EXPERIMENTS IN SMALL WATERSHED RESPONSE

by

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by

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ABSTRACT

There is need in hydrologic research for a facility in which some of the many variables in the natural hydrologic system can be controlled or varied at will. Size or scale is an important consideration. Some of the design features of the CSU Experimental Rainfall-Runoff Facility are discussed especially those which have been modified. Three classes of experiments are described. Experiments dealing with the flow hydraulics in the sheet of overland flow have been used to verify the kinematic wave theory and to define the character of roughness and resistance to flow. A second group of experiments have studied the erosion caused by the overland flow. These have contributed some experimental data on the evaluation of channel systems and the nature of sheet erosion. The third group of experiments have provided some data on the pollution hazards of spent oil shale residues resulting from both rainfall and snowfall.

EXPERIMENTS IN SMALL WATERSHED RESPONSE

Introduction

The ability to predict the response of a watershed to flood pro-
ducing rainfall has been the goal of hydrologists for many years. The
results of the study of floods measured on natural watersheds when good
information on the temporal and areal distribution of the rainfall is
known has been disappointing. The reasons for this lack of success is
attributed to the sampling error of the observations of both rainfall
and runoff and to the complexity of the loss and infiltration functions
in the hydrologic cycle. Direct measurements of many of the important
parameters are not possible and hydrologists resort to index values of
variables which have been measured and are correlated with the hydrologic
process.

In order to control some of the variability of the natural hydro-
logic processes, experiments are carried out on small model watersheds.
This type of material model is a physical representation of a complex
natural system which is assumed to be simpler and is also assumed to
have some of the properties similar to those of the prototype system,
Woolhiser and Schulz (1973).

Material models may involve a change in space or time scale or may
simply enable experiments to be carried out under more favorable con-
ditions than would be available in the original system. Experiments
on a natural watershed are very time consuming and the investigator has
no control over the inputs. The physical size of the system is also a
problem; so for practical reasons, some investigators attempted to model
hydrologic systems utilizing a change in scale, Chery (1966). They
found that this was not always a viable approach and Grace and

Eagleson (1966) demonstrated that small scale models are possible only in very special cases.

A material model that does not involve a change in scale may still be valuable because experiments may be carried out more conveniently or can be repeated at will. The CSU Rainfall-Runoff Facility is considered to be of prototype scale.

CSU EXPERIMENTAL RAINFALL RUNOFF FACILITY

The design and preliminary testing of the CSU facility has been described in previous reports, Schulz (1970) and Schulz and Yevjevich (1970). The experimental watershed consists of a conic sector having an interior angle of 104° and a radius of 116 feet. Two 88-foot by 70-foot long intersecting plane surfaces join the edges of the conic sector as shown in Fig. 1. The dimensions have been adjusted slightly to take advantage of the existing topography. Some operational diffi-culties have been encountered.

Rainfall Simulators - The basic design of the sprinklers has been satisfactory. We have found difficulties during the winter time. Sometimes small amounts of water have been retained in parts of the hydraulic operating valve or the pressure reducing valve where freezing has caused damage. (see Fig. 2 for location of these valves on the riser)

It was necessary to install a 1/8 inch diameter steel aircraft cable in both the transverse and longitudinal direction. The risers are each clamped to a cable at about eight feet above the surface of the watershed. The cables are connected to suitable anchors at each end. Thus the sprinklers are all held in place by a network of cables at 10 foot intervals.

