahan. The results showed that using a rainfall simulator not only decreases the required research period while giving reasonable results and precision, but also makes changing the intensity, duration and frequency of rainfall possible.

Sheridan *et al.* (2008) used a simulator to obtain a modified erodibility index which could be used to predict annual erosion rates for forest roads. They used a rainfall simulator on 1.5 x 2.0 m plots, and carried out simulations for 30 min with an intensity of 100 mm h^{-1} and an estimated kinetic energy of 0.295 MJ ha^{-1}mm $^{-1}$, which is similar to the kinetic energy of high intensity rainfall.

Stone *et al.* (2008) used a variable-intensity rainfall simulator to generate steady-state infiltration rates at multiple rainfall intensities on 2 × 6.1 m natural vegetation rangeland plots. He has shown from the plot data observed from rainfall simulator experiments and natural rainfall events that infiltration rates can increase with increasing rainfall rate instead of decreasing with time or infiltrated depth.

Shi *et al.* (2012) conducted 12 rainfall simulation experiments in a 1 m x 5 m box with varying steep slopes such as 10°, 15°, 20° and 25° and the simulated rainfall lasted for 1 h at a rate of 90 mm h^{-1}. For each simulated event, runoff and sediment were sampled at three minutes intervals, which were performed to study in detail the temporal change in size distribution of the eroded materials. Total soil loss is the sum of suspended, saltating and contact loads. He reported that suspension-saltation transports the finer than 0.054 mm size sediment was the most important erosion mechanism during interrill erosion processes. However, after rill development on hillslopes, bed-load transport by rolling of medium to large-sized sediment particles (coarser than 0.152 mm) became an increasingly important transport mechanism and it were also enhanced by increased slope.

2.3.1 Advantages and disadvantages of rainfall simulator

Renard (1985) examined the advantages and disadvantages of rainfall simulators. A significant advantage is cost efficiency. The cost of a rainfall simulator is relatively less when compared to the cost of a long-term hydrologic experiment that relies solely on natural rain events. Rainfall simulators also provide utmost control of an experiment, particularly with respect to data collection. The plot conditions can be readily changed for experiments with regard to instrumentation used. Antecedent moisture conditions can be varied prior to testing, and additional water can be added rather quickly. Rainfall intensity can be varied with ease to replicate certain storms of record. However, he noted the disadvantages of rainfall simulators, including the high cost of labour to conduct a rainfall simulation.

Most rainfall simulators are relatively small, limiting most experiments to a small plot scale. In addition, simulated rainfall intensities often do not mimic natural rainfall intensities with the same temporal variations and drop-size distributions (Renard, 1985). The biggest inadequacy of most rainfall simulators is the inability to produce water droplets that approach the terminal velocity of natural raindrops.

Meyer (1988) mentioned that the major advantages of rainfall simulator research are fourfold: it is more rapid, more efficient, more controlled and more adaptable than natural rainfall research. Meyer also pointed out that the ideal rainfall simulator should be inexpensive to build, easy to operate, simple to move, and could be used whenever and wherever needed. The most important is that the rainfall can also be adequately generated.

Agassi and Bradford (1999) suggested that the lack of a uniform coverage across a large area and the lack of a continuous coverage at low rainfall intensity were two of the main problems of rainfall simulation experiments under large areas; however, this is precisely the advantage of rain fall simulating experiments, that by keeping rain fall intensity and drop sizes constant, the task of discovering relationships between rainfall and runoff or erosion can be simplify (Lascelles *et al*., 2000).

Iserloh *et al.* (2013) suggested that rainfall simulation on micro-plot scale is a method used worldwide to assess the generation of overland flow, soil erosion, and interrelated processes such as soil sealing, crusting, splash and redistribution of solids and solutes. The so produced data are of great significance not only for the analysis of the simulated processes, but also as a source of input data for soil erosion modelling.

2.3.2 Types of rainfall simulator

The rainfall simulators are classified according to the drop formers used. The most common are pressure droppers or nozzles type and non-pressure dropper type including tubing tip type, either hypodermic needles or capillary tubes and hanging yarn type (De Ploey *et al.*, 1976).

In terms of size, rainfall simulators range from a simple, small, portable rainfall simulator with a 0.15 m diameter rainfall area (Bhardwaj and Singh, 1992) to the complex Kentucky rainfall simulator, which covers a plot 4.5 m x 22 m. Generally all rainfall simulators are constructed in order to simulate rain fall intensities of 10 to 200 mm per hour and drop sizes of 0.1 to 6 mm (Mark Grismer, 2012).

2.3.2.1 Tubing tip type

Capillary tubing made of glass or brass has been used at the larger drop size ranges. Hypodermic needles are good at producing smaller drops, although surface tension is a problem for these smaller drop sizes. This can be overcome by blowing a constant airstream over the drops to detach them from the needle, but this can be very complex to set up for most research purposes.

Capillary tubing and hypodermic needles are susceptible to clogging, especially where the quality of the water used is poor. This can lead to deposits of calcium, lime scale, salt and dust to block up the capillaries so that no drops can be formed.

Studies by Munn (1974) evaluated the erosion potential of seven different soil types in the Lake Tahoe Basin, under both natural and disturbed conditions. Munn built and used a highly portable drop-former rainfall simulator design. Rain occurred over a square plot of area 0.71 m x 0.71 m, employing catheter tubing to form drops with a fall height of 2.5 m; water was supplied by gravity from a 20 litre jug mounted at the top of the simulator. The square runoff collection frame of size 0.61 m x 0.61 m channelled runoff into collection jars during the 15 minute duration storms. He also reported that greater amounts of erosion from steeper slopes and estimated erosion from several soil series found in the Basin, identifying those most likely to present erosion problems.

Onstad *et al.* (1981) built a trailer mounted rainfall simulator. The simulator has four identical modules, and each module covers an area of 0.61 m by 0.91 m. The drop formers are stainless steel capillary tubes with inside diameter of 0.69 mm. Water is applied through these drop-forming tubes, and air is forced to flow around the tubes. Increasing air pressure increases the air velocity passing, which resulting in smaller drops. The drop size distribution is narrower than the natural rainfall with the same intensity. The simulator can generate rainfall intensity ranging from zero to 200 mm/h. The height of drop formers from soil surface is 2 m.

Bowyer-Bower and Burt (1989) used 15 mm lengths of Tygon tubing, with an internal diameter of 0.7 mm, and external diameter of 2 - 3 mm. The former determines the rates of water drop formation, the latter the size of drop created. These tubes gave median drop sizes of between 2 and 3 mm. Small drops were created by inserting 25 mm lengths of 0.55 mm nylon fishing line into each tube.

Kurien and George (1998) developed an oscillating tubing tip type rainfall simulator to study the soil loss and runoff at KCAET, Tavanur. Hypodermic needles were used as the drop formers. The uniformity coefficient varied from 82 to 88 per cent corresponding to intensity variations ranging from 4.77 to 8.8 cm/h. The soil loss increased with intensity of rainfall for all the slopes. A relationship between supply pressure and intensity of the following form was obtained,

$$\mathbf{I = 6.0386 - 31.9152\ P + 177.30\ P^2}$$

Where,

I - intensity in cm/h,

P - supply pressure, kg/cm^2.

Roshni (1998) developed a rainfall simulator and a soil trough to conduct the soil hydraulic study at KCAET, Tavanur, Kerala. The portable rainfall simulator comprised of a drop forming mechanism mounted on a supporting frame. The drop forming mechanism consisted of a tank with perforated bottom. Copper wire loops of 20 gauges were suspended through these perforations. A float valve ensured a constant head of water in the tank to get the desired intensity of rainfall. The moisture content, tension, surface runoff and outflow were monitored at different rainfall intensities.

Fernandez *et al.* (2008) reported that the standard small or laboratory scale rainfall simulator is a drip tank. The rainfall intensity ranged from 0 to 120 mm/h with an intentionally heterogeneous distribution. The drop size and rainfall intensity in drip tank rainfall simulators are controlled by the diameter of the holes and the pressure in the tank.

Sajeena *et al.* (2013) modified the existing rainfall simulator developed by Kurien and George (1998) at KCAET, Tavanur for better performance and to study the erodibility and runoff potential of the selected series of laterite soils of Mannamkulam, Naduvattom and Vellanikkara under simulated rainfall conditions. A relationship between supply pressure and intensity of rainfall of the following form was obtained.

$$\mathbf{I = -\ 87.205\ P^2 + 108.61\ P - 10.786 \qquad (R = 0.99)}$$

Where,

I - intensity of rainfall in cm/h,
P - Pressure in kg/cm^2,
R - Coefficient of regression.

2.3.2.2 Pressurized rainfall simulators

The first rainfall simulators for erosion studies used pressurised water, flowing through single or multiple nozzles. The principle behind the use of pressurised water is that drops sprayed out of a nozzle under pressure have an initial velocity imparted to them which should be sufficient for the drops to reach their terminal velocity at considerably less fall height than for drops falling from the skies. This reduction in necessary fall height is a notable advantage for these simulators over those which rely on gravity and free fall of drops to attain terminal velocity.

Pall *et al.* (1983) developed a rainfall simulator involving a large-capacity wide angle spray nozzle and a spray interception device has been developed for the soil erosion research program at Guelph. A rotating disk with multiple variable aperture openings has been used for spray interception. Calibration tests show that the simulated rainfall intensity and the uniformity of application are affected by the aperture angle, nozzle pressure, disk angular velocity and the interaction of nozzle pressure and aperture angle. Aperture angle has the greatest effect on intensity. Nozzle pressure demonstrates the most significant effect on uniformity of simulated rainfall. The uniformity of distribution for a small plot is also affected by the size of the collector units considered in the determination of the uniformity coefficient. For selected combinations of nozzle pressure, aperture angle, and disk angular velocity, the simulated rainfall intensity and the uniformity of distribution can be represented by a linear model involving the plot dimensions of length and width.

Miller (1987) introduced a portable, variable-intensity, low-cost, and nozzle-typed rainfall simulator. This simulator could be used both in small pan runoff-erosion studies and field studies. Electrically operated solenoid valves control intensity. The opening and closing of the solenoid valves, controlled by a rotating cam or microcomputer, varies the intensity of rainfall from approximately 1.44 to 86.4 mm/h, at 29 kPa water pressure. Kinetic energy of the rainfall is within the range for natural rainfall. The problem of varying intensity was addressed by oscillating the nozzles, diverting part of the spray from the plot, or injecting air into the water stream.

Lima *et al.* (2002) developed a three-dimensional numerical model from the movement of individual drops after their release from the nozzle of a downward-spraying rainfall simulator. He reported that drag forces, wind and gravity affect the original momentum of a single drop. Water application and kinetic energy were estimated from the coupling of a hydrodynamic model for drop movement, a drop generator representing a single full-cone spray nozzle, and an appropriate interception algorithm at the soil surface.

Misty *et al.* (2003) developed a pressurized nozzle type simulator with a cam-operated oscillating boom for vegetative and erosion control research. It emits uniform rainfall on a plot 1 m wide by 3.56 m long. The nozzles at 0.5 kg/cm^2, Spraying Systems Company's Floodjet 3/8K SS45, emitted an average drop size of 1.7 mm and a range of drop sizes of less than 1 mm to 7 mm correlating well to storms less than 50 mmh^{-1}. The structure of the simulator was built from aluminum, supporting the four-nozzle boom. The nozzles are spaced 99 cm apart. The computer-driven set up creates reproducible storm patterns that can be varied over a range of intensities.

Cornelis *et al*. (2004) constructed a wind tunnel and a rainfall simulator to study the effect of wind and rainfall characteristics on soil erosion. The simulator consisted of three pipes covering a 12 x 1.2 m section with sprinklers working with pressurized water.

Sepaskhah *et al.* (2006) conducted to determine the effects of different rates of polyacrylamide (PAM) such as 0, 1, 2, 4, and 6 kg ha^{-1} applied with sprinkler irrigation water followed by two sprinkler irrigations with no PAM application on runoff, soil loss, and improving infiltration on different soil surface slopes such as 2.5, 5.0 and 7.5 per cents under rainfall simulator in laboratory. It was found that at steep slopes, higher PAM application rates are required to enhance the final infiltration rate, to reduce the runoff and soil erosion.

Verbist *et al*. (2009) used a rainfall simulator documented to study hydric erosion and compare distinct methods of measuring soil loss. The simulator consists of a straight line of seven sprinklers with a 1 m space between sprinklers that work with pressurized water and cover an area of 5 x 2 m . Verbist *et al.* (2009) obtained soil loss values in 10 plots with bare soil in the Coquimbo Region. Each experimental simulation lasted 20 min, system pressure was 100 000 Pa, and rainfall reached a mean intensity of 130 mm h^{-1}.

Moussouni *et al.* (2012) conducted an experimental investigation in the laboratory of the water erosion using a rainfall simulator. They have focused on the influence of rainfall intensity on some hydraulic characteristics. The simulator which is used is an EID 340 ORSTOM type, with a spray nozzle fixed on a platform at a height of about four meters. Driven by a pendulum, the nozzle sprays a surface test of $2x1m^2$. The variation of the displacement angle allows the change of the rainfall intensity. The results obtained allowed to conclude that there is a significant correlation between rainfall intensity and hydraulic characteristics of runoff (Reynolds number, Froude number) and sediment concentration.

2.3.3 Testing of rainfall simulators

2.3.3.1 Intensity

There are a number of techniques used to measure intensity. Rain gauges are often used in the field, but usually the constraint is regarding the number available. Alternatively, rainfall is collected in catch cans over a set period of time. Catch cans with the same diameter as Ellison splash cups of seven centimetre diameter would serve as a practical compromise for plots up to 3 x 3 metres. The catch cans can be placed in a grid manner beneath the simulator, or randomly placed, using random numbers to identify sample coordinates. The amount of water collected in each catch can over a time can be converted into intensity by using the following formula (Esteves et al., 2000):

Intensity (mm/h) =

$$\frac{\text{Amount of rainfall collected } (\text{cm}\square)}{\text{Area of catch can } (\text{cm}^2)} \times \frac{60}{\text{Time of test } (\text{minutes})} \times \frac{10}{1}$$

Arnaez *et al.* (2004) developed a nozzle type rainfall simulator. He noted that the rainfall intensity was increased with increase in nozzle pressure.

Martinez-zavala *et al.* (2008) used small diameter nozzles for rainfall generation and experienced a drop in rainfall intensity, mean drop size and KE with increase in applied pressure. The effect noticed was due to decreased drop sizes and intensity.

Aidin *et al.* (2012) developed a portable single nozzle rainfall simulator. Rainfall intensity was calibrated by pressure gauge and five rain gauges distributed uniformly over the plot of area 0.48m^2. This procedure was repeated twice at nozzle pressures varying from 0.7 to 0.8 g cm^{-2} to ensure rate stability during simulations. Water in rain gauges was measured every 5 min.

2.3.3.2 Uniformity

Uniformity of rainfall application, often referred to as uniformity coefficient, was determined by the following Christiansen (1942) equation:

$$Cu = 100\left[1 - \frac{\Sigma x}{mn}\right]$$

Where,

Cu - Uniformity coefficient, per cent

m - Average value of all observations, mm

n - Number of observations

x - Numerical deviation of individual observations from the average application rate.

