



Hillslope Runoff Processes and Modeling

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Abstract: Water constitutes one of our most valuable natural resources. Forecasting runoff volume has always been an integral part of hydrology, and on the way of improvement in recent years, various estimation techniques have been developed. These concepts need to be further developed, refined and formalized through various combinations of rigorously designed field experiments and physically-based realistic mathematical models.

The present study is aimed at modeling hillslope flows which includes (i) infiltration excess overland flow, (ii) saturated excess overland flow and (iii) return flow through subsurface involving macropores. The physical processes along with runoff generation processes have been identified in which the factors considered were (i) characteristic slope, (ii) nature of flow in subsurface zone, (iii) connection between exposed surface of hilly area and micropore-macropore domain, and (iv) initial soil conditions at the commencement of rainfall. Both Horton and Dunne's variable source area runoff generation mechanisms are explicitly incorporated in the model. The physical processes governing hillslope runoff generation have been conceptualized in terms of parameters which are derived from the physical characteristics of the soil, the nature of macro-pores, and hillslope geometry. Thus the mechanisms involved in runoff formation process have been simulated to successfully compute hydrograph for a hilly catchment area.

Keywords: Hydrology, Runoff, Hillslope, Subsurface flow, Variable source area, Infiltration, Macropores, Micropores, Horton mechanism, Dunne mechanism

1. Introduction:

Hydrology is the study of the various components of hydrologic cycle. To understand these components many approaches and theories are defined. Modeling helps in studying the behavior of a catchment. Generally, a catchment model is a set of mathematical abstractions describing relevant parts of the hydrologic cycle, with the main objective of simulating the conversion of precipitation into a number of components, of which, runoff is the most important and its observed value is used to calibrate these models. The mathematical models provide a cost and time effective method of studying hydrological processes. Surface runoff consists of the water that drains off from a catchment, over which precipitation has occurred, in forms such as rain or snow, through a surface channel. It is a function of many variables including rainfall intensity and duration, soil type, soil moisture, land use, cover, and slope. In view of the numerous variables and uncertainties governing surface runoff, lumped-conceptual models are a useful approach of analysis. During the last part of 19th century many engineers used empirical formulae, derived from observed data and in the 20th century computer based algorithms have been developed, of which one is SWAT (1998).

SWAT has two methods to estimate the infiltration of precipitated water and runoff generation: SCS Curve Number method (USDA Soil Conservation Service, 1972) and Green-Ampt model (Green and Ampt, 1911). These methods are simple, conceptual and stable methods for estimation of direct runoff and produces satisfactory to good results for plain or gentle slope region. These methods are based on general mass balance equation and Darcy's law respectively. However, Darcy's law is based on the assumption of laminar flow, therefore, more rigorous mass balance equation should be used for the hillslope region. In hilly areas, the slopes are responsible for generating 95% of the water in the stream (Shakya, 1998). Modeling runoff for hillslope area includes modeling of infiltration, down slope flow and subsurface flow. Earlier explained method did not deal with these phenomena under steep slope condition, they did not give the return flow basis. Earlier models generally depended on Horton's infiltration excess mechanism (1933). However, they failed in a wide variety of forested hillslope areas. In order to explain the formation of runoff from hillslope Dunne (1983) developed a conceptual model for streamflow generated in watershed.

Routine methods of predicting storm hydrographs do not require accurate conceptual models of storm runoff processes. Application of hydrology to the analysis of

landform evolution and other scientific and land management problems requires realistic concepts of runoff generation and their variation within drainage basins. These concepts need to be refined, developed and formalized through more vigorous combination of rigorously designed field experiments and realistic physically-based mathematical model.

Hillslope hydrology is an essential and active growth area which has benefited hugely from the interaction between field works and modeling. In its short history, theory has continually been overturned by field observations and more effort to probe this area is still required. In the present study an effort has been made to model hillslope flows with emphasis on subsurface storm flows that involve macropores.

2. Literature review:

Hillslope hydrology is concerned with the transformation of precipitation as it passes through the vegetation and soil layers. During this transformation water is added to the atmosphere through transpiration and evaporation. Some amount of this water percolates through soil zone to contribute to ground water.

Catchments may be assumed as an interconnected network of moisture stores. Thus, for example, flow from a point on the watershed to the stream outlet may pass through stores for surface detention, infiltration, unsaturated vertical percolation, saturated downslope flow and channel flow. When rain and melt water reach the surface of the ground, they encounter a filter that is of great importance in determining the path by which hillslope runoff will reach the stream channel.

Path.1: If the rate of rainfall or melting is greater than the infiltration capacity on unsaturated ground or the water table rises up to surface, the excess water becomes overland flow.