10' Typical

Sprinkler Standpipes

40' Effective Radius Of Any Sprinkler

6" I.D. Supply Manifolds

5% Slope

110' Radius

104°26'

70'

5% Max. Slope

Upstream Flume & Stage Recorder

3% Slope

Upstream Flume Diversion Pipe

Downstream Flume & Stage Recorder

88'

17.5' Typical

2" I.D. Aluminum Supply Lines

0 10 30 50 Feet

Area Of Impervious Surface
Upstream Conic Sector = 12,700 sq. ft.
Two Planes   = 12,300 sq. ft.
Total   = 25,000 sq. ft.
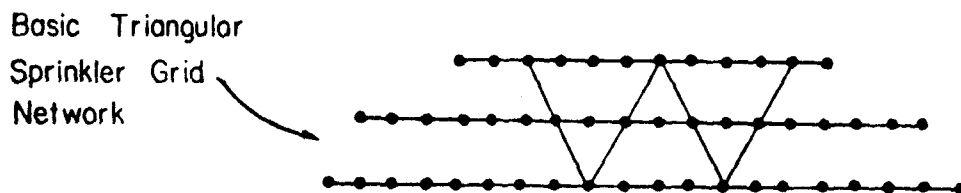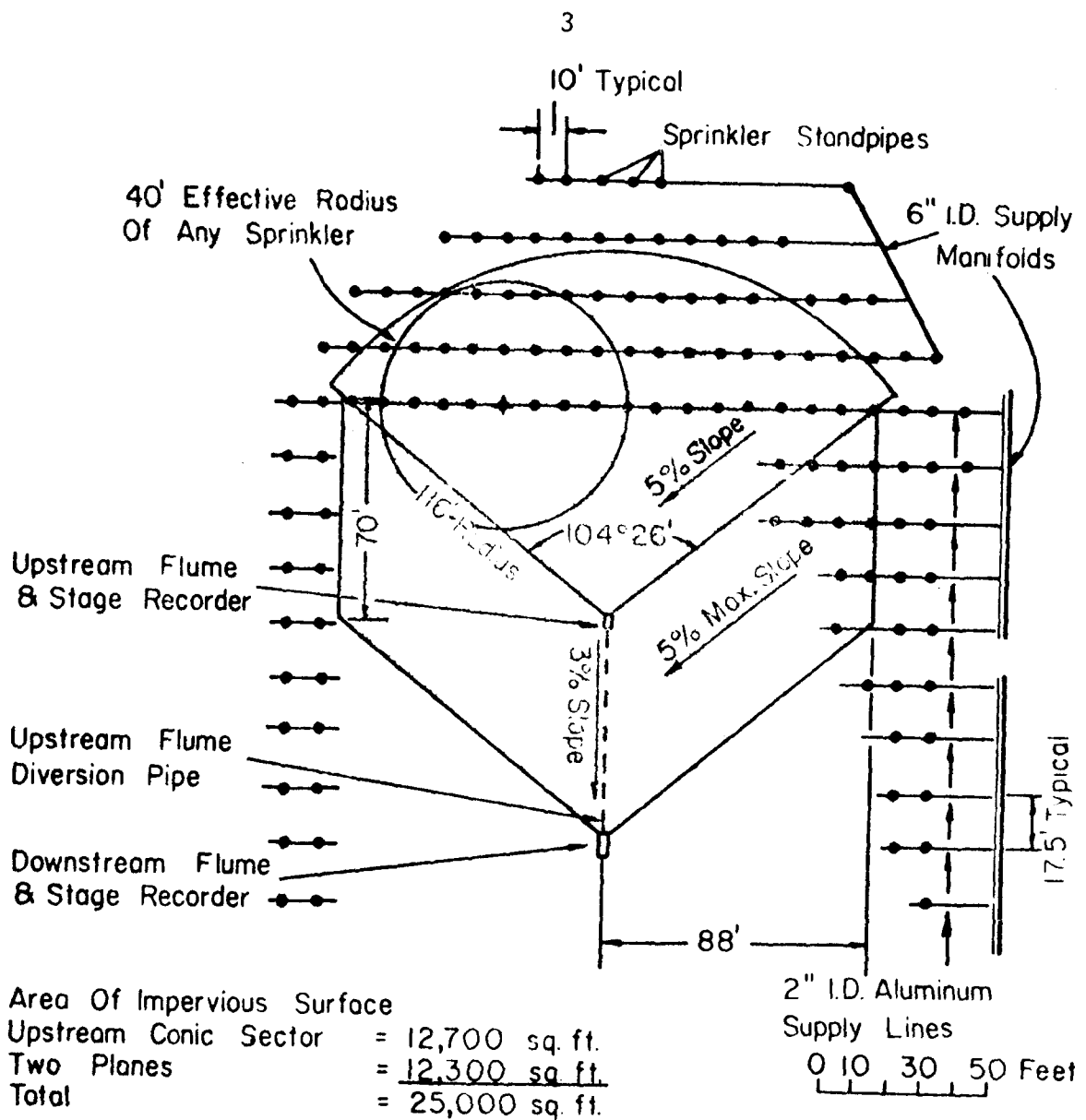
Basic Triangular Sprinkler Grid Network