Keller and Bliesner (1990) reported that the coefficient of uniformity depends on the design variables of the system such as the size and type of nozzle, pressure, sprinkler spacing and the height of the nozzle above the plot surface.

In a study to evaluate the uniformity of center pivot systems with fixed plate and rotator nozzles, Hanson and Orloff (1996) found that under both windy conditions with a speed of 2.2 to 4.5 m/s and no-wind conditions that rotating plate sprinklers resulted in more uniform water application than grooved plate spray sprinklers. In addition, they found that under windy conditions the application uniformity of grooved plate spray nozzles was higher than rotating plate nozzles.

Tarjuelo *et al.* (1999) determined for a solid set sprinkler system that coefficient of uniformity decreased as wind speed increased and that uniformity remained nearly constant beyond 6 m/s. They also showed that there is a linear relationship between coefficient of uniformity and distribution uniformity.

Esteves et al. (2000) developed a rainfall simulator which has a base unit that irrigates a 5m x 5m area with mean intensities from 60 to 76mmh^{-1}and a mean uniformity coefficient of 80.2 %.

Clark et al. (2003) found that application uniformity of grooved plate sprinkler nozzles tended to decrease as operating pressure decreased from 138 to 41 kPa.

Li *et al.* (2005) reported that sprinkler uniformity has been shown to influence nutrient concentrations in the soil and he also reported that a system with a coefficient of uniformity ranging from 72% to 84% did not result in differences in yield of winter wheat.

Christiansen’s uniformity coefficient seems to be the most popular coefficient of uniformity used by researchers on the global scale (Maroufpoor et al., 2010).

Moazed *et al.* (2010) reported that simulated rainfall can be considered uniform when uniformity is higher than 80 per cent.

2.3.3.3 Drop size

Hall (1970) reported that in a network of nozzles, an increase in working pressure increases the average intensity but decreases the drop sizes. Kohl (1974) also reported that low intensity rainfall simulators operating at low pressure result in large drop sizes, while drop size decreases with higher pressures.

The drops can then be measured with a microscope, or photographs are taken of the captured drops. The photographs are enlarged and measurement of drop diameter can be made directly from the photographs after allowing for scale effects. If the drops are caught in a transparent vessel or a glass bottomed dish, then an overhead projector can be used to project the oil and drops onto a screen, where again, direct measurements and correction can be made (Elwell and Makwanga, 1980).

Shelton *et al*. (1985) reported that as pressure is increased to reduce the drop size, the application rate generally increases. In the case of natural rainfall, mean drop size increases with increasing rainfall intensity due to high drop mass and fall velocity.

Cerda *et al*. (1997) used small diameter nozzles for rainfall generation and experienced a drop in rainfall intensity, mean drop size and KE with increase in applied pressure. The effect noticed was due to decreased drop sizes. The uniformity increased to a maximum at approximately 55 mm/h intensity of rainfall and then decreased.

Paige et al. (2003) reported that veejet nozzles working from a drop height of 2.44 m and at a nozzle operating pressure of 41 kPa results in a median drop size of 2.985 mm, while increasing that pressure to 55 kPa increasing the breadth of the drop-size distribution to a range of 0.29 – 7.2 mm while decreasing the median drop size slightly to 2.857 mm.

In a study of Dukes (2006) two types of low pressure sprinkler nozzles were tested under field conditions, stationary grooved plate (LDN) and off-center wobbling diffuser sprinklers (IWOB). Replicated uniformity measurements were conducted along the axis of a linear move irrigation system at low speed of <1.7 m/s, medium speed of 3.3-3.9 m/s and high speed of 5.0-6.6 m/s wind speeds and at two pressure levels of at least 200 kPa, which was in excess of the pressure regulator discharge pressure and less than 97 kPa, a pressure below nominal regulator discharge pressure. He reported that the IWOB sprinklers coefficient of uniformity (CU) was consistently 10% to 16% higher than the LDN sprinklers over all conditions and ranged from 87% to 93% and 70% to 85%, respectively. It was hypothesized that this improvement was due to the formation of larger drops falling in a more random pattern due to inadequate pressure.

Fernandez-Galvez *et al.* (2008) used a simulator with a range of 0 to 120mmh^{-1} with an intentionally heterogeneous distribution. The drop size and rainfall intensity in drip tank rainfall simulators are controlled by the diameter of the holes and the pressure in the tank.

But Hafzullah (2012) showed an opposite result as the mean diameter of rainfall was increased with increase of rainfall intensity. Because he used a periodically oscillating bar attached with nozzles for constructing the rainfall simulator. Therefore the drop size depends on the frequency of oscillations also.

2.4 Runoff and soil loss

Rai and Singh (1986) studied the runoff and soil loss on steep hill slopes varying from 0 to 100per cent in Meghalaya. The surface runoff varied between 68 mm on 10per cent slope to 268 mm on 21per cent slope. The runoff values showed increasing trend up to 21per cent, beyond which the runoff amount decreased with the increase in slope. The soil loss was found to vary between 7 t/ha at zero per cent slope to 891 t/ha at 21per cent slope and beyond this the soil loss decreased steadily with increase in steepness of the slope for the present study.

Blough *et al.* (1990) conducted a study to evaluate the effects of residue cover and surface configuration on runoff and erosion responses of Letort silt loam reconstructed in the laboratory under simulated rainfall. Four field conditions were simulated by producing surface configuration and residue covers comparable to field situations. Infiltration and surface storage created as a result of slit tillage nearly eliminated surface runoff and therefore erosion, until the slit overflowed. After the slit overflowed, the erosion rates were approximately equal to the other conservation tillage treatment. Surface residue decreased surface runoff and erosion and increased the amount of water that infiltrated into the soil. The surface storage provided by the slit treatment further increased the opportunity for infiltration.

McIsaac and Mitchell (1992) studied the temporal variation in runoff and soil loss from simulated rainfall on corn and soybeans. Soil loss per hectare from soybeans and soil loss per ha - mm of runoff from corn varied by as much as a factor of four from one year to another. Much of the variations in soil loss appeared to be related to variations in runoff, slope steepness and antecedent rainfall.

Grosh and Jarret (1994) studied the interill erosion and runoff from a 504 mm square box filled with disturbed Hagerstown silty clay loam under a simulated 20 min., 92 mm/h rainfall at six slopes ranging from 5 to 85 percent. Steady state wash soil loss increased linearly with slope, with measuring rates ranging from 3.34 g/m^2.min, at 5per cent slope to 22.47 g/m^2 .min, at 85per cent slope. Total splash detachment increased with slope. Ninety nine per cent of splash moved down slope at the 85 per cent slope. There were no differences between steady state runoff rates for slopes from 15 to 85 per cent, with a mean runoff rate of 66.5 mm/h.

Myers and Wagger (1996) studied runoff and sediment loss from a Pacolet sand clay loam soil in a two year field experiment. Conventional tillage (CT), no tillage grain production with surface residue (NTG) and no tillage silage production without surface residue (NTS) were compared under simulated rainfall of 12.7 and 50.8 mm/h. residue cover was greater than 90 per cent in NTG plots, 41 per cent in NTS and less than 10 per cent in CT. sediment loss (NTG<NTS<CT) was associated with residue cover. Average first event runoff in both years was 40 per cent for NTG, 44 per cent for NTS and 22 per cent for CT. Runoff doubled with CT on the second event each year suggesting soil surface seal development.

The effect of dead roots on runoff, soil erodibility, splash detachment, and aggregate stability were studied in laboratory by Ghidey and Alberts (1997). Dead roots had no effect on runoff but significantly influenced ($P<0.05$) soil loss and sediment concentrations. Soil loss and sediment concentrations from annual row crops were significantly higher than those from perennial crops; however, the differences in soil loss among the crops were small relative to the differences in root mass and root length. The effect of dead roots was not observed on splash detachment as they were on soil strength, aggregate index and dispersion ratio. Splash detachment was highest during the initial 10 min of simulation and then decreased approximately.

Humphry *et al.* (2002) conducted a plot scale runoff study using a portable rainfall simulator over a 1.5 x 2 m plot area with a coefficient of uniformity of 93 per cent. He reported that by utilizing a plot of 1.5 × 2 m, this simulator is capable of producing a continuous flow rain event with an intensity of 70 mm h^{-1}. He also suggested that a plot size of 1.5 × 2 m may not be appropriate for all research applications and is not intended to represent edge of field values from a large watershed, but this approach does allow relative comparisons and was sufficient in preliminary runoff studies for relating soil loss and runoff.

Benito *et al.* (2003) reported that erosion studies on agricultural soils have shown that when surface soils are at moisture contents greater than field capacity, soil losses increase considerably over that from comparably dry soils by as much as five times or much greater sediment concentrations.

Kinnell (2005) attempted to attack the kinetic energy-erosion rate question directly using two drop former type rainfall simulators generating average drop sizes of 2.7 and 5.1 mm from fall heights of 1.0, 3.6 and 11.2 m to generate erosion of the same 0.2 mm repacked sand used previously at flow depths of 3-14 mm. He reported that sediment discharge rates were linearly related to rainfall power at each flow depth considered such that for the 2.7 mm raindrop size and flow depth of 3 mm, average sediment discharge increased by 3.2 times and 5.5 times when increasing the fall height from 1.0 to 3.0 m and 1.0 to 11.2 m, respectively.

Parsons and Stone (2006) suggested that the present understanding of the processes of soil detachment and transport is inadequate to predict runoff and erosion rates associated with the temporal variability in drop sizes and intensities found in natural rain.

As forest dirt roads and trails are some of the greatest sources of sediment loadings to streams per unit land area, Folz *et al.* (2009) and Copeland and Folz

(2009) measured runoff and sediment concentration during simulated rainfall events for a variety of forest dirt road surfaces in Idaho and around the Tahoe Basin. Road slopes were generally on mild grades of approximately 10% or less and from both volcanic and granitic parent materials. Simulated rainfall intensities of 80-100 mm/h were used for 30-minute durations from a single Veejet 80100 nozzle located 3 m above the soil surface. They reported that recently opened or used roads generated greater sediment losses or erodibilities as compared to abandoned roads (Folz et al., 2009), Copeland and Folz (2009) found no soil dependence for bare disturbed soils on steeper slopes.

Ekwue and Harrilal (2010) reported that soil loss was consistently highest and runoff was consistently lowest in the sandy loam soil. The larger size of the sandy loam soil led to greater presence of large pores which enhanced infiltration. Hence the result showed low surface runoff. However, decreased soil cohesiveness and the presence of more loose detached sand particles ensured that the soil had greater soil loss.

Hany (2013) conducted a field experiment in the Shangnan Country using 33 small erosion plots of 7 m^2 in size was carried out to determine and compare the soil loss and surface runoff from five vegetation covers and the slope gradients ranged from 10º to 30º. Results showed that the slope gradient has an impact on the runoff and soil loss. Thus greater the slope, the higher will be the potential for runoff and soil loss.

2.4.1 Soil erosion from micro plots

The size of micro plot can vary from 0.05 to about 2 m^2. These plots are frequently used in laboratory experiments under simulated conditions to manipulate and understand principles of soil erosion processes and factors.

One of the best uses for runoff plots is demonstration of known facts. Another valid use is in comparative studies, for example to test, or demonstrate, or get an approximate indication of the effect on runoff or erosion of a simple comparison such as with or without a surface mulch, or the amount of runoff at the top and at the bottom of a slope. A third possible use is to obtain data which are to be used to construct or to validate a model or equation to predict runoff or soil loss. Micro plots of one or two square meters may be appropriate if the objective is a simple comparison of two treatments (Hudson, 1993).

Goff *et al*. (1993) found that soil loss increased linearly with runoff plot at down slope length for bare soils. The length - width ratio of the erosion plot is important and it can be suggested up to 1, or the considerable plot width is at least approximately 1 m (Agassi and Bradford, 1999).

Hamed *et al.* (2002) reported that erosion rates from small plot rainfall simulation studies are assumed to reflect interrill erosion processes and potentially miss the erosion produced in gullies at larger scales.

Yang *et al*. (2006) showed that simulated rainfall on small plots of size 1.5 x 3 m, at an intensity of 73 mm/h can cause twice a type of erosion after only 13 min of runoff.

Vahabi and Nikkami (2008) developed a 89 x 120 cm rainfall simulator producing 24.5 and 32 mm/h rainfall intensities for evaluating the effects of physical soil factors such as texture and antecedent soil moisture, along with land slope and vegetation cover over 144 soil erosion plots with dimensions of 95 x 125 cm. He reported that small erosion plots will allow the control of most influences, such as slope, soil texture, and moisture content, and thus the impact of one specific factor can be investigated.

Ries *et al.* (2013) reported that rainfall simulation on micro-plot scale is a method used worldwide to assess the generation of overland flow, soil erosion, infiltration and interrelated processes such as soil sealing, crusting, splash and redistribution of solids and solutes. The produced data are of great significance not only for the analysis of the simulated processes, but also as a source of input-data for soil erosion modelling.

2.5 Modelling of soil erosion

Many empirical and theoretical formulas have been developed to predict or estimate soil erosion. Although many researchers have pointed out the limitations they inherited, USLE and its modifications are still the most important soil erosion prediction tools ever been developed for soil erosion prediction.

Foster *et al.* (1981) reported that the relationship between raindrop diameter and velocity data to determine the kinetic energy of rainfall is:

$$E = 0.119 + 0.0873 \log I$$

Where,

E = kinetic energy (MJ/ha.mm),

I = rainfall intensity (mm/h).

Multiplication of E by total amount of rainfall (mm) gives total kinetic energy. Also, they found that, $E\ I_{30}$, the product of kinetic energy (E) and the maximum 30 minute intensity (I_{30}), was the best single rainfall parameter for prediction of soil loss.

Nearing (1997) claimed that erosion prediction technology needed to move towards development of process-based simulation models. This thinking was reflected in development of the “physically-based”, though continued semi-empirical erosion equations known as WEPP model, developed as something of a replacement for the empirically-derived USLE.

Siepel *et al.* (2002) expanded use of Manning’s roughness in determining erosion rates under grass vegetated surface conditions and show that a certain minimal cover is required to trap suspended sediment.

Soil erosion and sediment yield models therefore play a critical role in addressing problems associated with land management and conservation, particularly in selecting appropriate conservation measures for a given field or watershed (Sadeghi *et al.*, 2008).

Monitoring and modelling of erosion processes can help us better understand the causes, make predictions, and plan how to implement preventative and restorative strategies. The complexity of erosion processes and the number of areas that must be studied to understand and model them like climatology, hydrology and, geology makes accurate modelling quite challenging (Blanco *et al.*, 2010). Erosion models are also non-linear, which makes them difficult to work with numerically, and makes it difficult or impossible to scale up to making predictions about large areas from data collected by sampling smaller plots (Brazier *et al.,* 2011)

2.5.1 Universal soil loss equation (USLE)

The most widely used method of predicting soil erosion is the Universal Soil Loss Equation. The USLE was derived from statistical analysis of 10,000 plot-years of natural runoff plots data and the equivalent of 1000 to 2000 plot-years of rainfall simulators' data. The authors emphasized that the USLE is an erosion model designed to predict the longtime average soil losses from sheet and rill erosion, and from specific field areas in specified cropping and management systems. Many variables and interactions influence sheet and rill erosion. The USLE groups these variables under six major erosion factors, the product of which, for a particular set of conditions, represents the average annual soil loss (Wischmeier, 1976). The USLE (Wischmeier and Smith, 1978) is expressed as

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P$$

Where ,

A = the estimated soil loss (ton/acre-year),

R = the rainfall and runoff factor (hundreds of ft-ton-in/acre-year),

K = the soil erodibility factor (ton-acre-h/hundreds of acre-ft-ton-in),

L = the slope length factor,

S = the slope steepness factor,

C = the cover and management factor,

P = the supporting practice factor.

