A
Paper presentation
on

EXPERIMENTAL INVESTIGATION OF RAINFALL RUNOFF PROCESS

by

Ankit Chakravarti M.K.Jain Kapil Rohila

Department of Hydrology,
Indian Institute of Technology, Roorkee-247667

Introduction

- Rainfall-runoff processes plays an important role in hydrological cycle. The movement of water has mainly arisen from the need to evaluate the amount of available runoff water at a particular location to meet local demand as well as risk of flooding due to excess water.

- A number of models such as physically based and conceptual models have been used to simulate the rainfall runoff process. However, due to its complexity and spatio-temporal variation, few models can accurately simulate this highly non-linear process.

- Runoff is generated by rainstorms and its occurrence and quantity are dependent on the characteristics of the rainfall event, i.e. intensity, duration and distribution.

- The experimental investigations could be performed to understand surface, sub-surface or ground water runoff generation mechanism.

- The mechanism of surface runoff generation is however the focus of the present investigation. The main objective of this laboratory study is to quantify the rainfall runoff process.

Description of the laboratory set-up

- The rainfall simulator is designed to simulate the rainfall event over the catchment.
- Basic components of the simulator are-

  - Tilting flume for slope adjustment(rectangular cross-section having 1.25 m wide and 5 m long),
  - Spray Nozzles,
  - Storage Tank,
  - Pressure Gauges,
  - Electric Motor
  - Slope Adjustment Device (0-5%)
  - Runoff Recording System.

Fig. 1 Advanced Hydrologic system S-12 MKII-50 (Rainfall Simulator)

Methodology

- The experiments is carried out on a sand layer placed over an impermeable plane surface (smooth metal sheet),
- Sediment particle diameter of 0.5-1.0 mm is required to fill over the flume.
- Similar arrangement for rainfall intensity from 30 mm/hr to 90 mm/hr.
- With the help the spray nozzle artificial rainfall is spread over the catchment area in the flume filled with sand.
- During rainfall event water flows over surface of sand reaches to the outlet and the runoff water flows through collecting tank.
- The Depth sensor is attached below the collecting tank to give the height over weir.

Mathematical Modeling

- KW formulation has been widely used for modeling overland and stream flow. KW formulation uses physiographic parameters such Overland roughness, slope, drainage area and length, and soil characteristics for computation of overland flow.

- The KW approximation of Saint-Venant's equation can be written as:-

$$\frac{\partial A}{\partial t} + \frac{\partial (vA)}{\partial x} = q_l \quad \text{.....(1)}$$

$$Q = \alpha A^m \quad \text{.....(2)}$$

Where;

A is the area of watershed (m^2),

v is the flow velocity (m/s);

Q is flow rate (m^3/s),

t is the time (s),

x is the distance measured in the direction of flow (m)

α and m are parameters of the kinematic wave model which are closely related to the characteristics of the flow.

$$\frac{\partial A}{\partial t} + \alpha m A^{m-1} \frac{\partial A}{\partial x} = q_l \quad \text{..... (3)}$$

$$\frac{\partial h}{\partial t} + \alpha_o m_o h^{m_o - 1} \frac{\partial h}{\partial x} = r - f \quad \text{..... (4)}$$

$$q_o = \alpha_o h^{m_o} \quad \text{..... (5)}$$

The governing differential equation were solved numerically using explicit numerical method. From equation (1) and (2) using implicit finite difference method,

$$\frac{h_{i+1}^{t+1} - h_{i+1}^{t}}{\Delta t} + \frac{q_{i+1}^{t+1} - q_{i}^{t+1}}{\Delta x} = (r - f)_{i+1}^{t+1} \quad \ldots\ldots (6)$$

$$q_{i+1}^{t+1} = \alpha \left(h_{i+1}^{t+1}\right)^{m} \quad \ldots\ldots\ldots\ldots (7)$$

$$q_{i}^{t+1} = \alpha \left(h_{i}^{t+1}\right)^{m} \quad \ldots\ldots\ldots\ldots (8)$$

$$q_{i}^{t+1} = \alpha \left(h_{i}^{t+1}\right)^{m} \quad \ldots\ldots\ldots\ldots (9)$$