Path.2: Groundwater flow- if the soil and rock is deep and of uniform permeability, the subsurface water moves vertically to the zone of saturation and then follows a curving path to the nearest stream channel.

Path.3: Sub-surface flow- if at some shallow depth in the soil and rock, percolating water encounters an impeding horizon, a portion of water will be diverted parallel to hillslope and reach the stream channel by a much shorter route.

Path.4: Return flow is that part of subsurface flow which returns to the ground surface and leaves the hillside as overland flow because of saturation at the down slope.

At any point on a hillslope surface, or within the soil, water is moving under potential gradients and water pressure and tension. Flow through fine pores in the soil matrix is resisted mainly by the viscous stresses. Where pore sizes are randomly interconnected, the aggregate flow may be described satisfactorily by Darcy's law, as the flow can be assumed laminar having Reynolds

number less than 10. For flow through large sized pores/voids and overland, the critical Reynolds number for the onset of turbulence may be exceeded, so that initial resistances predominate, and it may also be necessary to take flow bypassing into account.

The studies led to the following conclusions:

- Presence of preferential paths, termed as macropores resulting in dominance of subsurface flow on hillslope (Whipkey, 1965, 1967; Mosley, 1979)
- Beneath the ground level these macropores are interconnected and form spatial networks. (Beven & Germann, 1982)
- These networks are the medium for water feed by microspores of soil and surface flow. (Beven & Germann, 1982)
- The macropores conduct appreciable volume of water to the saturated zone. (Beven & Germann, 1982)

At any point on a hillslope surface or in soil matrix, water flows under potential gradient, water suction and gravitational force, in form of subsurface flow or percolation. In micropores of the soil matrix flow is governed mainly by viscous stress. Beneath the ground pores are randomly interconnected and heterogeneously distributed. The resultant flow from the micropores may be described by Darcy's law, as the flow can be assumed laminar having Reynolds number less than 1. Reynolds number less than 10 can be categorized under laminar flow. For flow from macropores, Reynolds number exceeds to turbulent flow and can't be estimated by Darcy law. In hillslope subsurface flow covers the major part of runoff volume and timing of the storm hydrograph. Under such conditions water movement occurs in two domain, micropores and interconnected macropores of the soil matrix. The presence of macropores close to the soil surface of the soil may be particularly important in the process of infiltration of rainfall and solutes into the soil. This suggests the introduction of a domain concept to model combined macropores-micropores system.

The present model specifies the nature of flows in micropore and macropore domain. Infiltration excess mechanism and saturated excess surface flow is incorporated explicitly according to field conditions. Subsurface flow is estimated depended on infiltration volume and two- domain concept.

3. The model:

The hillslope per unit width under consideration in the model is represented by a rectangular storage element of length 'L' and depth 'D' with impermeable bed making angle ' α ' with the horizontal. The unsaturated zone of volume is made up of two domains represented by moisture store namely micropore store and macropore store, but here it is assumed to be made

of micropore store only, later macropore store will be added. The size of micropore store is determined by microporosity. Let initially 'L1' portion of lower part of hillslope is saturated because of water table and after precipitation water table rises and saturated length over hillslope increases to 'Ls1' in certain time step. Hill slope model is divided into three part as discussed earlier. This model is based on the physical processes on hillslope, when top most layer deals with precipitation and percolated water returns at surface as return flow. Total runoff will be estimated by adding saturation excess overland flow, infiltration excess overland flow and return flow.

The hillslope model ran for calibration and validation of the study area has assumed a homogeneous soil system which contains single type soil, constant average hillslope angle and uniform depth throughout the hillslope length.

3.1. Flow situations:

Three stages may be expected from the presence of macropore on the surface. Let

$P(t)$ = overall input (precipitation)

$O(t)$ = overland flow

$S1(t)$ = seepage into the macropores at the soil surface

$S2(t)$ = flow within the macropore

$I1(t)$ = infiltration into the matrix from the surface

$I2(t)$ = lateral flow into the matrix from the walls of the macropores

3.1.1. Case 1:

$$P(t) < I1(t)$$

$I1(t)$ water arriving at the surface is absorbed by micropores connected to the surface. Direct infiltration into the macropores can be neglected during the first stage, since they contribute very little to total surface area

3.1.2. Case 2:

$$I1(t) < p(t) < I1(t) + S1(t)$$

During this period, surface runoff on small scale may take place. Both macropores and micropores open to the soil surface take up water simultaneously.

As soon as there is a significant flow into the macropores, flow down the walls will also start [$S2(t) > 0$] and lateral infiltration into the matrix will be initiated [$I2(t) > 0$].