Modified Universal Soil Loss Equation (MUSLE) and the Revised Universal Soil Loss Equation (RUSLE) are the modifications of USLE.

Renard *et al*. (1991) and Renard *et al*. (1994) introduced the Revised Universal Soil loss equation. The RUSLE uses the same fundamental structure of USLE to link those thousands of plot years of data under both natural and simulated rainfalls that derived the USLE, and the factors of RUSLE have been broken down further to allow better definition and more accuracy of prediction. The equation is as

$$A = R\cdot K \cdot LS \cdot C\cdot P,$$

Where,

A = the estimated soil loss (ton/acre-year),

R = the rainfall and runoff factor (hundreds of ft-tonf-in/acre-yr),

K = the soil erodibility factor (ton-acre-h/hundreds of acre-ft-tonf-in),

L = the slope length factor,

S = the slope steepness factor,

C = the cover and management factor,

P = the supporting practice factor.

2.5.2 Regression analysis and models

In the multiple regression analysis, each predictor variable is weighted, the weights denoting their relative contribution to the overall prediction. In calculating the weights, the regression analysis procedure ensures maximal prediction from the set of independent variables in the variate. The computer software, SAS, a statistical data analysis package, was applied to conduct the regression analysis in this research.

Kurien and George (1998) developed an oscillating tubing tip type rainfall simulator to study the soil loss and runoff at KCAET, Tavanur. Empirical equation between soil loss and intensity, runoff and intensity was obtained for different land slopes as,

$$E = -982.384 + 2834.63\ S + 225.239\ I \qquad (R = 0.94)$$

$$Q = -216.174 + 1104.65\ S + 79.375\ I \qquad (R = 0.92)$$

Where,

I - Intensity of rainfall (cm/h) ranging from 4.77 to 8.8 cm/h,

S - Soil slope (per cent) ranging from 5 to 20 per cent,
E - Soil loss (kg/ha/h),
Q - Runoff (m3/ha/h),
R - Coefficient of multiple regression.

Hu Liu (1999) reported that the linear least-square regression analysis was performed to examine how variations in soil erosion amount can be explained by various soil and rainfall properties. The linear least square regression utilizes the relation between two or more quantitative variables so that one variable can be predicted from the other or others with minimum sum of squared errors of prediction.

In statistics, linear regression is a type of regression analysis used for predicting the outcome of a dependent variable, based on one or more predictor variables. Regression analysis measures the relationship between a dependent variable and, usually, one or several continuous independent variables by converting the dependent variable to probability scores. Then, a logistic regression is formed, which predicts success or failure of a given binary variable (e.g. 1 = “presence of erosion” and 0 = “no erosion”) for any value of the independent variables (Todd, 2006).

Sajeena *et al.* (2013) studied the runoff and soil loss on slopes varying from 5 to 25 per cent in KCAET, Tavanur using oscillating tubing tip type rainfall simulator. Tests were conducted at the selected intensities of rainfall ranging from 7.41 to 23 cm/h to study the effect of intensity of rainfall on runoff and soil loss. The tests were done on three series of laterite soil say; Mannamkulam series, Naduvattom and Vellanikkara series of soil. A relationship between intensity and soil loss; intensity and runoff of the following form was obtained at different land slopes.

Mannamkulam series,

$$E = 1167.797\ I + 109\ S - 21686.07 \qquad (R = 0.90)$$

$$Q = 65.016\ I + 16.747\ S - 235.923 \qquad (R = 0.99)$$

Naduvattom series,

$$E = 324.766\ I + 112.799\ S - 3912.219 \qquad (R = 0.97)$$

$$Q = 74.542\ I + 19.434\ S - 394.323 \qquad (R = 0.99)$$

Vellanikkara series,

$$E = 1115.662\ I + 431.064\ S - 11512.284 \qquad (R = 0.98)$$

$$Q = 58.742\ I + 26.837\ S - 310.019 \qquad (R = 0.99)$$

Where,

I - intensity of rainfall (cm/h) ranging from 7.41 to 23 cm/h,

S - land slope per cent, ranging from 5per cent to 25 per cent,

E - soil loss (kg/ha/h),

Q - runoff (m^3/ha/h),

R - coefficient of multiple regression.

MATERIALS AND METHODS

CHAPTER 3

MATERIALS AND METHODS

The present study was carried out in KCAET campus Tavanur. A laboratory study was conducted to evaluate the performance of the developed rainfall simulator. Micro soil loss plots were established to study the erosion process. The soil is reddish brown and belongs to the textural class of sandy loam of Naduvattom series. The experimental set up consisted of three units viz., the runoff plot, the rainfall simulator and the runoff-sediment collection unit. Twelve runoff plots with twelve different slopes of 1.5, 2.0, 2.6, 3.0, 3.2, 4.0, 5.0, 6.0, 9.0, 10, 12 and 13 per cent and each with a size of 2 x 1.5 m were prepared.

The rainfall simulator designed and fabricated could apply the desired flow over the runoff plot. The runoff containing the sediments was collected at the outlet for analysis. The designed intensity of water was applied over the runoff plot using the rainfall simulator developed using *Rainbird* 12/15/18 Van Pop up sprinklers. The materials used and methodology adopted during the study are described in this chapter.

3.1 Design and fabrication of rainfall simulator

A pressurized nozzle type rainfall simulator using Pop-up sprinkler was designed and fabricated. The simulator consisted of *Rainbird* 12/15/18 Van Pop up sprinkler heads with pressurized water supply. The principle behind the use of pressurized water is that drops sprayed out of a nozzle under pressure have an initial velocity imparted to them which should be sufficient for the drops to reach their terminal velocity at considerably less fall height than for drops falling from the skies. This reduction in necessary fall height is a notable advantage for these simulators over those which rely on gravity and free fall of drops to attain terminal velocity.

Supply and discharge consisted of an elbow to connect a water supply pipe to the sprinkler system, two fast closing cut off valves: one opening or closing the interflow of water to the sprinklers and another allowing the discharge of water from the system when the sprinkler interflow was closed. It also had a pressure regulation valve for the functioning of the sprinklers. The pressure of the supplied water determined the rainfall characteristics simulated. Most pressurised rainfall simulators use a range of pressures between 0.35 and 1.42 kg/cm^2.

3.1.1 Selection of intensity of rainfall

Langsholt (1992) conducted studies on the water balance in the lateritic terrain of Kerala. She reported that the maximum intensity of 10-minutes rainfall recorded was 78.6 mm/h, the simulator was designed to produce rainfall intensities up to 88 mm/h.

Rainfall simulators should be able to simulate a number of design storms, especially medium to high intensity events, as these are likely to be associated with measurable amounts of soil loss. Rainfall must be uniform in space and time during the course of experimental studies. So the intensity must be tested with respect to space and time.

3.1.2 Design of the supporting frame work

Rainfall was simulated using *Rainbird* 12/15/18 Van Pop up sprinkler heads. In order to support the entire sprinkler unit, a frame was fabricated. A square frame work of 3m x 3m was fabricated with PVC pipe of diameter 25 mm. The pipes were joined at the corners using an elbow, made of PVC of diameter 32 mm. Each sprinkler was fitted at the centre point of all sides of the square frame using 20 mm diameter MTA to the PVC riser of 15 mm diameter to 50 cm height. The frame work was supported by legs of height 50 cm at the four corners.

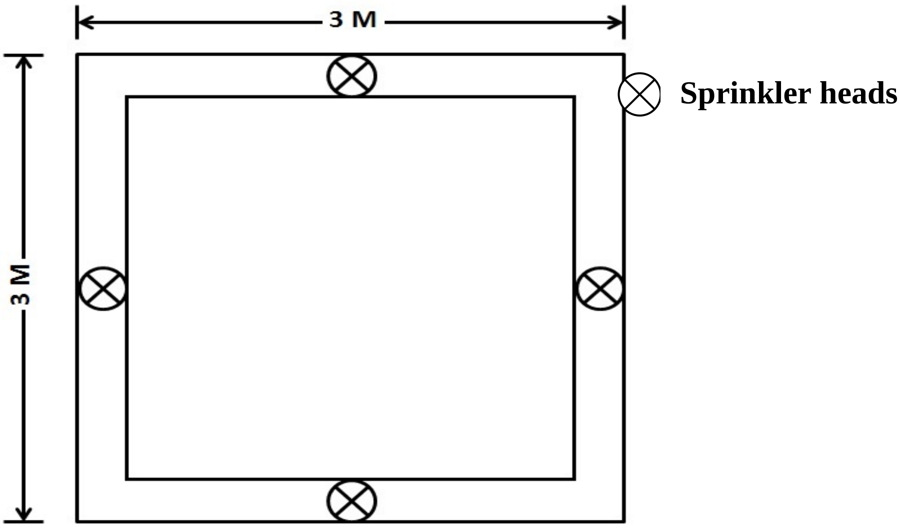
Plate 1. Installation of rainfall simulator on micro plot

3.1.3 Selection of sprinkler heads for rainfall simulator

The sprinklers used for the study are the Pop-up sprinklers with adjustable nozzles. The Pop-up sprinklers used were *Rainbird* make to 12/15/18 Van type. The sprinkler unit was connected to the risers and mounted onto the framework. It can be operated at 0-2 kg/cm^2 in adjustable spray pattern from 25 to 360^o. The maximum diameter of throw of the selected sprinkler was 4 m. The simulated rainfall could produce rainfall of intensities varying from 8.16 to 8.8 cm/h.

Four sprinkler heads were selected accordingly to get maximum intensity and uniformity. Each sprinkler was connected to the riser using female threaded adaptor and mounted on the framework. The spacing between the sprinklers was fixed as 3m in order to get maximum intensity and uniformity within the study area. The developed rainfall simulator has showed in Plate 2.

Plate 2. Rainfall



simulator

Fig. 1. Top view of rainfall simulator

3.2 Installation of rainfall simulator

The rainfall simulator was tested in the Soil and Water Conservation laboratory for intensity, uniformity and average drop size of simulated rainfall. Later it was transferred to the experimental site for the erosion study. The experimental sites were located at the KCAET campus area. The installation of rainfall simulator on micro plot has showed in Plate 1.

3.2.1 Experimental set up

A framework was developed to support the sprinklers. A tank of 2000 litre capacity was used to hold the water and an electric motor was used to pump the water from the tank. A PVC pipe was connected to the filter unit before the inflow and the framework for the rainfall simulation was fitted on this PVC pipe and there were two inflows into the sprinklers to simulate the rainfall. The final set up of rainfall simulator was placed over the micro plot in order to get maximum uniformity of rainfall to produce runoff and soil loss. The experimental setup has showed in Plate 3.

Plate 3. Experimental set up

3.2.2 Water supply to the rainfall simulator

The water supply to the sprinkler system was provided using a PVC elbow attached from a filter unit. Two fast closing cut off valves are fitted for opening or closing the inflow of water to the sprinklers and another allowing the discharge of water from the system when the sprinkler interflow was closed (connected to an evacuation hose); furthermore, it had a pressure regulation valve for the functioning of the sprinklers as shown in Plate 4. A discharge cut off valve was provided immediately before the frame work to operate the simulator water supply without delay. An electrically operated centrifugal pump was used to lift water from a storage tank of 2000 litres capacity and to supply to the simulator.

The specifications of the motor pump as follows:

Size(mm)	: 25 x 25
Head (m)	: 20
Head range	: 17.0 - 23.0
Capacity range (lps)	: 0.6 -1.8
Rpm	: 2200
Kw/Hp	: 0.75/ 1.02
Overall efficiency (%)	: 28.0

PH-1; 50 Hz; 210V; 5.5 A

Plate 4. Water supply to the rainfall simulator

3.2.3 Testing of rainfall simulator

3.2.3.1 Intensity

The pressure of supply water was maintained at 0.5 kg/cm². The entrapped air was removed and the simulator was operated freely for 10 minutes. Catch cans were placed at 50 cm grid spacing below the simulator while raining as shown in Plate 5. The catch cans were reasonably small so that measurements were not impractical. Catch cans with thirteen centimetre diameter were used. The amount of water collected over a time in each catch can was converted into intensity by using the following formula,

Intensity (mm/h) =

$$\frac{[\text{Amount of rainfall collected } (\text{cm}^3)]}{[\text{Area of catch can } (\text{cm}^2)]} \times \frac{60}{[\text{Time of test (minutes)}]} \times \frac{10}{1}$$

The unit was operated for 10 minutes. The volume of water collected in each can was recorded. The volume of water collected was converted into its equivalent depth. The test was repeated for different pressure. The intensity was calculated for each supply pressure of water.

3.2.3.2 Uniformity

The pressure of supply water was maintained at 0.5 kg/cm². The entrapped air was removed. Catch cans were placed in the rain at a 50 cm grid stations. The unit was operated for 10 minutes. The volume of water collected in each can was recorded and was converted into its equivalent depth of rainfall. The uniformity coefficient (Cu) percent was calculated using the Christiansen's formula (1942);

$$Cu = 100\left[1 - \frac{\Sigma x}{mn}\right]$$

Where,

Cu - Uniformity coefficient, per cent

m - Average value of all observations, mm

n - Number of observations

x - Numerical deviation of individual observations from the average application rate.

The uniformity coefficient was calculated for the inner area of size 2 m x 1.5 m. The experiment was repeated for various intensities of rainfall.

Plate 5. Rainfall simulator testing

3.2.3.3 Average drop size

Elwell and Makwanga (1980) explained how raindrops can be caught in a heavy, dense liquid such as a high quality vacuum pump oil or solvent, where the drops are held without absorption by the oil or similar fluid. The raindrops are captured without deformation from their original shape (Shelton *et al.*, 1985). This makes measurement of drop diameter much easier. There are minimal evaporation losses between drop formation and capture also with this method.

In this study petroleum jelly was used as the dense fluid and it was smeared to a thin layer over a glass plate as shown in Plate 6. The drop diameters were measured from the photographs and using graph sheets also.