Fig. 1. CSU Experimental Rainfall-Runoff Facility

These anchors are required to prevent damage to the relatively thin aluminum main in the event that wind driven debris becomes lodged on the sprinkler riser.

Butyl Rubber Surface - The carefully graded watershed surface was covered with a fabric reinforced butyl rubber material. Accidental punctures occur which have been patched. These patches create minor disturbances to the flow. Some of the butyl material has de-laminated and upper layer of rubber has flaked off. An additional layer of butyl rubber has been placed on top of parts of the badly worn places. It is believed that the deterioration will no longer occur when a layer of soil is placed on the watershed which is in the plans for the near future. The soil layer will protect the rubber from the sun and air and excessive temperature changes.

The rubber surface performs two functions: 1) the watershed surface is stabilized and does not change as a result of erosion and 2) there is no infiltration so that all of the rainfall appears as runoff and the analysis of the data is simplified. Other experiments on a somewhat smaller scale have been conducted on watersheds having erodible surfaces. These experiments will be discussed later.

Measuring Flume - The flood runoff is measured in an H-flume (USDA, 1962). There are two flumes - one located at the vertex of the conic sector and the second one located at the outflow of the combined surfaces. The H-flume is located at the downstream end of a 2-foot wide by 7-foot long rectangular approach channel.

The depth of flow through the measuring flume is recorded by means of an FW-1 float-operated water stage recorder. The clock has been modified to provide a full revolution of the chart drum in a

Sprinkler Head
10' Above Surface

Clamp

Steel Cable Support

$\frac{3}{4}$" Galvan.
Steel Pipe
7' Long

- Watts Low Pressure
  Regulator
  100 p.s.i. max.(high)
  10 - 30 p.s.l. (low)