Where r = rainfall intensity in mm/hr, f = infiltration rate in mm/hr, $m_o = 5/3$, $\alpha_o = s_o^{1/2} / n_o$

After simplifying the these equation,

$$f\left(h_{i+1}^{t+1}\right)=\frac{\Delta t}{\Delta x}\alpha\left(h_{i+1}^{t+1}\right)^{m}-\left(\frac{\Delta t}{\Delta x}\alpha\left(h_{i}^{t+1}\right)^{m}+h_{i+1}^{t}+\Delta t\left(r-f\right)_{i+1}^{t+1}\right)+h_{i+1}^{t+1}$$

…….… (10)

By solving the above equation using Newton-Raphson iterative method,

$$\left(h_{i+1}^{t+1}\right)_{k+1}=\left(h_{i+1}^{t+1}\right)_{k}-\frac{f\left(h_{i+1}^{t+1}\right)_{k}}{f^{/}\left(h_{i+1}^{t+1}\right)_{k}} \quad \text{…..(11)}$$

Where $$f^{/}\left(h_{i+1}^{t+1}\right)=1+\frac{\Delta t}{\Delta x}\alpha\, m\left(h_{i+1}^{t+1}\right)^{m-1} \quad \text{…….… (12)}$$

❑ Nash Sutcliffe Criterion

$$NES(\%) = \left(1 - \frac{\sum_{i-1}^{n}(Y_o - Y_c)^2}{\sum_{i-1}^{n}(Y_o - Y_m)^2}\right) \times 100$$

Where,

Y_o = Observed flow (Experimental rainfall flow) value at time t

Y_c = Computed flow (kinemaic flow) value at time t

Y_m = Mean of observed values.

❑ Error in Runoff Volume Computation

$$\text{Volumetric error, in \%} = \left(1 - \frac{Y_c}{Y_o}\right) \times 100$$

Y_c = volume computed

Y_o = volume observed

Analysis of the data

- Experimental data obtained from Advanced Hydrologic system (rainfall simulator) is analyzed using one dimensional KW overland flow simulation model using FORTRAN programming.

- The simulation was done using time step of 5 sec and spatial grid size is taken as 1 cm.

- Experimental data were simulated using developed model in order to study the overland flow roughness due to variation of slope and rainfall intensity on the catchment.

- Data was observed for catchment slope between 1 % to 4 % and rainfall intensity varies between 30 to 90 mm/hr.

- Developed KWM was calibrated for manning's roughness coefficient "n" to fit into data observed from experiment for 30 mm/hr rainfall intensity for different slopes.

Table 1 Pertinent characteristics of observed and computed hydrograph for 30 mm/hr intensity of rainfall.