3.1.3. Case 3:

$$P(t) > I1(t) + S1(t)$$

Significant amounts of water will begin to be stored at the soil surface, and overland flow will start on a large scale [$O(t) > 0$].

3.2. Unsaturated zone

On initiation of rainfall event of precipitation at the surface, hillslope is divided into two zones.

3.2.1. Unsaturated zone

This part of hillslope governs the overland flow generated by rainfall when it's intensity greater than infiltration rate of soil strata.

Mathematically:

$$\text{Precipitation rate} > \text{infiltration rate}$$

During this period both the micropore and macropore stores in the unsaturated zone are unable to absorb the total input from the surface (Horton mechanism). In such case overland flow occurs because of ponding due to difference of input and quantity of water which can be absorbed by the hillslope. Macropore in this case remain fully saturated.

$$Q_{in\text{over}} = (Q_{in} - f)$$

Where

Q_{in} = precipitation rate (mm/day)

$Q_{in\text{over}}$ = outflow generated from unsaturated area of hillslope on basis of horton mechanism (mm³/day)

f = capacity of infiltration rate at that time step. (mm/day)

Using Horton cumulative infiltration equation, total infiltration volume can be estimated upto time t . difference between area under cumulative infiltration curve upto time t and $t-1$ will give the infiltrated volume in this time interval. For steep slope hydraulic conductivity also depends on hillslope. On the basis of Richard equation, effect of hillslope on the hydraulic conductivity is analyzed by Philip (1991). The analysis of infiltration between horizontal plane and sloping surface assumes the same horizontal projection length rather than the same slope length. In unsaturated zone hydraulic conductivity depends on soil suction and moisture content. Verma and Brutsaert (1970) define the hydraulic conductivity at the beginning of time step by the Brooks and Corey (1964) function given by equation.

$$k = k_{sat} \left(\frac{\theta - \theta_r}{\eta - \theta_r} \right)^{1/n} \cdot \cos \alpha$$

Where θ and θ_r are the moisture content at present time step and residual moisture content respectively. k_{sat} is saturated hydraulic conductivity.

3.2.2. Circumference length of macropore

Let L_{min} and L_{max} be the circumference length of a single macropore with radius R_{min} and R_{max} respectively. Since it is not practical to measure each size of macropore radius, let assume that macropore domain have only minimum sized and maximum sized macropore. Therefore

$$L_o = \frac{\max\{L\} + \min\{L\}}{2}$$

After simplification,

$$L_o = \left(\frac{1}{R_{min}} + \frac{1}{R_{max}} \right) \cdot A_m$$

Where A_m is macropore area (Shakya, 1995).

Since, any total flow capacity from the same given area will be higher than flow capacity of minimum size macropore only and lower than flow capacity of maximum size macropore only. This can be given as,

$$\{Q_{min}\} = \mu \cdot Q_{min}$$

$$\{Q_{max}\} = \gamma \cdot Q_{max}$$

Where Q_{min} and Q_{max} are the flow capacity of single minimum and maximum size macropore respectively and estimated as given below.

$$Q_{min} = \frac{\pi g R_{min}^4}{8v}$$

$$Q_{max} = \frac{1}{n} \left(\frac{R_{max}}{2} \right)^{2/3} \pi R_{max}^2$$

Where,

n =manning coefficient

v = viscosity of water

3.2.3. Flow from micropore domain

Using a one dimensional flow equation combined with Darcy's equation, Shakya (1995) computed the rate of horizontal movement. As,

$$i = S_r / 2t^{-1/2}$$

where S_r is the sorptivity, which was computed using Young's estimation formulae (1981).

$$S_r = 6.3(\Theta - \Theta_r)^{0.5} K_{sat}^{0.25}$$

Knowing these parameters, the lateral flow (Q_{micl}) from macropores to micropores is given by

$$Q_{micl} = i \cdot L_o \cdot \text{depth} \cdot \Delta t$$

Total Hortonian overland flow will be,

$$Q_{in\over} = (Q_{in} - f) \cdot (L - L_s)$$

$$L = \frac{1}{2D_d}$$

where, D_d = drainage density

L_s =saturated length of hillslope

Drainage density can be define as the ratio of total drainage length to the total catchment area. It gives average width of catchment area. Half of average width defines the total length of overland flow or total hillslope length.

3.3. Saturated zone

The component of input Q_{in} (precipitation over unsaturated zone) which is diverted to saturated portion

of the hillslope get added to surface store and flows either as runoff as overland flow (Saturated excess mechanism). The saturated zone gets created due to the rise of water table starting from the lower end of the hillslope.