- Toro Hydraulic Valve
  $\frac{3}{4}$", 0 - 100 p.s.i. range

Tire Pressure Tap
on $\frac{3}{4}$" Connector

$\frac{3}{4}$" x 2"
Nipple

Pressure Regulator
Set For 28 p.s.i.
Hydraulic Valve

Pressure Line To Control System

1" - $\frac{3}{4}$" Reducer

1" Pipe, 1' Long

Aluminum 1" Nipple Welded To Main

Approx. $\frac{1}{2}$" Layer Of
Compacted Sand

Tipod Support Base

Aluminum Main 2" Diameter

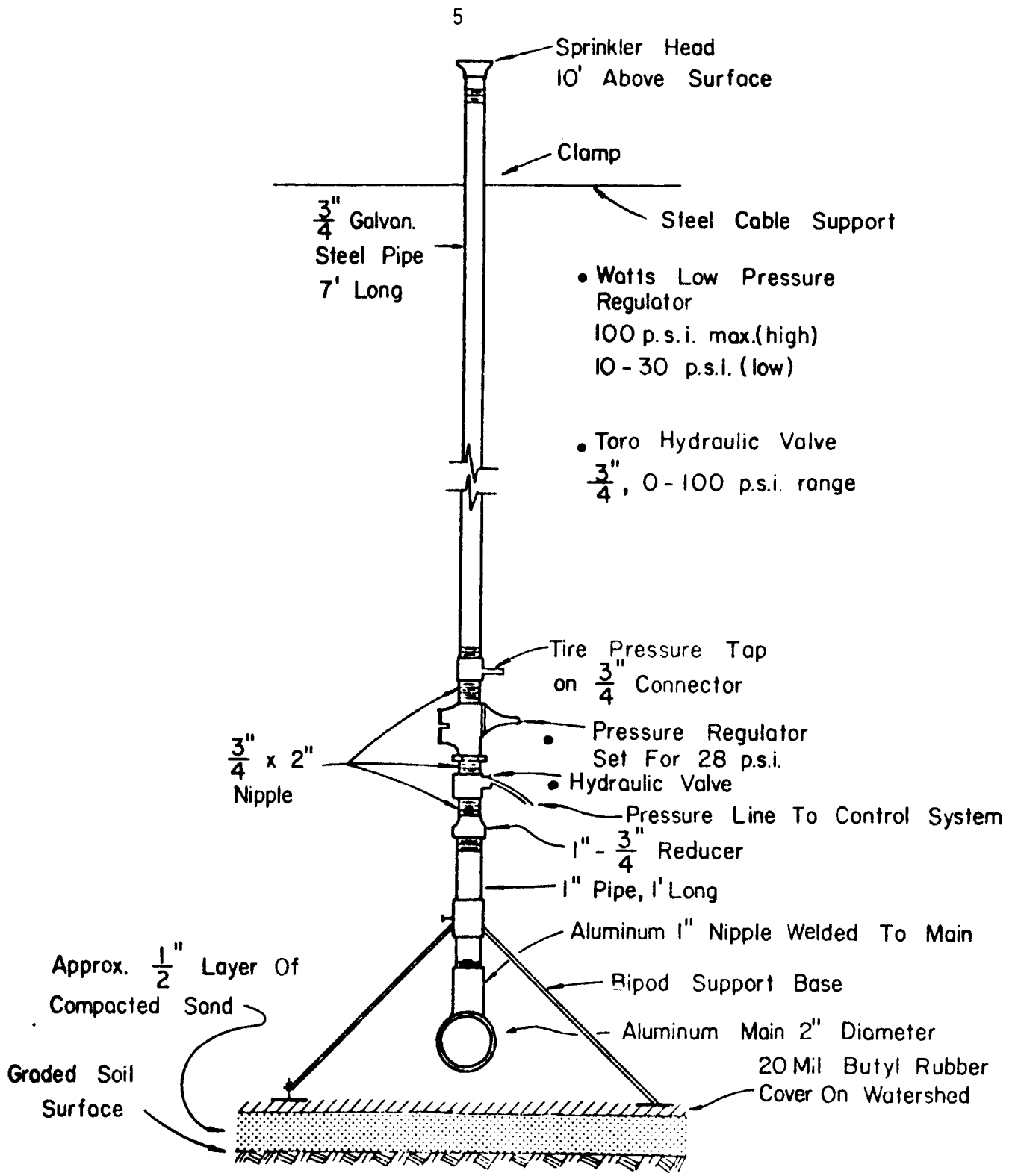Graded Soil
Surface

20 Mil Butyl Rubber
Cover On Watershed

Fig. 2 Sprinkler Riser Assembly

30-minute period of time. The recorder has also been fitted with an event timer which indicates the time of beginning and ending of rainfall. The float stilling well has been reduced in size from 12 inches in diameter to 5 inches in diameter to reduce the stilling well lag time.

Originally the measuring flume was also fitted with a second 2-inch stilling well equipped with a capacitance stage probe. This equipment was found to have circuit stability problems and has not been used because of its unreliability. The float wheel of the FW-1 recorder had also been fitted with precision micro-torque potentiometer which is an active element in a Wheatstone bridge circuit. The voltage across the bridge is proportional to the stage in the flume. This voltage was automatically digitized at selected time intervals and the voltage-time pairs of data were automatically punched onto cards by an IBM Card Punch. The digitizer is located at a remote location from the outdoor facility and this method of producing the output data has proved to be undependable.