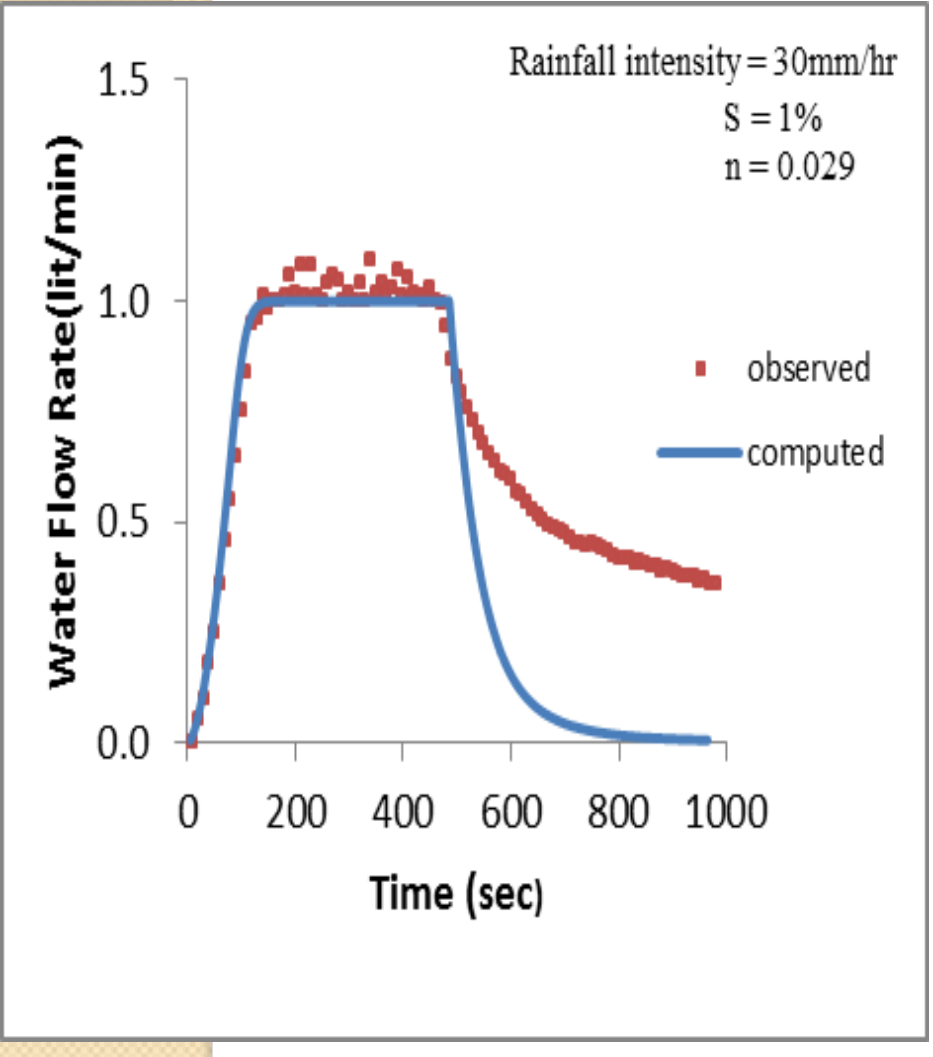
S.No	Slope (%)	Volume			Time to Peak			NSE (%)
		Observed (lit)	Computed (lit)	Error (%)	Observed (min)	Computed (min)	Error (%)	
1	1	9.3	7.9	4.3	2.7	2.4	11.1	98
2	2	6.3	5.9	6.3	2.3	2.1	8.6	97.2
3	3	8.3	7.9	4.8	2.1	2.0	4.7	91
4	4	7.6	7.3	3.9	2.0	1.8	5	93.2

Table 2 Pertinent characteristics of observed and computed hydrograph for 60 mm/hr intensity of rainfall

S.No	Slope (%)	Volume			Time to Peak			NSE (%)
		Observed (lit)	Computed (lit)	Error (%)	Observed (min)	Computed (min)	Error (%)	
1	1	12.5	12.2	2.4	3.9	3.5	10.2	97.8
2	2	10.4	10.1	2.8	3.2	2.9	9.3	96.6
3	3	16.2	15.8	2.4	2.8	2.6	7.1	97.0
4	4	12.5	12.1	3.2	2.5	2.4	4	92.6

Table 3 Pertinent characteristics of observed and computed hydrograph for 90 mm/hr intensity of rainfall

S.No	Slope (%)	Volume			Time to Peak			NSE (%)
		Observed (lit)	Computed (lit)	Error (%)	Observed (min)	Computed (min)	Error (%)	
1	1	16.1	15.7	2.4	3.6	3.3	8.3	96
2	2	18.3	17.9	2.1	3.1	2.9	6.4	97
3	3	15.4	14.9	3.2	3.2	3	6.2	96.1
4	4	15.1	14.7	2.6	2.6	2.5	3.8	96.7