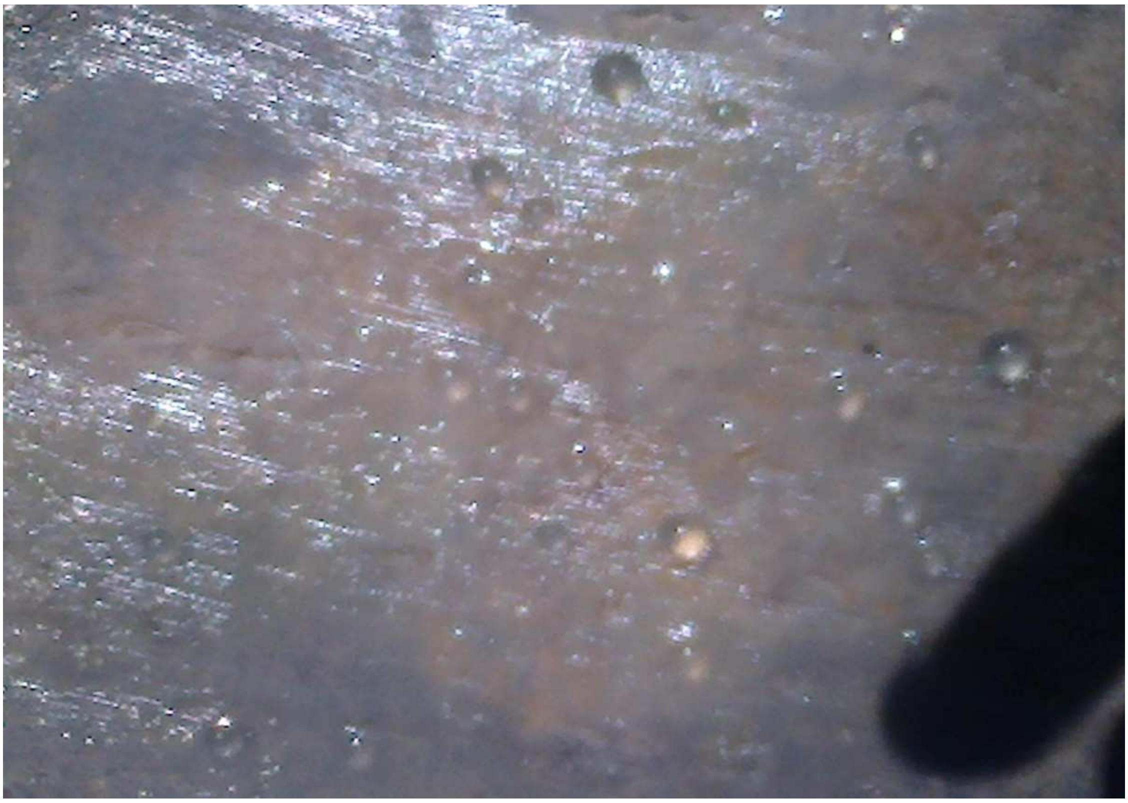


Plate 6. Testing for average drop size of simulated rainfall

3.3 Determination of soil properties

The soil in the study area could very precisely designated by knowing the physical properties. A study was taken to work out the physical properties in terms of texture and consistency.

3.3.1 Texture analysis

Texture analysis of the soil was done by determining the particle size distribution. The analysis was performed at two stages: (1) sieve analysis and (2) sedimentation analysis.

3.3.1.1 Sieve analysis

The soil sample was collected and dried in the oven at 104°c for 24 hours. From the dried soil 375g was taken for the analysis. The analysis consisted of coarse and fine analysis. A set of 2mm, 1mm, 600µ, 300µ, 212µ, 150µ and 75µ sieves were used. The set of sieves were placed one above the other on a hand sieve shaker such that the 2mm sieve containing the soil sample was on the top and the 75µ sieve at the bottom, with a receiver below it. The sieve shaker was operated for 10 minutes and the portion retained on each sieve was weighed and noted. The percentage of soil retained on each sieve was worked out on the basis of the total mass of soil sample taken and from this results, percentage passing through each sieve was calculated. If the portion passing 75µ size is substantial, wet analysis has done for further sub-division of particle size distribution (Punmia *et al.*, 2005).

3.3.1.2 Sedimentation analysis

The sedimentation analysis was done with the help of a hydrometer. The hydrometer analysis is based on Stoke's law, according to which the velocity, at which grains settle out of suspension, all other factors being equal, is dependent upon the shape, weight band size of the grain. 100 g of soil was first treated with hydrogen peroxide solution to remove organic material. Next, the soil was treated with 0.2 N hydrochloric acid to remove calcium compounds, or if any. After washing the mixture with warm water till there was no acid reaction to litmus, the oven dried soil was weighed and 100 ml dispersing agent (sodium hexa metaphosphate) was added. The soil suspension was washed through a 75 micron IS sieve; the mass of those passing through the sieve was transferred to a 1000 ml measuring cylinder making up the volume accurately to 1000 ml. The hydrometer was immersed in it and the readings were taken at different time intervals. The percentage finer (N) was determined and a particle size distribution curve was plotted (Punmia *et al.*, 2005).

3.3.2 Consistency

Consistency limits which are most useful for engineering purposes are liquid limit and plastic limit. These limits are expressed on a water content index (Punmia *et al.*, 2005).

3.3.2.1 Liquid limit

The liquid limit was determined with the help of the standard liquid limit apparatus designed by Cassagrande. About 120 g of the specimen passing through 425µ sieve was mixed thoroughly with distilled water to form a uniform paste. A portion of the paste was placed in the cup of the Cassagrande apparatus and spreading to position and a groove was made on soil pat using the Cassagrande BS tool. The number of blows required for the two parts of the soil sample to come to contact at the bottom of the groove was noted. The water content was determined by taking soil sample from near the closed groove and subjecting it to oven drying method. A graph was plotted between number of blows as abscissa on a logarithmic scale and the corresponding water content as ordinate. The water content corresponding to 25 blows was taken as the liquid limit (Punmia *et al.*, 2005).

3.3.2.2 Plastic limit

The soil specimen, passing through 425µ sieve was mixed thoroughly with distilled water so that the soil mass could be easily moulded with fingers. A ball was formed of 10 g of the soil mass and rolled between fingers and a glass plate into a thread of uniform diameter. When the diameter was 3 mm, the soil was remoulded again into ball. The process of rolling and remoulding was repeated till the thread starts just crumbling at a diameter of 3 mm. The water content of the crumble threads was determined. The test was repeated twice with the fresh samples. The plastic limit was taken as the average of the three water contents (Punmia *et al.*, 2005).

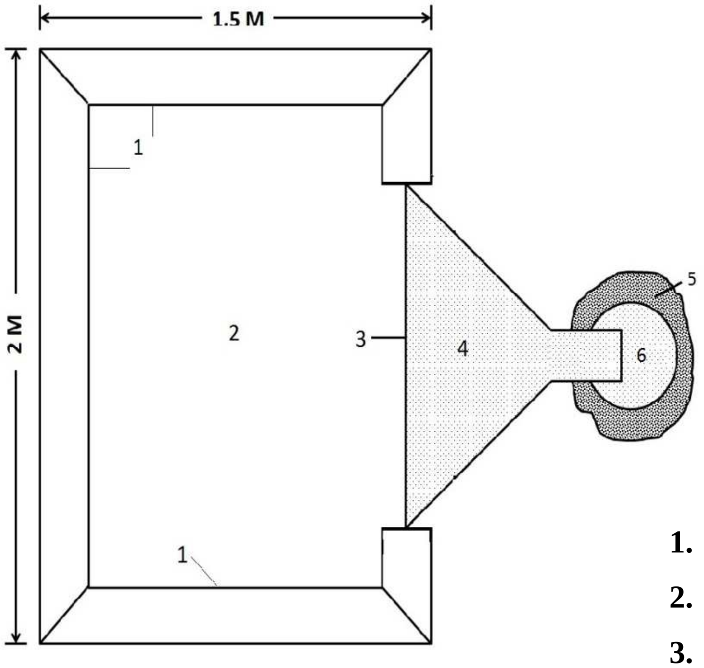
3.4 Soil Erosion Estimation

3.4.1 Establishment of micro plot

Erosion plots were established for monitoring runoff and soil loss with the size of 1.5 m wide and 2 m in length as shown in Plate 7. Twelve micro plots with twelve different slopes were prepared. The plot sizes were selected with the agreement of Meyer (1988) that the plot area should be of sufficient size for satisfactory representation of treatments and erosion conditions. The plots were delineated at its four sides by raising the soil level to form bunds with 10 cm height. The bunds were raised to a level such that the water falling over the plot does not over flow to the surrounding area. At the top of the erosion plot, the bunds were made at right angles for the corners. At the bottom edge of each plot the bunds were angled across the slope towards a triangular tray made of 22 gauge GI sheet. The runoff generated in the plot was directed to a collector using the triangular tray. The tray had a cover made of the same material to prevent the simulated rain falling outside the test plot from mixing with the runoff. The outlet of the tray was directed to a catch pit of size 1m x 1m x 1m. The rainfall simulator was placed over the plot in order to get maximum uniformity over the plot. The runoff was collected in collection bucket placed in the pit after 5 minute duration.

Plate 7. Erosion plot

Top view



1. **Plot boundary**
2. **Plot surface**
3. **Surface-trough interface or LIP**
4. **Collection trough**
5. **Collection pit**
6. **Collection bucket**

Side view

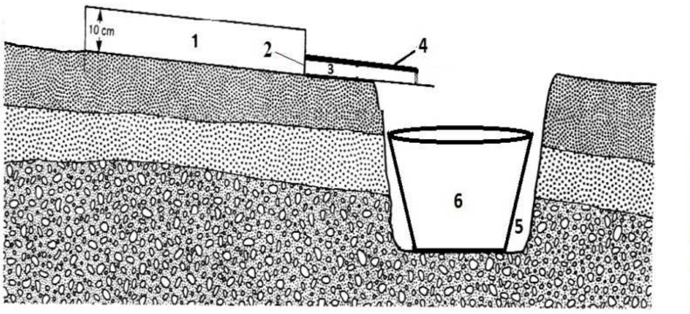


Fig. 2. Rainfall simulator and soil erosion plot

3.4.2 Study of runoff

The experimental plot was exposed to a simulated rainfall of intensity 8.16 cm/h by adjusting the pressure of water supply. The rainfall simulator in operation on erosion plot has showed in Plate 8. A wet run was given until a steady state of runoff generated in the plot. The runoff with eroded soil was collected in a collection bucket placed in the catch pit below the narrow channel of the triangular tray for a period of 5 minutes. The amount of runoff was recorded. The same procedure was repeated for rainfall of intensities 8.28, 8.44 and 8.8 cm/h and collected the corresponding runoff with eroded soil.

Plate 8. Rainfall simulator in operation on erosion plot

3.4.3 Computation of sediment load

The runoff sample was allowed to settle for a period of one week. Then the clear water was removed and the sediment was separated by evaporation technique. The weight of the sediment was recorded. The test was conducted for rainfall of intensities 8.16, 8.28, 8.44 and 8.8 cm/h. The same procedure was repeated for other plots. The runoff and sediment collection unit has showed in Plate 9.

Plate 9. Runoff and sediment collection unit

3.5 Data analysis and model development

3.5.1 Regression Analysis

The linear least-square regression analysis was performed to examine how variations in soil erosion are influenced by various slope and rainfall intensities. The linear least square regression utilizes the relation between two or more quantitative variables so that one variable can be predicted from the other, or others with minimum sum of squared errors of prediction. In the present study, the dependent (criterion) variables are soil loss and runoff and the independent (prediction) variables are slope and intensity of rainfall. First, univariate tests are performed to determine the correlation between intensity-pressure and uniformity-pressure. Second, a multiple regression analysis was performed to analyze the relation between the slope, intensity and soil loss as well as slope, intensity and runoff. In the multiple regression analysis, each predictor variable is weighted, the weights denoting their relative contribution to the overall prediction. In calculating the weights, the regression analysis procedure ensures maximal prediction from the set of independent variables in the variate. The computer software, SPSS, a statistical data analysis package, was applied to conduct the regression analysis in this research.

3.5.2 3D Surface plot Analysis

Computer software, MATLAB (a statistical data analysis packages) was used as the surface fitting tool to develop the 3D views for representing the relation between slope, intensity and soil loss as well as slope, intensity and runoff. The erosion prediction equations were also developed from the 3D surface plot analysis.

RESULTS AND DISCUSSION

CHAPTER 4

RESULTS AND DISCUSSION

A rainfall simulator was developed and tested to determine the intensity and uniformity of application of the rainfall produced. After the performance evaluation of the simulator, it was used for erosion studies. The results of the study are presented in this chapter.

4.1 Testing of rainfall simulator

4.1.1 Intensity of rainfall

The simulator was tested under various intensities of rainfall produced by changing the supply pressure of water to the simulator. The intensity of rainfall produced at each supply pressure was measured. The results are given in Table 1. It was found that the intensity of simulated rainfall increased with the increase in supply pressure. A maximum intensity of 8.80 cm/h was obtained for a pressure of 2 kg/cm^2. The intensity reduced to 8.16 cm/h for a supply pressure of 0.5 kg/cm^2. The increase in intensity with pressure was due to the increase in the application rate of water.

Shelton *et al*. (1985) experienced similar results using nozzle type rainfall simulators. Cerda *et al*. (1997) used small diameter nozzles for rainfall generation and experienced a drop in rainfall intensity, mean drop size and KE with increase in applied pressure. The effect noticed was due to decreased drop sizes. The uniformity increased to a maximum at approximately 55 mm/h intensity of rainfall and then decreased.

A graph was plotted with the supply pressure as abscissa and intensity as ordinate and is shown in Fig. 3. A relationship between supply pressure and intensity of rainfall of the following form was obtained.

$$\mathbf{I = 0.24P^2 - 0.184P + 8.2 \qquad (R^2 = 0.994)}$$

Where,

I - Intensity of rainfall (cm/h),

P - Supply pressure (kg/cm^2).

4.1.2 Uniformity of rainfall

The Christiansen's uniformity coefficient was worked out at different intensities of rainfall and the results are given in Table 2. As per Keller and Bliesner (1990) the coefficient of uniformity depends on the design variables of the system such as the size and type of nozzle, pressure and sprinkler spacing. A uniformity of 92.70 per cent was obtained at an intensity of 8.8 cm/h. The uniformity coefficient reduced to 89.01 per cent at an intensity of 8.16 cm/h. At higher pressures of application the variation in the discharge from sprinkler heads was less and this in turn gave higher values of uniformity. Fister *et al.* (2012) and Lascano *et al.* (1997) could get uniformities ranging between 88 to 94 per cent on a 1.25 m^2 plot with sprinkler nozzles.

According to Moazed *et al.* (2010) simulated rainfall could be considered uniform when uniformity is higher than 80 per cent. The uniformities worked out in the present study ranged from 89.01 to 92.70 per cent. So from the results it could be seen that the performance was satisfactory from the point of view of uniformity. A graph plotted with the intensity as abscissa and uniformity as ordinate is shown in Fig. 4. From the graph it could be seen that the uniformity of simulated rainfall increased with increase of intensity of simulated rainfall. A relationship between intensity and uniformity of the following form was obtained.

$$\mathbf{Cu = 2.179I^2 - 31.30I + 199.3 \quad (R^2 = 0.997)}$$

Where,

Cu - uniformity coefficient (%),

I - intensity (cm/h)

4.1.3 Average diameter of rain drops

In the present study the diameter of rain drops was measured at different intensities of rainfall and the results are given in Table 3. An average diameter of 2.8 mm was obtained for an intensity of 8.16 cm/h. The average diameter reduced to 1.5 mm for a simulated intensity of 8.8 cm/h. According to Kohl (1974) low intensity rainfall simulators operating at low pressure result in large drop sizes, while drop size decreases with higher pressures. Furthermore, as pressure is increased to reduce the drop size, the application rate generally increases (Shelton et al., 1985). In the case of natural rainfall, mean drop size increases with increasing rainfall intensity due to high drop mass and fall velocity. In a network of nozzles, an increase in working pressure increases the average intensity but decreases the drop sizes (Munn, 1974).