Reduction of the Runoff Data - It was previously pointed out that the digitizing of the data proved undependable. As a result, we found we were relying upon the ink charts from the FW-1 recorder for the runoff hydrographs. An alternate method of processing the stage hydrograph data was used. The FW-1 charts were traced in an Autotrol coordinate digitizer. This equipment produced a deck of IBM cards having the coordinate values of the traced line punched on the cards at suitable intervals along the time scale of the chart. The IBM cards were then processed by digital computer to produce discharge hydrographs.

This procedure for processing the data has proved to be the most practical and dependable. The FW-1 charts are filed and can be used for checking any questionable data. The time interval selected can be easily adjusted to faithfully reproduce all significant features of the stage hydrograph because the operator can intervene to punch the coordinates of all significant points of the hydrograph. The method has the potential disadvantage of introducing operator errors in tracing.

Computation of Rainfall Intensity - Since the rainfall is not measured directly, but computed from the output hydrograph, we are assuming it has no losses. The establishment of the condition of continuity under these assumptions results in the application of some corrections to the data. There are four types of experiments:

1) Equilibrium runs,

2) Partial equilibrium runs,

3) Complex rain patterns,

4) A rainfall pulse occurring on base flow.

These four types of hydrographs are illustrated in Figs. 3, 4, 5 and 6.

An equilibrium hydrograph is illustrated in Fig. 3. Two points T1 and T2 are selected during the steady state conditions. The total volume of runoff occurring in the interval T2 to T1 is computed and is divided by the time (T2 - T1) to obtain the average discharge. It is assumed that the average rate of equilibrium discharge is equal to the uniform rate of rainfall.

The total volume of the rainfall and runoff are computed. Any difference in these two volumes is assumed to be caused by errors in rainfall time measurements or initial absorption losses by the butyl or
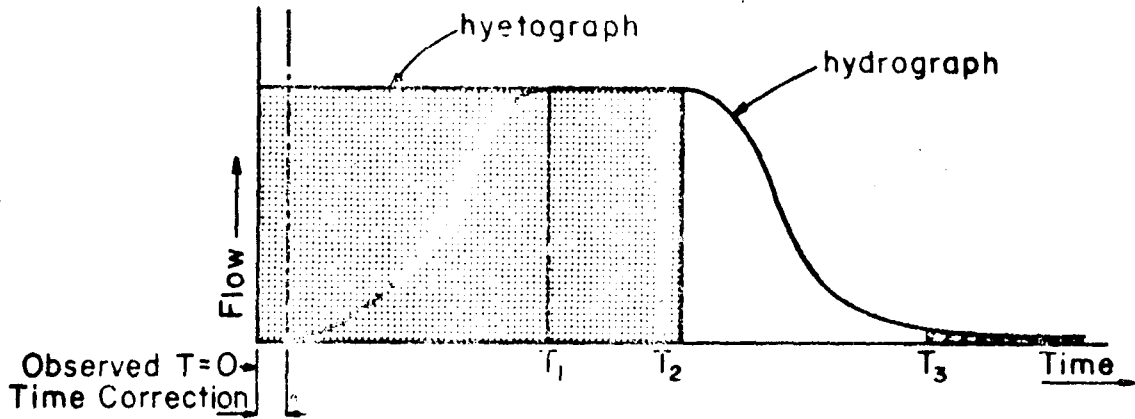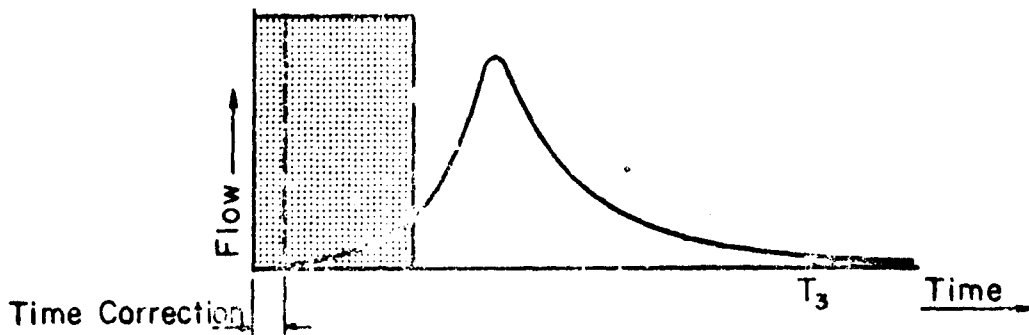
Fig. 3. Typical Equilibrium Hydrograph.