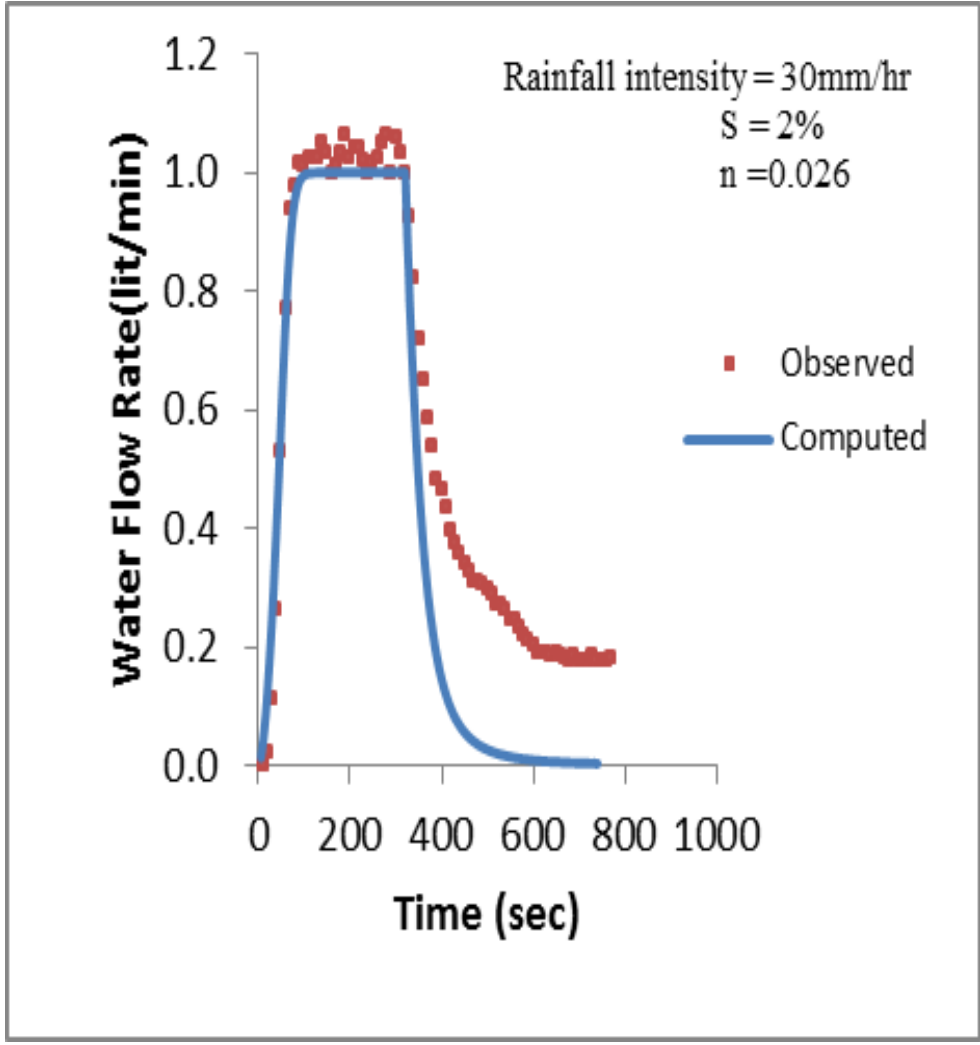