As mentioned above, the result showed that at high intensity of rainfall there was a reduction in the droplet size as demonstrated in Fig. 5. This was in agreement with the findings of Shelton *et al*. (1985).

But Hafzullah (2012) reported an opposite result as the mean diameter of rainfall was increased with increase of rainfall intensity. Because he used a periodically oscillating bar attached with nozzles for constructing the rainfall simulator. This is a fact already mentioned by Cerda *et al.* (1997) among others, who stated that lower spraying velocity and increasing oscillation result in larger drops.

A relationship between intensity and diameter of the following form was obtained as shown in Table 3.

Table 1. Effect of supply pressure on intensity of simulated rainfall

Pressure (kg/cm$^{2)}$	Intensity (cm/h)
0.5	8.16
1.0	8.28
1.5	8.44
2.0	8.80

Table 2. Effect of intensity of simulated rainfall on uniformity

Intensity (cm/h)	Uniformity (%)
8.16	89.01
8.28	89.72
8.44	90.36
8.80	92.70

Table 3. Effect of intensity of rainfall on average drop diameter

Intensity (cm/h)	Average Drop diameter D (mm)
8.16	2.80
8.28	2.20
8.44	1.90
8.80	1.50

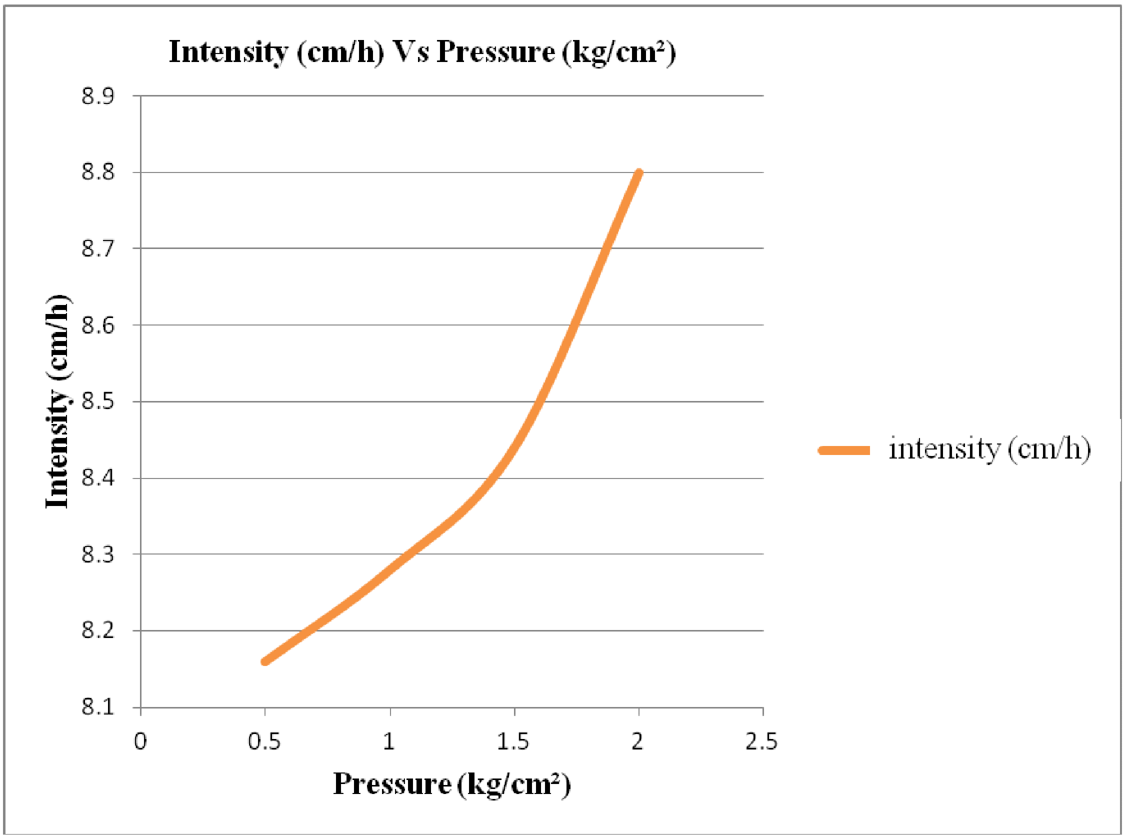


Fig. 3. Effect of supply pressure on intensity of rainfall

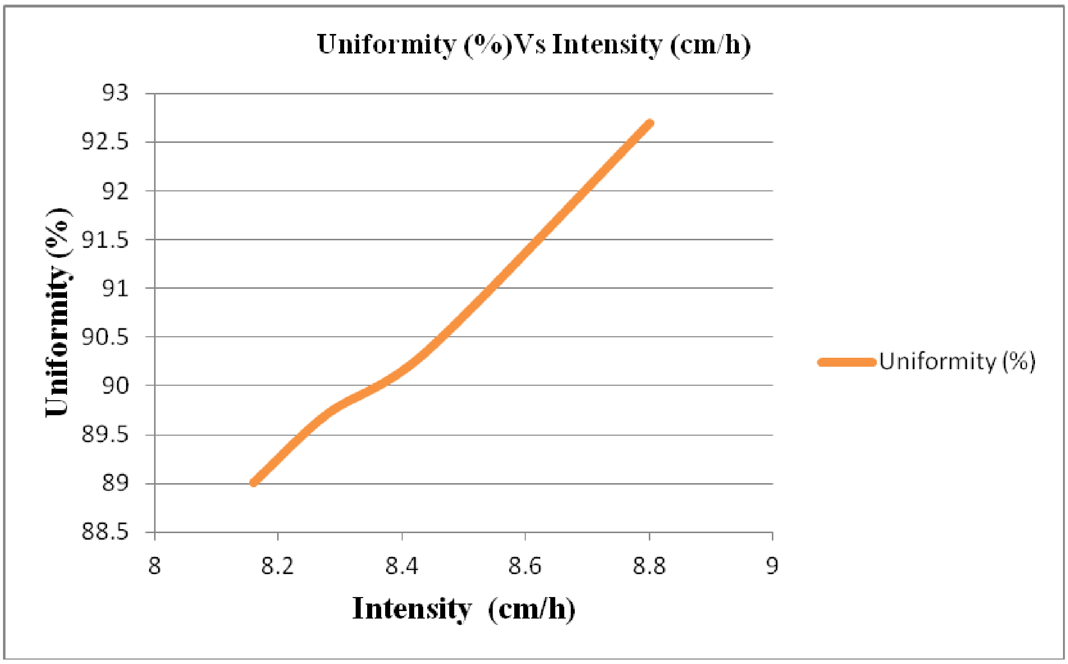


Fig. 4. Effect of intensity of rainfall on uniformity of rainfall

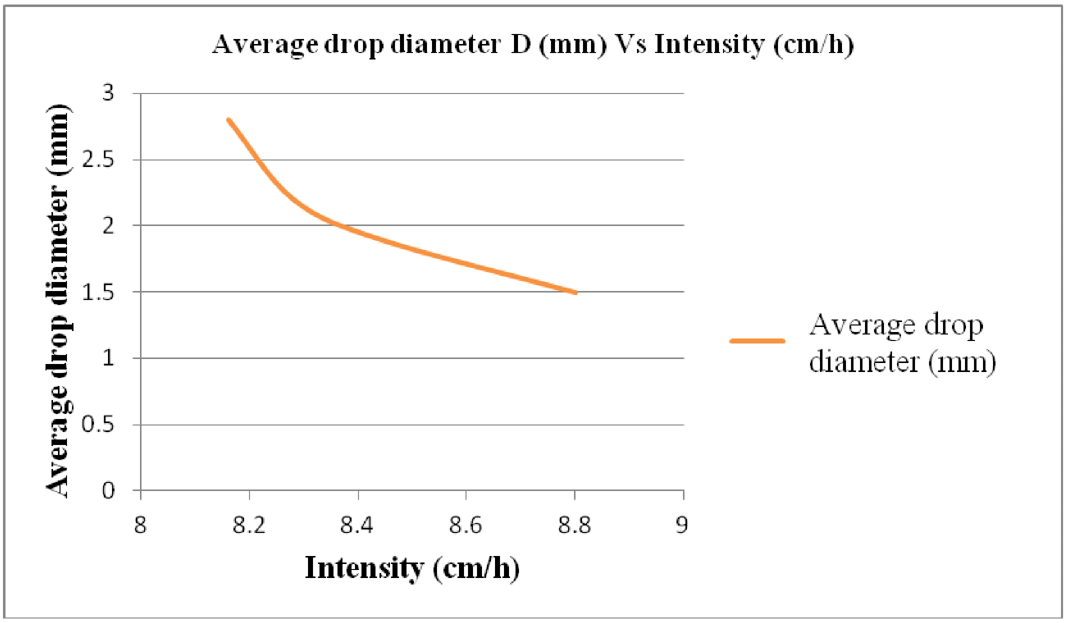


Fig. 5. Effect of intensity of rainfall on diameter of rain drops

4.2 Soil physical properties

4.2.1 Texture analysis

Soil texture analysis could help to understand the textural properties of the soil. The sieve analysis and hydrometer analysis were chosen as the soil textural analysis methods in this study. The relative proportions of the different grain sizes which make up the soil mass of each plot of soils were determined. The result showed that the soil belongs to the class sandy loam.

Finkel (1986) pointed out that the amount of soil rolling at the bottom of surface flow increases with the velocity of the stream and decreases with the soil particle size. Chow and Rees (1994) studied the effect of content and size of soil coarse fragments on soil erosion. He reported that the runoff and soil loss were found to decrease with increasing size and content of coarse fragments. Bradford and Foster (1996) reported that sediment size will influence on sediment yield and the splash process.

The particle size distribution curve of soils of each plot is given in Fig. 6. The results of sieve and sedimentation analysis are shown in Appendix VII.

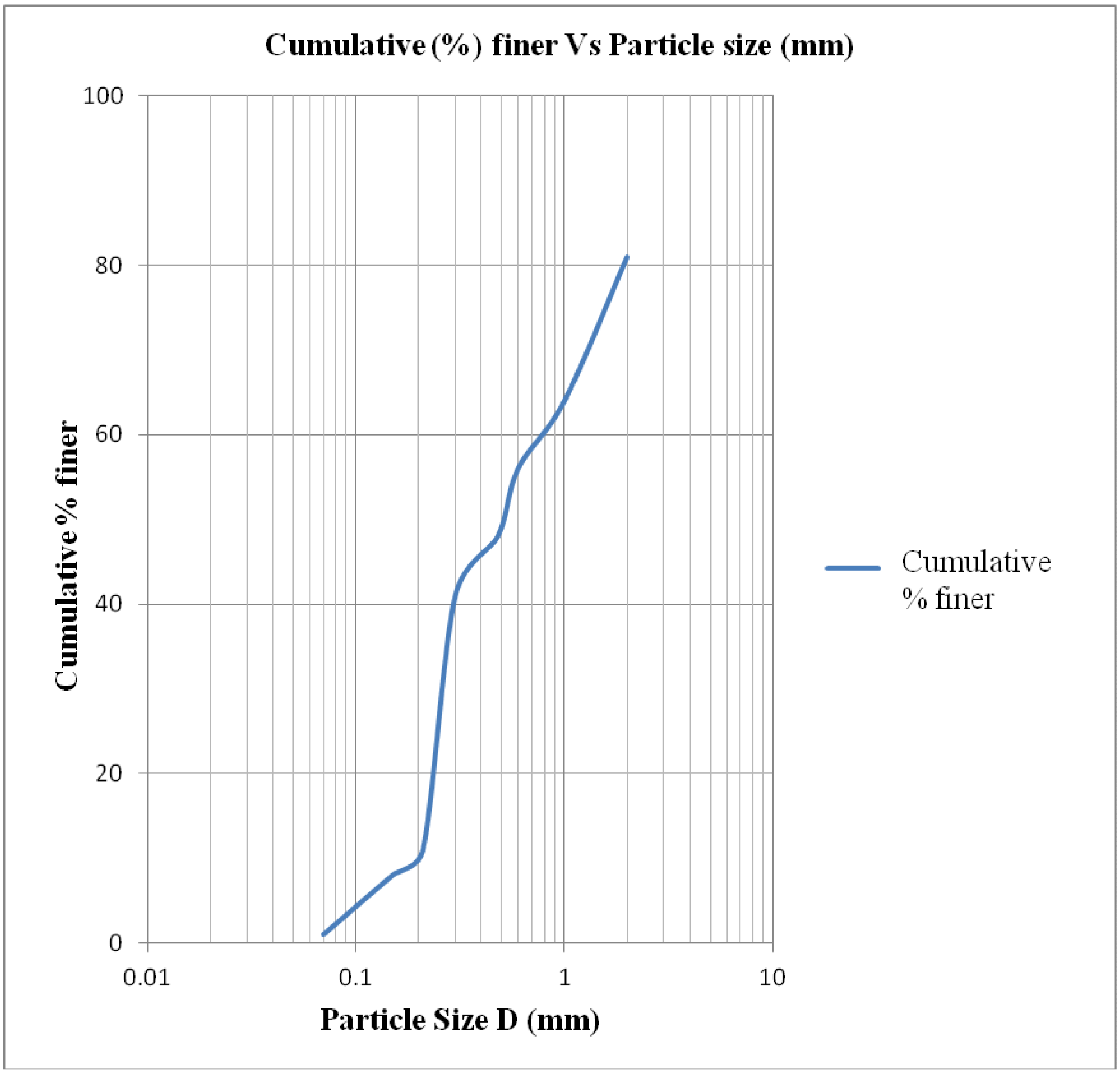


Fig. 6. Particle size distribution curve

4.2.2 Soil Consistency

Consistency limits which are most useful for engineering purposes are liquid limit and plastic limit. Consistency denotes the firmness of the soil which may be termed as soft, firm, stiff or hard. Romkens *et al.* (2001) observed that the total sediment yield for the initially smooth surfaces was generally appreciably smaller than that for the initially medium-rough and rough surface conditions for corresponding slope steepness and rainstorm intensity regimes.

Experiments were conducted to evaluate the liquid and plastic limits of the soils and the results are given in Table 4.

Table 4. Consistency of soils

Antecedent Moisture Content (%)	**Liquid limit (%)**	**Plastic limit (%)**
21.24	22.27	26.86

4.3 Micro soil loss plots for erosion study

Twelve numbers of micro soil loss plots of size 1.5 m x 2 m were prepared on twelve different land slopes ranged from 1.5 to 13 per cent. The micro soil loss plots were selected on the bare soils under natural condition. Hence the results showed a fast and higher runoff and soil loss on each land slope compared to the previous studies (Sajeena *et al*., 2013) which are carried out in disturbed soil and covered with or without vegetation.

Humphry *et al.* (2002) conducted a similar study using a portable rainfall simulator over a 1.5 m x 2 m plot area with a coefficient of uniformity of 93 per cent. He stated that the selected micro plot size was sufficient for the detailed study of runoff and soil loss under simulated rainfall conditions on different land slopes.

With this agreement of Humphry *et al.* (2002), the selected plot size was sufficient for uniform distribution of rainfall with the rainfall intensities ranged from 8.16 to 8.80 cm/h and detailed study of runoff and soil loss under simulated rainfall conditions on different land slopes.