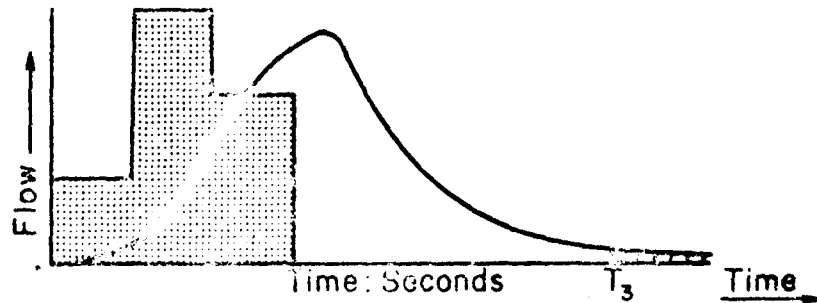Fig. 4. Typical Partial Equilibrium Hydrograph.

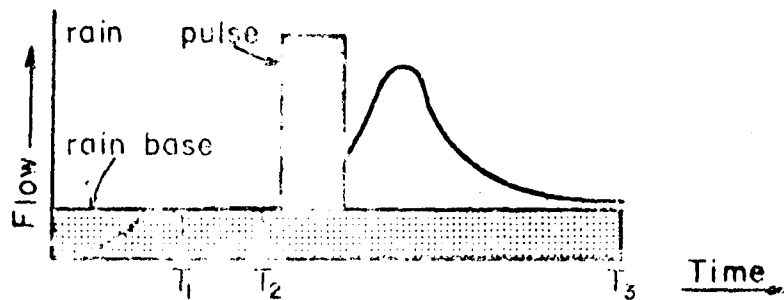

Fig. 5. Typical Complex Rain Hydrograph.

Fig. 6. Typical Rain Pulse on Base Flow Hydrograph.

gravel surface or water retained on the surface by surface tension. The actual runoff is delayed for a short interval of time by these losses.

A time correction is made by dividing the difference between the rainfall and runoff volumes by the computed rainfall rate and deducting the result (which has units of time) from the observed time. (See the time correction at T = 0 in Fig. 3.) In the equilibrium runs a condition of continuity is thus imposed upon the experiment.

In the case of the partial equilibrium run (as illustrated in Fig. 4), it is not possible to establish a condition of continuity in quite the same way. It was assumed that the time correction required was equal to the time correction as the equilibrium run for the same nominal rainfall intensity; i.e., the same ΔT correction was applied at the start of the run as was applied for the equilibrium run for the same nominal intensity.

The runoff hydrographs obtained from a complex rainfall pattern or from a rainfall pulse occurring on a base flow were reduced in a different manner. The rainfall intensities are obtained from the rainfall intensities computed for the equilibrium runs. No time corrections are made for these two types of runs.

Inspection of these hydrographs shows that the small volume of runoff occurring in the recession after T3 is neglected. The hydrograph was arbitrarily terminated when the discharge rate had recessed to 0.001 cfs. This is done for practical reasons. It was noted that the evaporation losses after the end of rainfall could be significant when the air temperatures were in the excess of 90°F and the relative humidity was as low as 30% and the recession limb of the hydrograph was in the order of 10 minutes duration. Terminating the hydrograph at T3

eliminated some of the uncertainty caused by variations which are caused by these evaporation losses.

EXPERIMENTS ON AN ERODIBLE SURFACE

Evaluation of Channel Networks - There have been two types of experiments carried out in which the soil erosion of the surface was a studied variable. The first type of experiment was carried out on a 30-foot by 50-foot watershed. The watershed soil consisted of a 6-foot layer of selected clay loam material. This soil was placed into a large box. The soil surface was sloped at 0.5% toward one end. The watershed surface was a plane surface. The maximum length of overland flow was 50 feet.