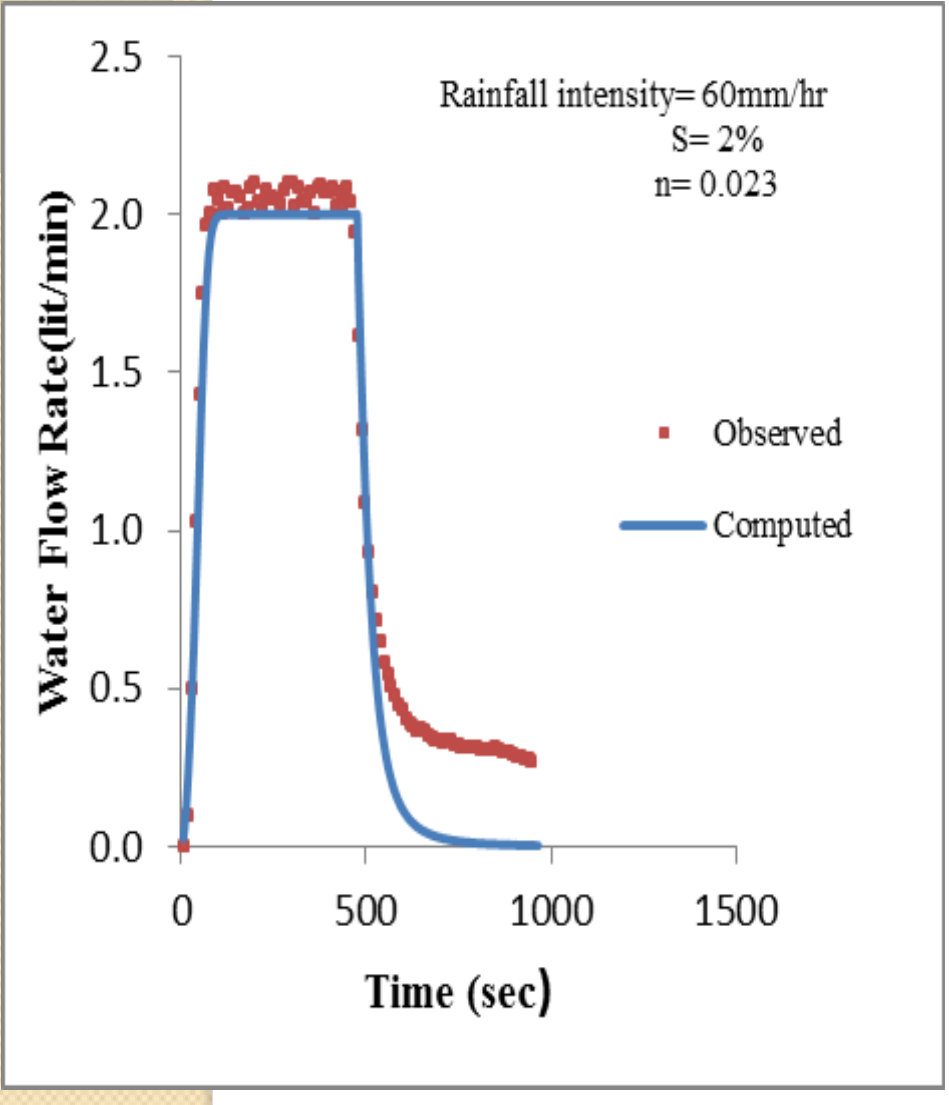