4.4 Soil loss and runoff study

A rainfall simulator was developed in the study of erosion from 12 micro soil erosion plots selected in the lateritic terrain. The micro soil erosion plots were of size 2 m x 1.5 m. Vahabi and Nikkami (2008) reported that small erosion plots will allow the control of most influences, such as slope, soil texture, and moisture content, and thus the impact of one specific factor can be investigated.

The soil was found to be sandy loam and belonged to *Naduvattom* series. Ekwue and Harrilal (2010) reported that soil loss was consistently highest and runoff was consistently lowest in the sandy loam soil. The larger size of the sandy loam soil led to greater presence of large pores which enhanced infiltration. Hence the result showed low surface runoff. However, decreased soil cohesiveness and the presence of more loose detached sand particles ensured that the soil had greater soil loss.

The soil loss and runoff were measured at different intensities of rainfall on different slopes.

4.4.1 Effect of intensity of rainfall on runoff

The effect of intensity of rainfall on runoff under different land slopes was studied. The simulated rainfall intensities at different supply pressures were measured to 8.16, 8.28, 8.44 and 8.8 cm/h. Tests were conducted at all intensities on the twelve test plots identified on twelve different slopes. The obtained results are presented in Appendix I.

The results were found that the maximum runoff 230.2 m^3/ha/h was measured at the highest intensity of 8.8 cm/h and the runoff was found to be less at the lowest intensity of rainfall on each slope.

Sajeena *et al.* (2013) also showed the similar results that runoff increased with increase in intensity of rainfall under different slopes in all three series of soils studied.

Graph plotted between runoff and intensity for each test plot is shown in Fig. 7.

4.4.2 Effect of land slope on runoff

The effect of land slope on runoff was obtained by measuring the runoff under twelve different land slopes on the test plots. The slopes were selected on bare soil surfaces and the slopes ranging from 1.5 per cent to 13 per cent. Simulation studies were conducted at intensities of 8.16, 8.28, 8.44 and 8.8 cm/h at each test plots. The results obtained are shown in Appendix II.

The result found that at 1.5 per cent slope the runoff obtained for an intensity of 8.16 cm/h was 44 m^3/ha/h. On increasing the intensity to 8.28 cm/h, the runoff increased to 52.4 m^3/ha/h and the runoff reached a value of 66 m^3/ha/h at 8.8 cm/h intensity. It was observed that as the slope increases the runoff also increases. The maximum runoff was obtained from the plot of 13 per cent at an intensity of 8.8 cm/h and was 230.2 m^3/ha/h.

Romkens et al. (2001) noted the similar results of increased runoff with the increased intensity of rainfall and slope steepness. Veena and Devidas (2010) also found that the runoff was less at gentle slopes and more at steep slopes on bare soil surfaces.

The graph plotted in between slope and runoff is shown in Fig.8. From the graph also it is clear that the runoff increases with the slope. Furthermore it can be noticed that at 4 to 6 per cent slope there was a greater increase of runoff with increase of intensity and at 6 to 10 per cent slope there was no considerable change in the runoff values and it did not show much variations at all intensities. When the slope increased to 13 per cent, there noticed a further increase of runoff at all intensities simulated rainfall.

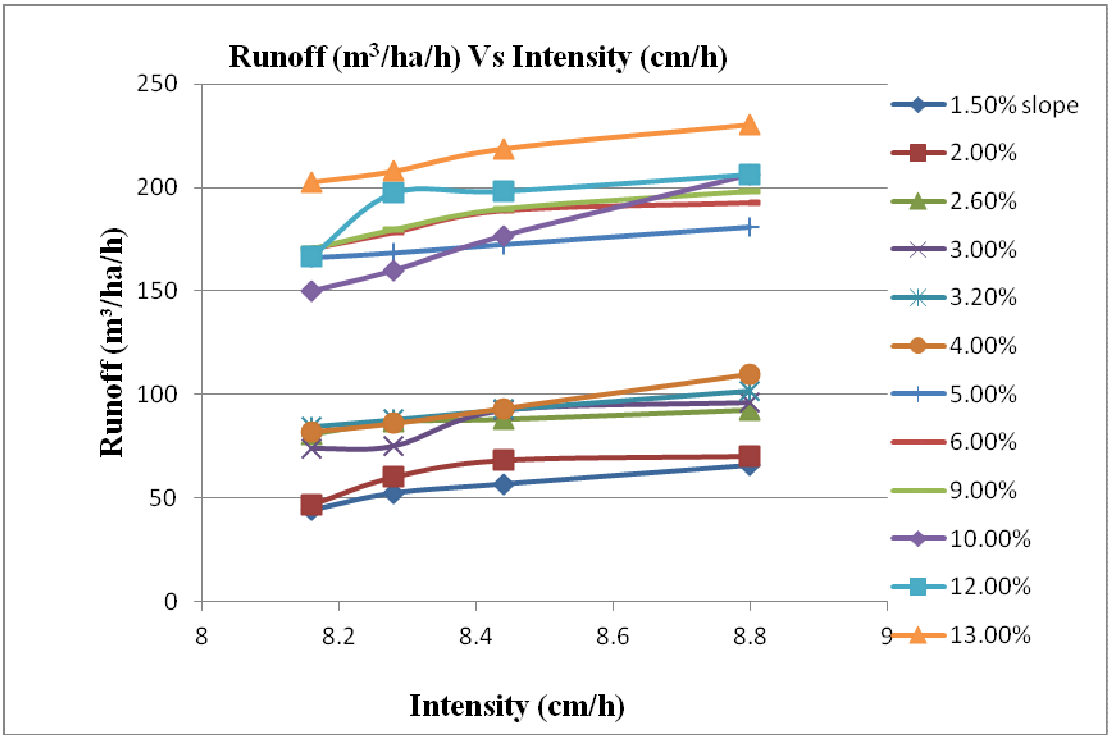


Fig. 7. Effect of intensity of rainfall on runoff

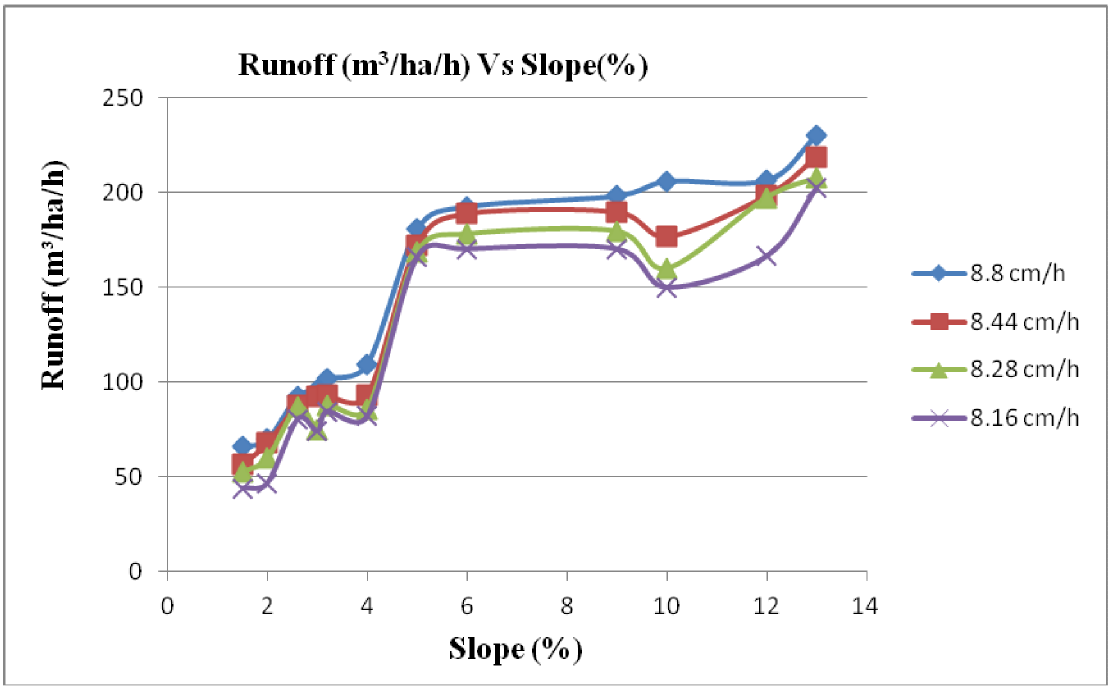


Fig. 8. Effect of landslope on runoff

4.4.3 Effect of rainfall on soil loss

Experiments were conducted to study the effect of intensity of rainfall on soil erosion. The field study was made at the intensities of 8.16, 8.28, 8.44 and 8.8 cm/h. Tests were conducted at the selected plots with varying land slopes. The results obtained are presented in Appendix IV.

The result showed that the maximum soil loss 228 kg/ha/h was obtained at an intensity of 8.8 cm/h on 13% slope and the soil loss decreases with decrease in intensity of simulated rainfall. Furthermore it could also be found that the soil loss decreased with decrease in intensity at every experiment conducted on each twelve micro plot. This result is because of higher rainfall intensities have more net kinetic energy to apply to the surface to erode the soil, and the increased runoff volume will transport more eroded soil away from the site (Hu Liu ,1999).

Kurien and George (1998) developed an oscillating tubing tip type rainfall simulator using hypodermic needles to study the soil loss and runoff. They have also observed the similar results that the soil loss increased with intensity of rainfall for all the slopes.

Romkens *et al.* (2001) also agreed that the sediment concentration increased gradually with the data of the increasing intensity sequence. These increases are due to the development of rills or incisions in the soil bed following the breakdown of the surface seal.

Graphs plotted between soil loss and intensity of rainfall for each plot is shown in Fig.9.

4.4.4 Effect of land slope on soil loss

To study the effect of land slope on soil erosion, the experiments were conducted at different slopes. The selected slopes were ranged from 1.5 to 13%. As mentioned above the experiments were conducted at intensities of 8.16, 8.28, 8.44 and 8.8 cm/h on the selected test plots. The results are showed in AppendixV.

It was found that at an intensity of 8.16 cm/h the soil loss from 1.5 per cent slope was 10.8 kg/ha/h, whereas the value increased to 50.3 kg/ha/h for 2 per cent slope. At a higher intensity of 8.8 cm/h, the soil loss from the plot of 1.5 per cent slope was 40.8 kg/ha/h while it was 300 kg/ha/h when slope was increased to 13per cent. A general trend of increase in the soil loss with the slope is seen from whole observations.

Higaki *et al*. (1999) reported the similar results in his study, that surface erosion rate on laterite slopes was increased with increase of slope.

Kinnell (2000) reported that sediment concentration in flow from side slopes increased with slope gradient, particularly if this exceeded 10per cent. However, studying erosion from small plots with slope gradients of 4per cent and 8 per cent in tilled fields, Chaplot and Bissonnais (2003) reported that sediment concentration in runoff was not correlated with slope gradient.

Suhua Fu (2009) reported that the total soil loss was increased with slope, and then decreased after a maximum value was reached. He also indicated that the slope gradient has greatest effect on down slope soil erosion and least impact on lateral erosion.

A graph was plotted in between slope and soil loss as shown in Fig. 10. From the graph it can be seen that there was a considerable increase of soil loss at 1.5 to 2 per cent slope at all intensity of simulated rainfall and then the soil loss decreased at 3 to 5 per cent slopes. The soil loss at 6 to 10 per cent slope was found to be without any noticeable differences. This may be due to the fact that the observed runoff at 6 to 10 per cent slope was almost similar. Ben-Hur, (2006) also showed the same results that for the mild slopes of five per cent and nine per cent, the sediment concentration is stable, which could characterize either a transport limited or a detachment limited process.

And after that the graph showed that the soil loss again increased to its maximum level at the maximum slope of 13 per cent at each application of intensity of simulated rainfall.

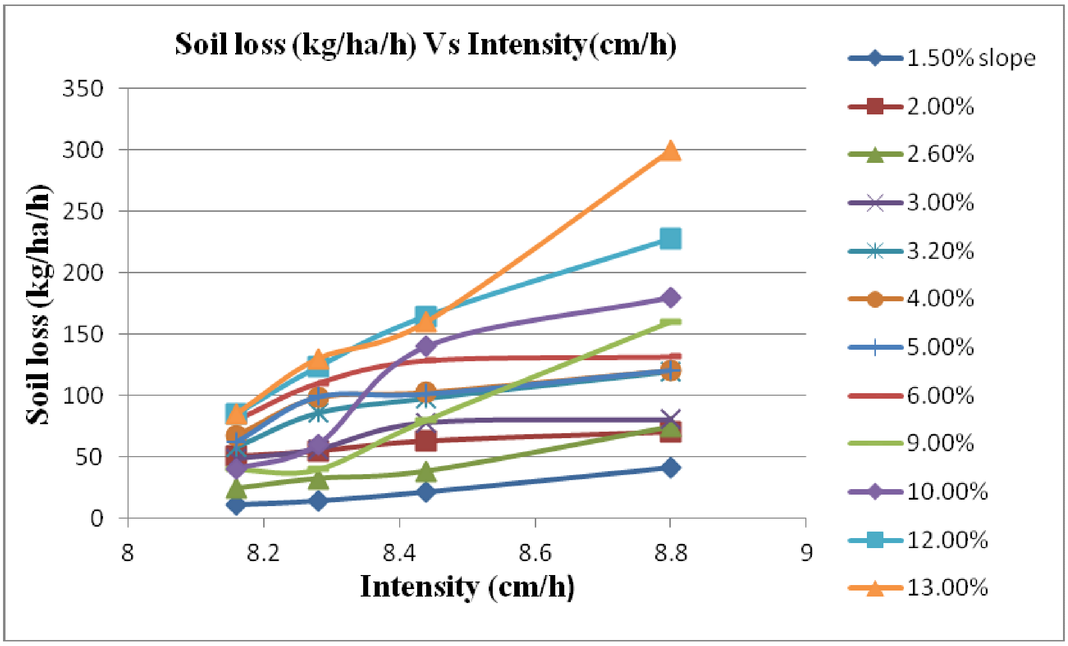


Fig. 9. Effect of intensity of rainfall on soil loss

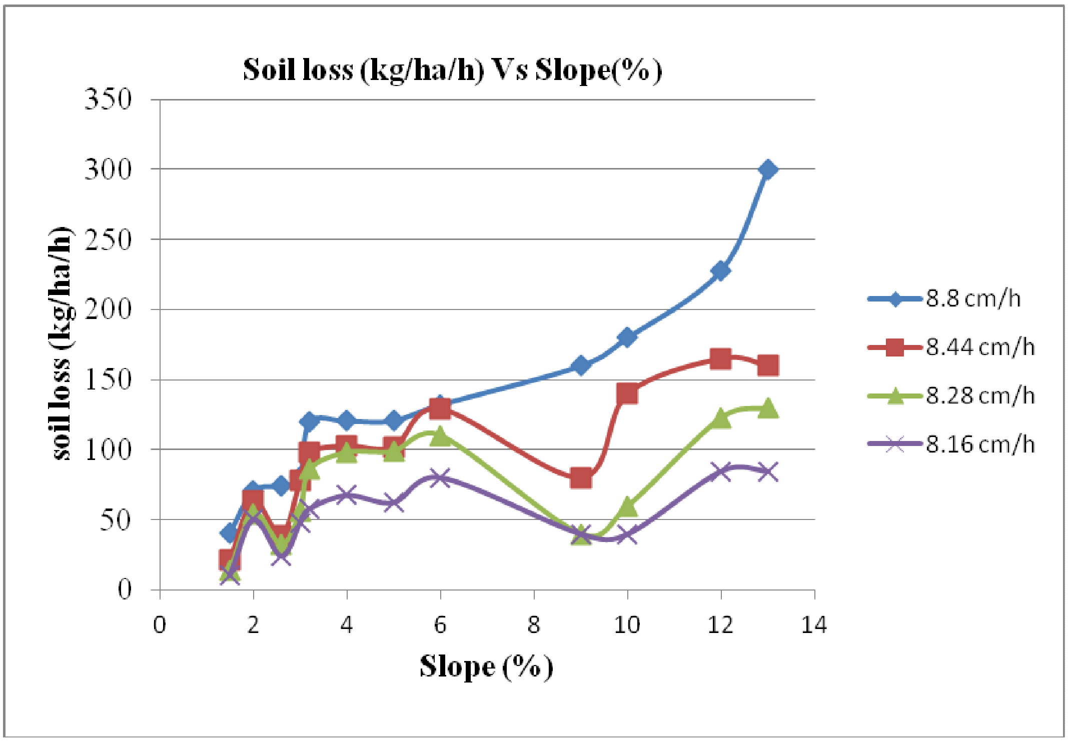


Fig. 10. Effect of landslope on soil loss

4.5 Data analysis and model development

Linear multiple regression equations showing the effect of land slope and intensity of rainfall on runoff as well as soil loss were worked out using SPSS software. The results of regression analysis are described in Appendix III and VI. The results observed from the output tables are discussed below.