Rainfall was produced by a network of the rainfall simulators installed such that the plane of the sprinkler heads was 10 feet above the soil surface. The runoff was discharged into a sedimentation basin. The desilted effluent was measured in a small 6-inch H-flume.

The rain storm was started and continued until a stable channel channel network was eroded in the watershed surface. The channel network was photographed by a camera suspended over the watershed. Profiles of the channel network was measured by analysis of a stereo-pair of photographs in a Wild STK-1 Precision Stereo Comparator. These profile measurements were also checked by means of a point gage operating from special carriage spanning the experimental watershed.

When all of the data had been obtained, the stream channel erosion cycle was initiated again by removing a stop log at the outlet sill, thereby allowing the channel to erode down to the edge of the next stop log. As the channel steepened, an increasingly more complex channel

system was eroded in the watershed surface. The sequence of 1) stop-log removal, 2) rainfall, 3) channel erosion, 4) channel network development and 5) channel network measurement was repeated until the channel network eroded to the edge of the model box.

Sheet Erosion - A second type of soil erosion was conducted to obtain information on sheet erosion. Kilinc (1972) conducted tests on a soil surface in a 5-foot wide by 16-foot long box filled with a sandy soil. The watershed was graded to six different uniform slopes varying from 5.7 to 40%. The rainfall intensity varied from 1.75 to 4.6 inches per hour. In addition four experimental runs were made on the steepest slope (40% grade) when about 40% of the surface was covered by winter wheat vegetation. In each run, the sediment yield, mean velocity of flow, water temperature and runoff were measured. The water and sediment were measured by leaving the runoff flow into a sedimentation basin and then through a small H-flume.

It should be realized that the results in any erosion process is limited by the fact that the kinetic energy applied to the surface is somewhat smaller for a given intensity in this facility than is absorbed by the surface in a natural rain storm.(The rain drops are smaller in size in the CSU facility than in a natural rain storm.)

EXPERIMENTS ON SPENT OIL SHALE RESIDUES

The development of oil shale resources is under consideration in Colorado, Utah and Wyoming. The oil shale deposit is mined or quarried and then heated in a retort to vaporize the hydrocarbons which are then condensed and processed into the fuels or petroleum products or petrochemicals. The process most likely to be commercially used in the

TOSCO II process. The crushed oil shale is reduced to a pulverized rock in the retorting. The spent oil shale has 60% of the bulk volume of the original material. Since the minimum economic sized shale oil plant will probably produce in excess of 50,000 tons of processed shale per day, there will be a considerable quantity of waste residue which will have to be discarded, Ward et al. (1971). Because of the large quantities of spent oil shale residues which are likely to exist in excess of that which can be returned to the mine (or quarry), it was necessary to investigate the impact of these wastes on the environment.

A test bed of spent oil shale was installed at one edge of the rainfall-runoff facility. A horizontal excavation 8 feet wide at the bottom and 80 feet long was lined with an impermeable plastic membrane. A four inch layer of sand was placed on top of the plastic membrane. This was to provide a drain for any ground water which percolated through the bed of shale. A three-inch perforated plastic pipe was placed in the sand filter to collect the percolation water. This ground water was collected in a 50-gallon steel storage drum. Approximately 68 tons of TOSCO unweathered spent oil shale residue was placed in this excavation on top of the sand drain and the plastic membrane at the edges of bed. When completed, the shale bed was 80 feet long, 8 feet wide at the bottom, 12 feet wide at the top and approximately 2 feet deep. The surface had a slope of 0.75% which is approximately the maximum permissible slope if excessive erosion is to be prevented.

Rain storms were created at different intensities on the shale bed. The rainfall continued until an equilibrium concentration in the surface runoff was achieved. Virtually no rainfall percolated through the shale bed to the sand layer.