Fig. 2 Comparison of observed and computed hydrograph for rain fall intensity 30 mm/hr at 1 % slope.

Fig. 3 Comparison of observed and computed hydrograph for rain fall intensity 30 mm/hr at 2 % slope.



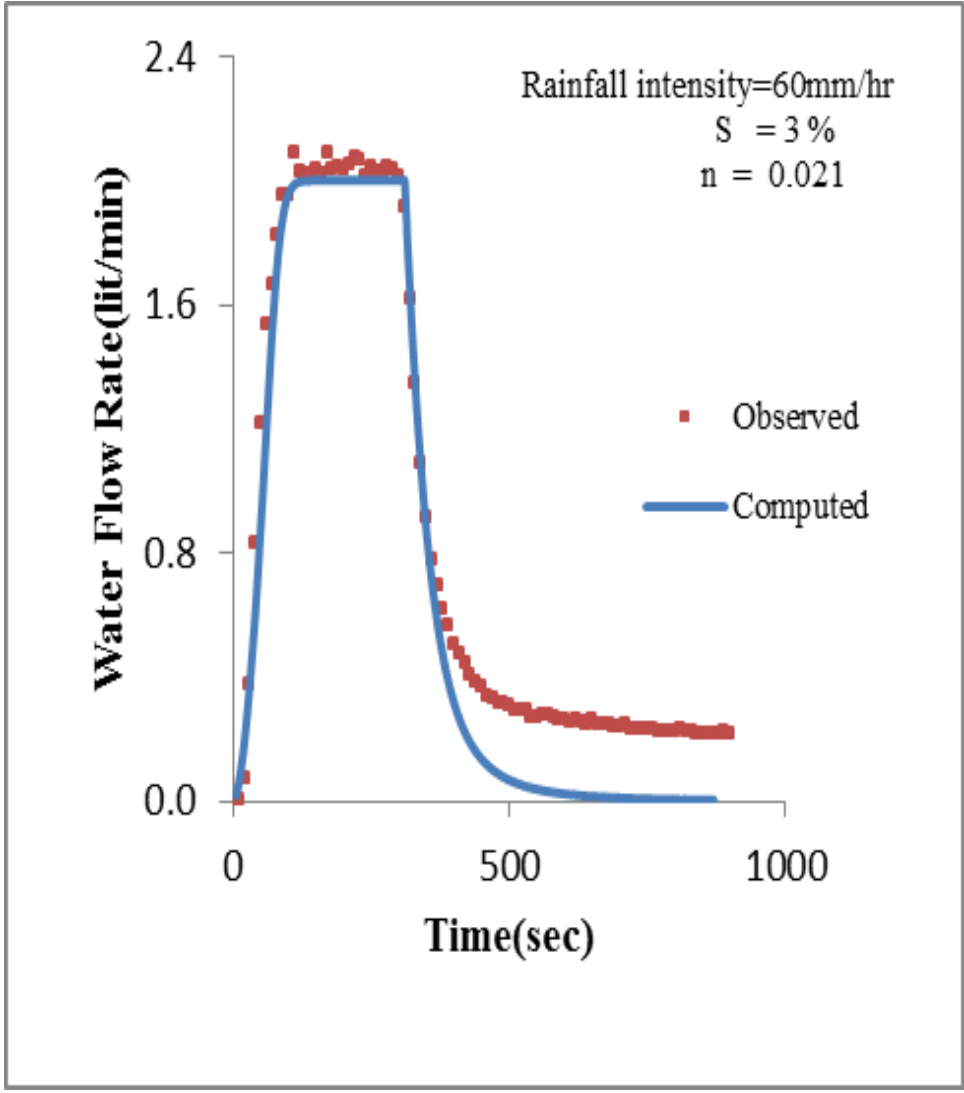


Fig 4 Comparison of observed and computed hydrograph for rainfall intensity 60mm/hr at 2% slope of the plane.

Fig 5 Comparison of observed and computed hydrograph for rainfall intensity 60mm/hr at 3% slope of the plane.