4.5.1 Regression analysis of runoff

Statistical significance

The F-ratio in the **ANOVA** table tested whether the overall regression model is a good fit for the data. The table showed that the independent variables such as slope and intensity were statistically significantly predicted the dependent variable runoff, F (2, 45) = 41.586, *p* < .0005 (i.e., the regression model is a good fit of the data).

Estimated model coefficients

The general form of the equation to predict runoff from slope and intensity was:

$$\mathbf{Q = 38.945\, I^{*} - 11.606\, S^{***} - 126.391 \qquad (R^{2} = 0.649)}$$

This relationship was developed from the Coefficients table.

Where,

Q = Runoff in m^3/ha/h
I = Intensity of rainfall in cm/h, ranging from 8.16 to 8.8 cm/h
S = Land slope in per cent, ranging from 1.5 to 13 per cent
R = Coefficient of multiple regression

Statistical significance of the independent variables

From the coefficient table it was found that slope is statistically significant at 0.01 levels and the intensity is statistically significant at 0.1 levels to predict runoff.

4.5.2 Regression analysis of soil loss

Statistical significance

The ANOVA table showed that the independent variables such as slope and intensity were statistically significantly predicted the dependent variable soil loss, F (2, 45) = 9.507, p < .0005 (i.e., the regression model is a good fit of the data).

Estimated model coefficients

The general form of the equation to predict soil loss from slope and intensity was:

$$E = 124.356\ I^{***} - 0.807\ S^{*} - 951.420 \qquad (R^2 = 0.307)$$

This relationship was established from the Coefficients table.

Where,

E = Soil loss in kg/ha/h
I = Intensity of rainfall in cm/h, ranging from 8.16 to 8.8 cm/h
S = Land slope in per cent, ranging from 1.5 to 13 per cent
R = Coefficient of multiple regression

Statistical significance of the independent variables

From the coefficient table it was found that slope is statistically significant at 0.1 levels and the intensity is statistically significant at 0.01 levels to predict runoff.

As the variants explained was satisfactorily enough to explain the runoff and soil loss, it may be concluded that the causative factors namely slope and intensity are bearing directive impact on soil erosion.

*** denotes "significant at 1 per cent level".

. * denotes "significant at 10 per cent level".

4.6 3D Surface plot Analysis

Exact relationship can be measured if response of surface could be fitted for runoff and soil loss based on slope and intensity. The same was fitted using MATLAB package. The results are as follows;

$$Q = 130.8 - 28.72\ S + 48.12\ I + 2.11\ S^2 - 1.544\ S\ I$$

$$E = -647.4 - 49.26\ I + 86.94\ S - 0.3206\ I^2 + 6.296\ S\ I$$

Where,

Q = Runoff in m^3/ha/h
I = Intensity of rainfall in cm/h, ranging from 8.16 to 8.8 cm/h
S = Land slope in per cent, ranging from 1.5 to 13 per cent
E = Soil loss in kg/ha/h

These equations are representing quadratic models.

In statistics, linear regression is a type of regression analysis used for predicting the outcome of a dependent variable, based on one or more predictor variables. Regression analysis measures the relationship between a dependent variable and, usually, one or several continuous independent variables by converting the dependent variable to probability scores. Then, a logistic regression is formed, which predicts success or failure of a given binary variable (e.g. 1 = “presence of erosion” and 0 = “no erosion”) for any value of the independent variables (Todd, 2006).

3D graph was plotted using MATLAB for representing the relation between slope, intensity and soil loss as well as slope, intensity and runoff as shown in Fig.11 and Fig.12.

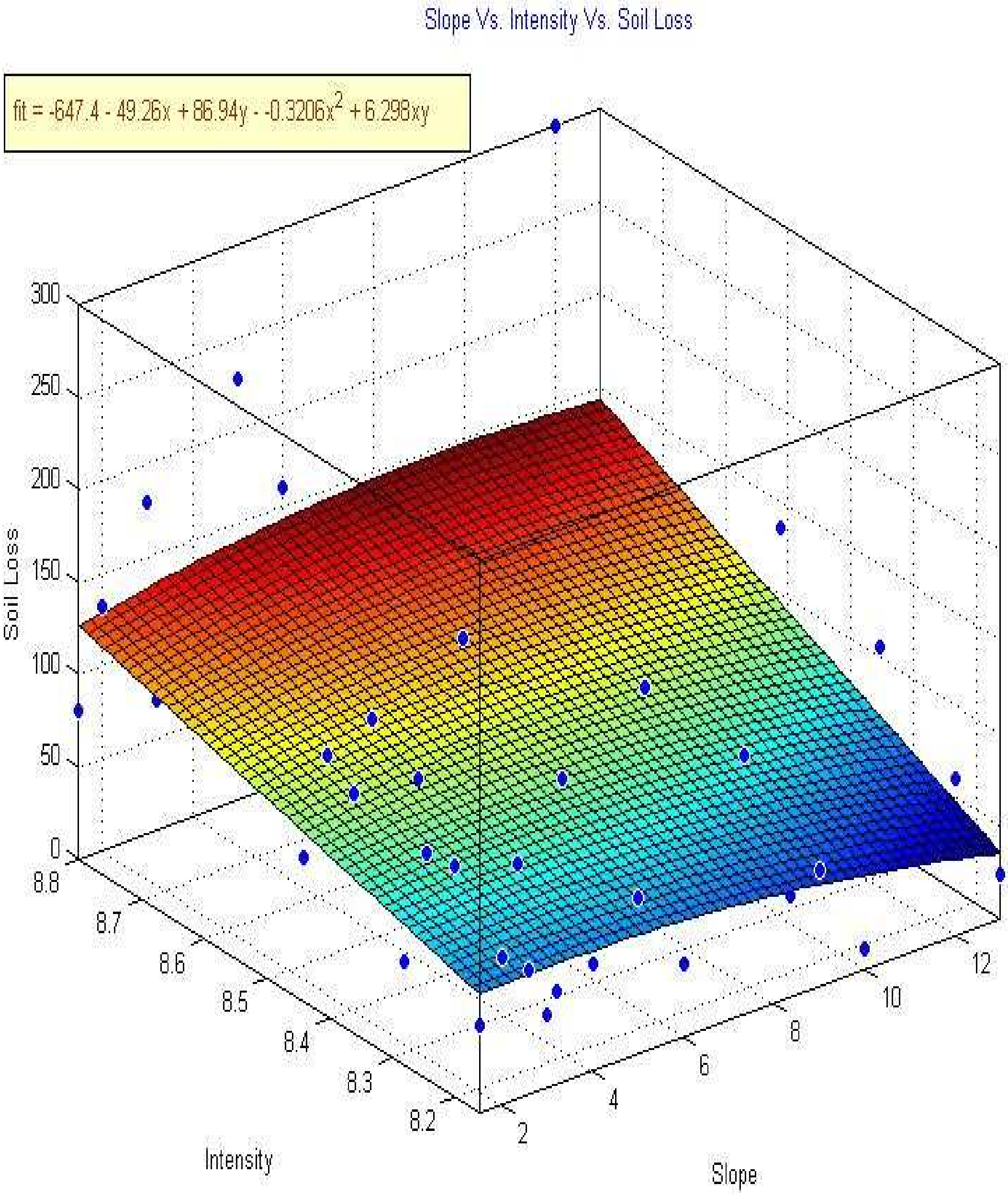


Fig. 11. Effect of intensity of rainfall and land slope on soil loss

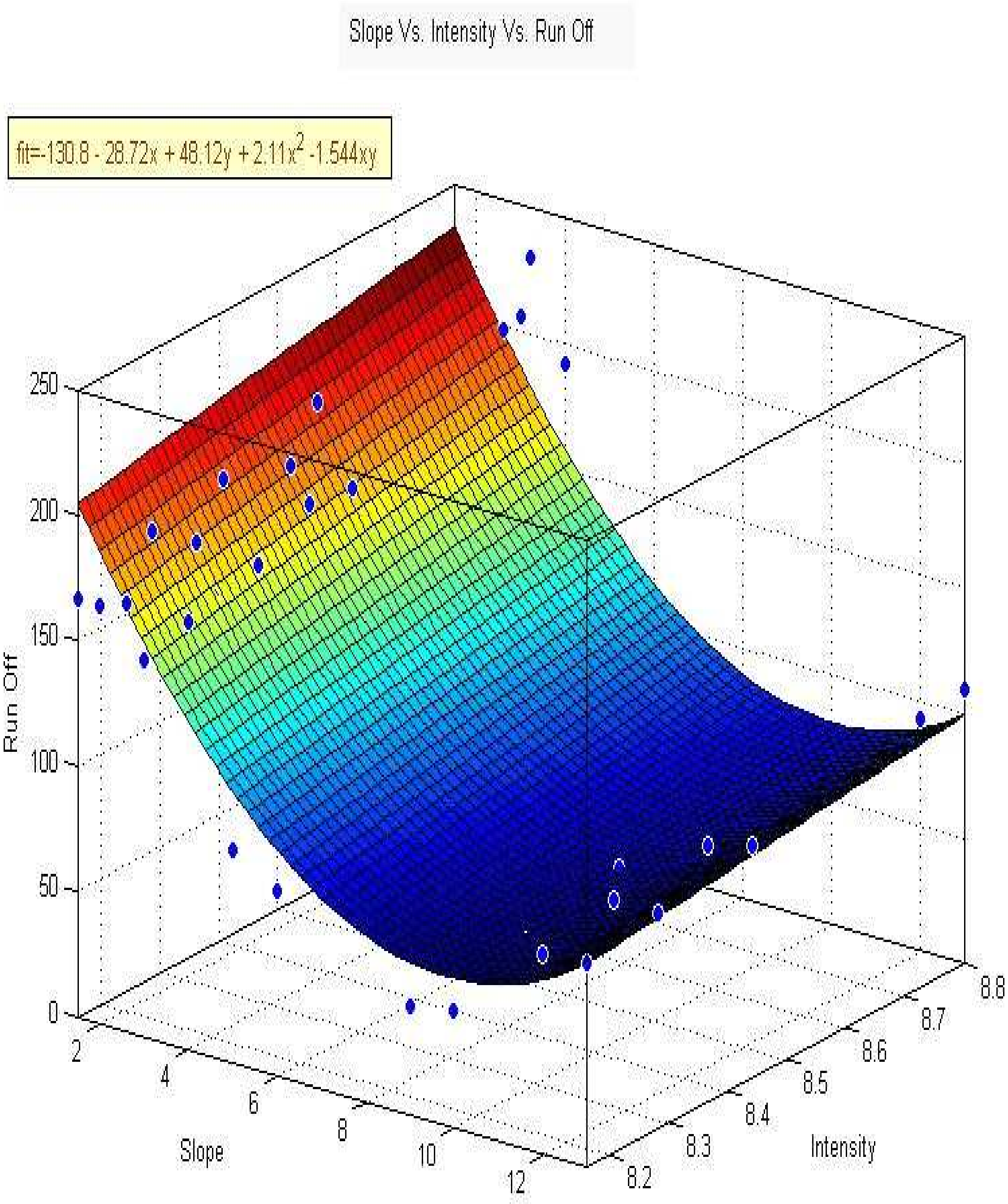


Fig. 12. Effect of intensity of rainfall and land slope on runoff

4.7 Canonical Analysis

The vector of parameters using slope and intensity determine the effect on runoff and soil loss. Since a vector of characteristics was involved together as a cause and effect phenomenon, it was most appropriate to use multivariate correlation to measure the relationship between cause and effect. Canonical correlation was found to be more suitable to explain the relationship.

Canonical R was computed and the same was 0.82034 and it is significant at 1 per cent level. Hence it may be concluded that the vector of process including slope and intensity as parameters together navigates the ultimate impact namely runoff and soil loss.

4.8 Practical / Scientific Utility

Researchers studying runoff and soil loss from rainfall have recognized the desirability of using rainfall simulators to supplement and enhance their investigations. The use of a rainfall simulator enables nearly immediate evaluation of carefully controlled plot conditions as well as observations of the erosion process involved. Knowledge of runoff and soil loss values under varying field conditions is predominant in the design of soil conservation structures. In Kerala, Laterite soils are the most important soil group covering the largest area. The lateritic terrain of Kerala occupies the midland region of the state and this tract can be considered as the backbone of the state. Studies on soil erosion from lateritic terrain are comparatively less. This study will provide useful information in estimating soil erosion from laterite soil. Erosion models are developed for agricultural areas and are designed to compare predicted annual rates of soil loss from the field plots. The developed model will help in quantifying the soil loss from the test plots. This will help in the prioritization of watersheds and design of soil conservation structures.

4.9 Suggestions for future work

In this study the rainfall simulator was developed using Pop-up sprinklers and the experiments were carried out with short duration of simulated rainfall on 1.5 x 2 m size micro plot. In future higher simulating heads can be chosen for developing rainfall simulator and the studies can be carried out with longer durations of rainfall and for larger sizes of field plots.

The erosion experiments in this study were conducted without considering the influence of wind flow and the experimental plots were prepared on bare soil only. So in future studies a detailed investigation is suggested for knowing presumptive influence of wind flow, vegetative cover and other features on erosion and runoff.

SUMMARY AND CONCLUSION

CHAPTER 5

SUMMARY AND CONCLUSION

Research on erosion include the use of experimental plots for the measurement of soil loss and surface runoff and use of rainfall simulators using which the characteristics of natural rains of a region can be reproduced at specific time and place .Rainfall simulators are research tools designed to apply water in a form similar to natural rainstorms. Rainfall simulators are widely used for numerous soils agricultural and environmental studies, particularly for those dealing with a phenomenon of soil erosion. The advantage of using simulated rainfall is the rapid data collection under relatively uniform conditions.