During periods of dry weather between rain storms, the soil moisture evaporated from the surface and deposited a white layer of salt at the surface. This salt crust was dissolved in the next rainfall and caused high concentrations of the salt in the initial parts of the surface runoff. These high salt concentrations are one of the pollution hazards from the spent oil shale. A complete summary of the pollution hazards from rainfall on the oil shale was reported by Ward, Margheim and Löf (1971).

Snowfall on Oil Shale Residues - The runoff from snowmelt is more intimately associated with percolation into the soil. It was reasoned that the potential hazards of the spent oil shale residues might be quite different than the hazards resulting from surface runoff from rainfall. In the area where the oil shale deposits are likely to be developed in the USA, more than 1/2 of the annual precipitation occurs as snowfall.

The natural snowfall occurring during the winter of 1970-71 was augmented by simulated snow storms. Four experimental runs were conducted on the CSU experimental facility. Three of these were simulated snow storms and one was natural. Long periods of freezing weather followed by long periods of above freezing weather made it impossible to conduct any more experiments during this period.

Artificial snow can be generated by contacting high pressure water with high pressure air in an expansion nozzle, Ward and Reinecke (1972). The nozzle is designed to atomize the water into tiny droplets and eject them at high velocity. Snow is formed if these droplets are chilled in a sufficiently low ambient air. Snow could be generated at the CSU experimental facility when the air temperature was -2°C. Optimum snow generation occurred when the air temperature was lower than -5°C.

Compressed air was obtained from a 250 cfm air compressor. Water at 100 psi was available at the experimental facility. The relatively low capacity of the air compressor made it necessary to use the 3/8 inch nozzle tip for the *Blizzard King* expansion nozzle. This nozzle could blow snow over an area 60 feet long and 10 to 14 feet wide. The nozzle was moved periodically to distribute snow over the shale bed.

The experiments with the snowmelt runoff provided some interesting contrasts with the finding of the experiments on rain surface runoff.

1. Virtually no rainfall percolated through the shale bed; whereas the long contact period associated with snowmelt results in percolation into a bed of oil shale residue and subsequent saturation.

2. This saturation reduces the density of the shale residue bed.

3. This saturation increases the hazard from creep and slides.

4. The dissolved solids concentration in snowmelt water is increased by contact with the oil shale residue but the concentrations are not as high as the initial surface runoff occurring after a period of drying (salt crust formation).

5. The oil shale need not be saturated for percolation from snowmelt to occur.

6. Weathering of the oil shale residue increases the tendency for percolation to occur.

OVERLAND FLOW EXPERIMENTS

There is considerable evidence in the literature regarding the nature of the flow resistance regime in the overland flow. Woolhiser et al. (1971) have shown that both laminar and turbulent flow must exist

within the overland flow. In an effort to verify some of these facts,
M. Correia (1972) carried out experiments in an effort to measure the
velocity within the sheet of overland flow by tracing dye injected into
the sheet at various distances upstream from the sampling point.
Correia was able to demonstrate the fact that under raindrop impact
the overland flow demonstrated characteristics of turbulent flow in
that the friction factor was not dependent upon the Reynolds Number -
hence not laminar.

Utilizing a flow model proposed in a paper by Woolhiser et al.,
Fawkes (1972) used an optimization technique to evaluate parameters in
a friction model which is required in the application of the kinematic
wave theory to the hydraulics of the overland flow.

CONCLUSIONS

The feasibility of conducting experiments on overland flow in a
relatively large rainfall-runoff facility has been demonstrated.
Several improvements have been developed and reported herein.

The experiments have been carried out on several different types
of watersheds. One type of experiment was carried out on a smooth
noninfiltering watershed covered by a sheet of butyl rubber. A second
type of experiment was carried out on an erodible watershed. Channel
erosion patterns and the sheet erosion were measured in these experi-
ments. A third type of experiment was carried out where the water
quality was a variable.

Experiments have been carried out with both simulated rainfall and
simulated snowfall on the experimental facility.

It is hoped that additional experiments can be carried out as the
infiltered water becomes a larger and larger component in the

resultant runoff. These experiments will require thicker and thicker layers of soil over the butyl surface.

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