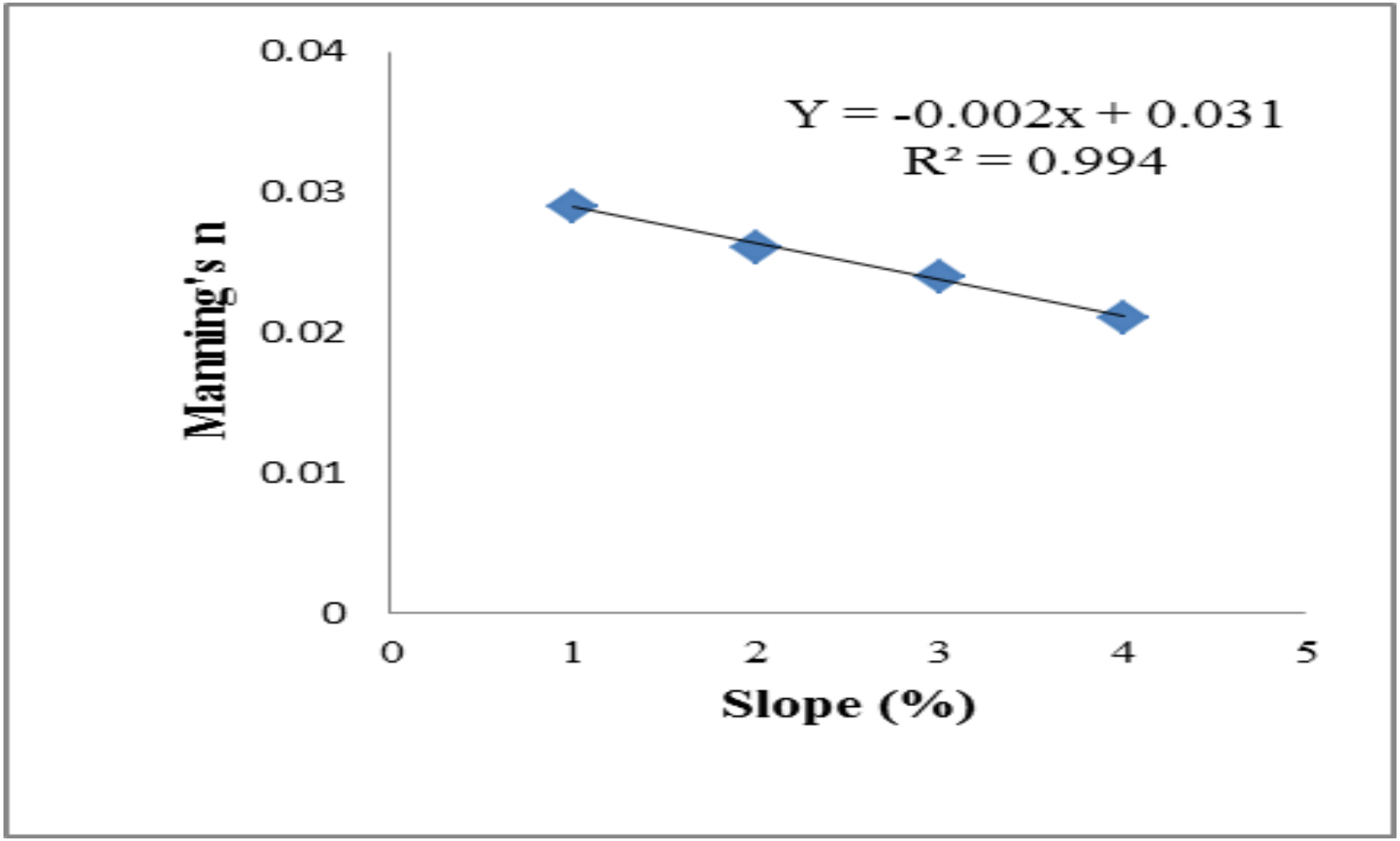


Fig 6 Variation of Manning's roughness with overland flow plane slope for rainfall intensity 30 mm/hr.