Forty eight rainfall-induced soil erosion simulations were conducted to assist in predicting soil loss during rainfall event. Artificial rainfall was simulated using *Rainbird* 12/15/18 Van Pop up sprinkler heads. A square framework made of PVC pipe was fabricated, to support the entire sprinkler unit. An electrically operated centrifugal pump was used to lift water from a storage tank of 2000 litres capacity and to supply to the simulator. The rainfall simulator was placed above the micro plots of size 1.5 x 2 m. This experimental setup allowed to understand the effects of rainfall characteristics on runoff and soil los.

The performance of the rainfall simulator was evaluated by measuring the intensity, depth and average drop diameter of simulated rainfall and uniformity of simulated rainfall by changing the pressure of water supply in the laboratory.

The intensity of simulated rainfall was found to range between 8.16 to 8.8 cm/h, the depth ranged between 1.36 to 1.47 cm and the average drop diameter between 1.5 to 2.8 mm. The intensity and depth of simulated rainfall was found to increase with the increase of supply pressure to the simulator. The average drop diameter of simulated rainfall was found to decrease with the increase of intensity of simulated rainfall and pressure of water supply.

From the test results a relationship was established between intensity of simulated rainfall and supply pressure of water as,

$$\mathbf{I = 0.24P^2 - 0.184P + 8.2 \qquad (R^2 = 0.994)}$$

Where,

I - intensity of rainfall (cm/h),

P - supply pressure (kg/cm^2).

Christiansen's uniformity coefficients were worked out at different intensities of rainfall. Higher values of uniformity coefficients were obtained at higher intensities. The uniformity coefficients varied from 89.01 to 92.07 per cent corresponding to intensity variations ranging from 8.16 to 8.8 cm/h. A relationship between coefficient of uniformity and intensity of simulated rainfall was developed as,

$$\mathbf{Cu = 2.179I2 - 31.30I + 199.3 \quad (R^2 = 0.997)}$$

Where,

Cu - uniformity coefficient (%),

I - intensity (cm/h).

Twelve micro plots with twelve different slopes were prepared. The area of micro plots was taken as 2 x 1.5 m. Boundaries were prepared by raising the ground level to 10 cm height on each side of the rectangular plot for preventing the overflow from the test plot to the surroundings. The collector was placed at the down slope of the plot for directing the runoff flow to the collecting tank. The rainfall simulator was placed over the plot in order to get maximum uniformity of rainfall over the plot.

Physical properties of the soils were determined. The particle size distribution curves when plotted showed that the soils were sandy loam. The soil belonged to Naduvattom series. The liquid limit and plastic limits of the soils were 22.27 per cent and 26.86 per cent respectively.

Tests were conducted to study soil loss and runoff at rainfall intensities of 8.16, 8.28, 8.44 and 8.8 cm/h. The runoff increased with increase in the intensity of rainfall for all runoff plots. A general trend of increase in runoff with increase in the land slope was observed for all the simulated intensities of rainfall.

From the test results, it was found that the soil loss increased with intensity of rainfall and land slopes and there were no much variations on runoff and soil loss at 6 to 10 per cent land slopes.

A linear multiple regression analysis was used to incorporate slope and rainfall intensities into a single prediction equation of soil loss and runoff.

The linear equations developed by the regression analysis are as follows:

$Q = 38.945\ I^{*} - 11.606\ S^{***} - 126.391$ ($R^2 = 0.649$)

$E = 124.356\ I^{*} - 0.807\ S^{***} - 951.420$ ($R^2 = 0.307$)

Where,

Q = Runoff in m^3/ha/h

I = Intensity of rainfall in cm/h, ranging from 8.16 to 8.8 cm/h

S = Land slope in per cent, ranging from 1.5 to 13 per cent

R = Coefficient of multiple regression

E = Soil loss in kg/ha/h

As the variants explained was satisfactorily enough to explain the runoff and soil loss, it may be concluded that the causative factors namely slope and intensity are bearing directive impact on soil erosion.

*** denotes significant at 1 per cent level,

* denotes significant at 10 per cent level.

The erosion prediction equations were also developed from the 3D surface plot analysis using MATLAB package.

The results are as follows;

$Q = 130.8 - 28.72\ S + 48.12\ I + 2.11\ S^2 - 1.544\ S\ I$

$E = -647.4 - 49.26\ I + 86.94\ S - 0.3206\ I^2 + 6.296\ S\ I$

A canonical analysis was worked out to determine the effect on runoff and soil loss by the vector of parameters using slope and intensity. Canonical R was computed and the same was 0.82034 and it is significant at 1 per cent level. Hence it may be concluded that the vector of process including slope and intensity as parameters together navigates the ultimate impact namely runoff and soil loss.

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APPENDICES

Appendix I

Effect of intensity of rainfall on runoff at different slopes

Slope (%)	Intensity (cm/h)	Runoff (m^3/ha/h)
1.5	8.8	66
	8.44	56.8
	8.28	52.4
	8.16	44
2	8.8	70
	8.44	68
	8.28	60
	8.16	46.8
2.6	8.8	92.6
	8.44	88
	8.28	86.8
	8.16	80.4
3	8.8	96
	8.44	92.2
	8.28	75.2
	8.16	74
3.2	8.8	102
	8.44	92.8
	8.28	88
	8.16	84.6
4	8.8	109.6
	8.44	93.2
	8.28	86
	8.16	82

5	8.8	180.6
	8.44	172.4
	8.28	168.5
	8.16	166.2
6	8.8	192.6
	8.44	188.8
	8.28	178.2
	8.16	170.3
9	8.8	198.2
	8.44	189.7
	8.28	179.6
	8.16	170.3
10	8.8	206
	8.44	176.6
	8.28	160
	8.16	150
12	8.8	206.4
	8.44	198.3
	8.28	197.4
	8.16	166.5
13	8.8	230.2
	8.44	218.6
	8.28	207.8
	8.16	202.5

Appendix II

Effect of land slope on runoff at different intensities

Intensity (cm/hr)	Slope (%)	Runoff (m³/ha/h)
8.8	1.5	66
8.44		56.8
8.28		52.4
8.16		44
8.8	2	70
8.44		68
8.28		60
8.16		46.8
8.8	2.6	92.6
8.44		88
8.28		86.8
8.16		80.4
8.8	3	96
8.44		92.2
8.28		75.2
8.16		74
8.8	3.2	102
8.44		92.8
8.28		88
8.16		84.6
8.8	4	109.6
8.44		93.2
8.28		86
8.16		82

8.8	5	180.6
8.44		172.4
8.28		168.5
8.16		166.2
8.8	6	192.6
8.44		188.8
8.28		178.2
8.16		170.3
8.8	9	198.2
8.44		189.7
8.28		179.6
8.16		170.3
8.8	10	206
8.44		176.6
8.28		160
8.16		150
8.8	12	206.4
8.44		198.3
8.28		197.4
8.16		166.5
8.8	13	230.2
8.44		218.6
8.28		207.8
8.16		202.5

Appendix III

Result of statistical analysis for runoff

Model Summary				
Model	**R**	**R Square**	**Adjusted R Square**	**Std. Error of the Estimate**
1	.806(a)	.649	.633	34.84646
a Predictors: (Constant), INTENST, SLOPE				
b Dependent Variable: RUNOFF				

ANOVA						
Model		**Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
1	**Regression**	100994.013	2	50497.006	41.586	.000(a)
	Residual	54642.397	45	1214.275		
	Total	155636.410	47			
a Predictors: (Constant), INTENST, SLOPE						
b Dependent Variable: RUNOFF						

Coefficients						
Model		**Unstandardized Coefficients**		**Standardized Coefficients**	**t**	**Sig.**
		B	**Std. Error**	**Beta**		
1	**(Constant)**	-126.391	176.089		-.718	.477
	SLOPE	-11.606	1.300	-.789	-8.927	.000
	INTENST	38.945	20.884	.165	1.865	.069
a Dependent Variable: RUNOFF						

Appendix IV

Effect of intensity of rainfall on soil loss at different slopes

Slope (%)	Intensity (cm/hr)	Soil loss (kg/ha/h)
1.5	8.8	40.8
	8.44	21.2
	8.28	14
	8.16	10.8
2	8.8	70.8
	8.44	63.1
	8.28	54.8
	8.16	50.3
2.6	8.8	74.4
	8.44	38.4
	8.28	32.4
	8.16	24.4
3	8.8	80.6
	8.44	78.2
	8.28	56.3
	8.16	48.2
3.2	8.8	120
	8.44	98
	8.28	86
	8.16	58
4	8.8	120.6
	8.44	102.7
	8.28	98.4
	8.16	67.6

5	8.8	120.8
	8.44	101.6
	8.28	99.2
	8.16	62.4
6	8.8	132.2
	8.44	128.9
	8.28	110.4
	8.16	80.2
9	8.8	160
	8.44	80
	8.28	40
	8.16	40
10	8.8	180
	8.44	140
	8.28	60
	8.16	40
12	8.8	228
	8.44	164.8
	8.28	123.2
	8.16	84.8
13	8.8	300
	8.44	160
	8.28	130
	8.16	84.8

Appendix V

Effect of land slopes on soil loss at different rainfall intensities

Intensity (cm/hr)	Slope (%)	Soil loss (kg/ha/h)
8.8	1.5	40.8
8.44		21.2
8.28		14
8.16		10.8
8.8	2	70.8
8.44		63.1
8.28		54.8
8.16		50.3
8.8	2.6	74.4
8.44		38.4
8.28		32.4
8.16		24.4
8.8	3	80.6
8.44		78.2
8.28		56.3
8.16		48.2
8.8	3.2	120
8.44		98
8.28		86
8.16		58
8.8	4	120.6
8.44		102.7
8.28		98.4
8.16		67.6

8.8	5	120.8
8.44		101.6
8.28		99.2
8.16		62.4
8.8	6	132.2
8.44		128.9
8.28		110.4
8.16		80.2
8.8	9	160
8.44		80
8.28		40
8.16		40
8.8	10	180
8.44		140
8.28		60
8.16		40
8.8	12	228
8.44		164.8
8.28		123.2
8.16		84.8
8.8	13	300
8.44		160
8.28		130
8.16		84.8

Appendix VI

Result of statistical analysis for runoff

Model Summary				
Model	**R**	**R Square**	**Adjusted R Square**	**Std. Error of the Estimate**
1	.545(a)	.307	.266	47.84163
a Predictors: (Constant), INTEN, SLOPE				

ANOVA						
Model		**Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
1	**Regression**	43520.347	2	21760.174	9.507	.000
	Residual	102996.967	45	2288.821		
	Total	146517.315	47			
a Predictors: (Constant), INTEN, SLOPE						
b Dependent Variable: SOILLOSS						

Coefficients						
Model		**Unstandardized Coefficients**		**Standardized Coefficients**	**t**	**Sig.**
		B	**Std. Error**	**Beta**		
1	**(Constant)**	-951.420	241.757		-3.935	.000
	SLOPE	-.807	1.785	-.056	-.452	.653
	INTEN	124.356	28.673	.542	4.337	.000
a Dependent Variable: SOILLOSS						

Appendix VII

Results of sieve and sedimentation analysis

Sl. No.	**IS Sieve**	**Particle Size D (mm)**	**Mass retained (g)**	**% retained**	**Cumulative % retained**	**Cumulative % finer**
1	2 mm	2.00 mm	065.50	19	19	81
2	1 mm	1.00 mm	057.00	17	36	64
3	600 µ	0.60 mm	027.00	08	44	56
4	475 µ	0.48 mm	029.00	08	52	48
5	300 µ	0.30 mm	025.00	07	59	41
6	212 µ	0.21 mm	101.00	30	89	11
7	150 µ	0.15 mm	010.50	03	92	08
8	75 µ	0.07 mm	022.50	07	99	01

ABSTRACT

SOIL EROSION STUDIES UNDER SIMULATED RAINFALL CONDITIONS IN A LATERITIC TERRAIN

by

PRAVEENA K K

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ABSTRACT OF THE THESIS

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KELAPPAJI COLLEGE OF AGRICULTURAL ENGINEERING AND TECHNOLOGY

TAVANUR - 679573, MALAPPURAM

KERALA

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ABSTRACT

Soil erosion is a complex phenomenon involving the detachment and transport of soil particles, storage and runoff of rainwater and infiltration. Soil erosion depends on several factors such as climate, soil type, topography, cropping and land management practices, the antecedent conditions and the size of the area under consideration.

The present study was carried out in the lateritic terrain of KCAET campus, Tavanur, Malappuram District. This study was aimed at developing a rainfall simulator and studying the performance of the developed rainfall simulator, the effect of rainfall on soil loss, the effect of rainfall on runoff and developing a soil erosion model.

A rainfall simulator was fabricated to study the erosion processes. *Rainbird* 12/15/18 Van Pop up sprinkler heads were used as the drop formers. The simulator evaluated for its performance. The soil was reddish brown and belonged to the textural class of sandy loam. It belonged to the *Naduvattom* series. The experimental set up consisted of three units viz., the runoff plot, the rainfall simulator and the runoff-sediment collection unit. Twelve runoff plots with twelve different slopes of 1.5, 2.0, 2.6, 3.0, 3.2, 4.0, 5.0, 6.0, 9.0, 10, 12 and 13 per cent in different locations, each plot with a size of 2 x 1.5 m were prepared.

The fabricated rainfall simulator could produce rainfall intensities varying from 8.16 to 8.80 cm/h. The uniformity of rainfall varied from 89.01 to 92.70 per cent and the average drop size varied from 1.5 to 2.8 mm. A relationship between supply pressure and intensity of rainfall as well as intensity and uniformity of rainfall was developed.

Studies were conducted on soil loss and runoff at different land slopes under simulated rainfall conditions. The soil loss and runoff was found to increase with

increase in rainfall intensity and land slopes and there were no much variations on runoff and soil loss at 6 to 10 per cent land slopes.

A linear multiple regression analysis and 3D surface plot analysis was used to incorporate slope and rainfall intensities into a single prediction equation of soil loss and runoff using SPSS software and MATLAB package.

The linear equations developed by the regression analysis are as follows:

$$\mathbf{Q = 38.945\ I - 11.606\ S - 126.391 \qquad (R^2 = 0.649)}$$

$$\mathbf{E = 124.356\ I - 0.807\ S - 951.420 \qquad (R^2 = 0.307)}$$

The quadratic equations developed by the 3D surface plot analysis are as follows:

$$\mathbf{Q = 130.8 - 28.72\ S + 48.12\ I + 2.11\ S^2 - 1.544\ S\ I}$$

$$\mathbf{E = - 647.4 - 49.26\ I + 86.94\ S - 0.3206\ I^2 + 6.296\ S\ I}$$

As the variants explained were satisfactory enough to explain the runoff and soil loss, it may be concluded that the causative factors namely slope and intensity are bearing directive impact on soil erosion.

A canonical analysis was worked out to determine the effect on runoff and soil loss by the vector of parameters using slope and intensity. Canonical R was computed and the same was 0.82034 and it is significant at 1 per cent level. Hence it may be concluded that the vector of process including slope and intensity as parameters together navigates the ultimate impact namely runoff and soil loss.