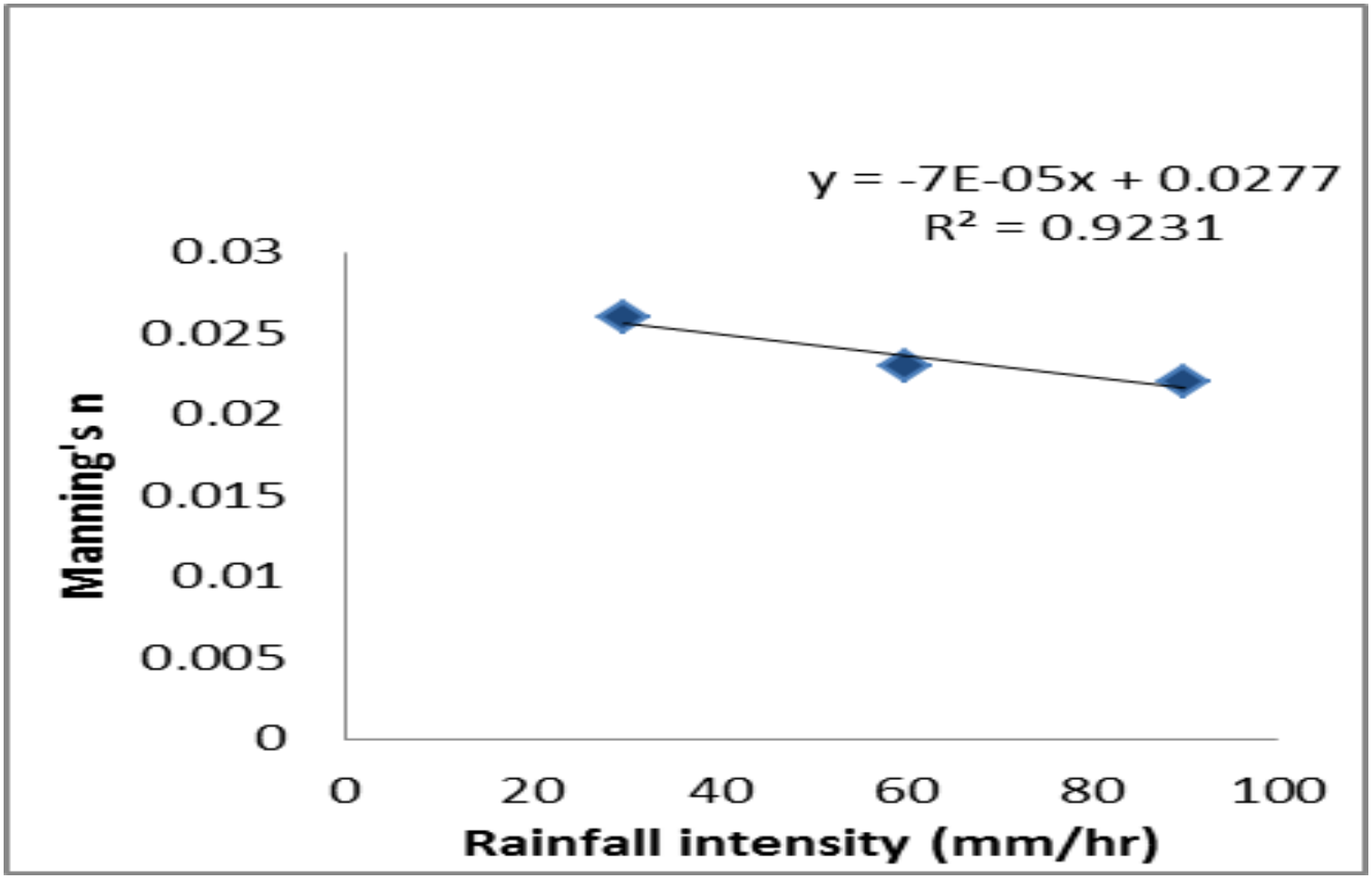


Fig. **7** Variation of Manning's roughness with rainfall intensity for 1% slope of the plane.

Discussion of results

- The plote between observed and model computated hydrograph are shown in **Fig. 2 to 5** for slope of 1%, 2%, and 3% respectively

- It can be seen that, after the start of the rainfall on the catchment, the water flow rate at the outlet increases raipdly with time, this portion of hydrograph is known as the rising limb.

- However at a certain time the water flow rate at the outlet equals the rainfall intensity, this time is known as time to peak.

- When the rainfall intensity is stopped the water flow rate at the catchment outlet start reducing at a very slow rate, this is known as the falling limb of the hydrograph.

- The KWM could reproduce resonably well rising limb of the observed hydrograph as well as steady state discharge. In case of falling limb of the hydrograph, two segments are clearly visible.

- Where only surface runoff dominates which is reproduced well by KWM.

- The release of water from sand bed, which the KWM has not simulated because the mechanism of release of water from sand bed was not incorporated in the KWM.

- Form **Fig 6** the value of n decreases linearly with increase in overland flow plane slope. This may be due to rapid draining of the water due to increased surface slope.

Conclusion

- The overland runoff hydrographs presented in this study was conducted in the laboratory with equipment consisting of a rainfall simulator (nozzle spray), an impermeable overland flow plane.

- The results indicate that there is less difference in the amount of runoff volumes, peaks at different rainfall intensities and slope of the catchments. But considerable difference in falling limb of hydrograph shapes.

- Laboratory and field experiments will test relationships for a wider range of conditions that will include the use of other rainfall intensity, different slopes and infiltrating surfaces.

- Future work should also include the comparison of the experimental results with numerical results i.e. kinematic wave theory.

Thank You