Let the initial saturated length of hillslope is L_1 . Water contributes in water table rise will be lateral flow diverted to lower zone, and total saturated zone will be,

$$L_s = L_1 + Q_{micl} \cdot \frac{t}{A_u \cdot \sin \alpha}$$

Where, L_s , saturated length at the end of time t A_u is unsaturated hillslope area diverting flow towards saturated zone, α is hillslope angle

Precipitation over exposed rock surfaces will direct to contribute runoff. This follows Hortonian overland flow mechanism, But estimation of this runoff is similar to estimation of runoff from saturated area.

Total overland flow from saturated area

$$Q_{sat\over} = (L_s + L_{rock}) \cdot Q_{in}$$

$Q_{sat\over}$ is overland flow (saturation excess mechanism), L_s is saturated hillslope length, L_{rock} is exposed impermeable rock area per unit width, and Q_{in} is input (precipitation).

3.4. Return flow

This module incorporates a kinematic storage model for subsurface flow developed by Sloan (1983). It simulates return flow in a two-dimensional cross-section along a flow path down a steep hillslope. SWAT also uses the same Kinematic approximation. Approximation assumes that the lines of flow in the saturated zone are parallel to the impermeable boundary and the hydraulic gradient equals the slope of bed.

The net return flow at the hillslope outlet Q_{return} , can be estimated,

$$Q_{return} = H_o \cdot V_{lat} \cdot (L - L_s)$$

where Q_{return} is the return flow (mm^2/day), H_o is the saturated thickness normal to the hillslope at the outlet expressed as a fraction of the total thickness (mm/mm), $(L - L_s)$ is the unsaturated length of hill, V_{lat} is the velocity of flow at the outlet (mm/day) and it can be defined mathematically as-

$$V_{lat} = k_{sat} \cdot \sin(\alpha)$$

Where, α is the hillslope angle

3.5. Total outflow

The total outflow from the hillslope can be expressed as the sum of the overland flow produced by unsaturated zone, saturated excess flow generated from saturated zone and return flow from the outlet of hillslope.

$$Q_{total} = (Q_{in\over} + Q_{return} + Q_{sat\over}) \cdot L_b$$

where L_b = drainage length of basin (mm).
 Since main stream divide watershed area into two hillslope area or area, and here Length of hillslope is taken as half of the average width of basin.
 Therefore total contribution of runoff will be estimated by multiply of two in total runoff volume.

$$Q_{total} = 2 \cdot (Q_{infover} + Q_{return} + Q_{satover}) \cdot L_b$$

where Q_{total} is total outflow contribution in main stream (mm^3/day), $Q_{infover}$ is outflow generated from unsaturated area of hillslope on basis of horton mechanism (mm^3/day), Q_{return} is outflow from the outlet of the hillslope at bottom near stream (subsurface flow) (mm^3/day) and $Q_{satover}$ is outflow generated by saturated length of hillslope (in mm^3/day)

4. Model application

The model was applied to observed data set are taken from gauge station Yashwant Nagar (Himachal Pradesh). The Yamuna River originates in Yamunotri Glacier ($31^\circ 1' 20''$ N, $78^\circ 24' 37''$ E) at an elevation of

6,387 m above M.S.L in Uttarkashi District of Uttarakhand. Length of the river is 1,376 km and the total basin area is 3,66,220 km^2 . Presented location shows one of the tributaries of Yamuna called, Giri tributary. Its catchment area is 1317 km^2 . And length of tributary is 69.87 km.

Hillslope model is yet to be added in the SWAT program as a module, therefore, in this paper the current model has been run in FORTRAN language program and the result corresponding to the selected study area has been compared with output of existing SWAT module.

5. Results and discussion

The result of the simulation run for study area Yamuna basin is compared with hillslope model, observed cumulative discharge on a slope and observed hydrograph on hillslope. Input data for the model is taken from table 1. Simulation results of hillslope model and SWAT are compared to observed data.

Table 1: Characteristic parameter of different soil

Soil type	Micropore sat. hydraulic conductivity (cm/min)	Micro porosity	Macro porosity	Total hydraulic conductivity (cm/min)	Max macro size (cm)	Min macro size (cm)
A	0.00123	0.495	0.003	0.0223	0.5	0.005
B	0.0123	0.495	0.003	0.0334	0.5	0.005
C	0.0123	0.495	0.003	0.00169	0.05	0.005
D	0.0123	0.495	0.003	0.0128	0.05	0.005

(Beven & Germann, 1981)

5.1. Comparison of hydrograph on hillslope

The present model is used to compute the runoff hydrograph for one month rainfall using the data of Yashwant Nagar station GIRI tributary, Yamuna River.

Evaporation loss is neglected during the event. Model is calibrated with September, 1988 data (fig.1) and validated with August, 1988 data (fig.2).

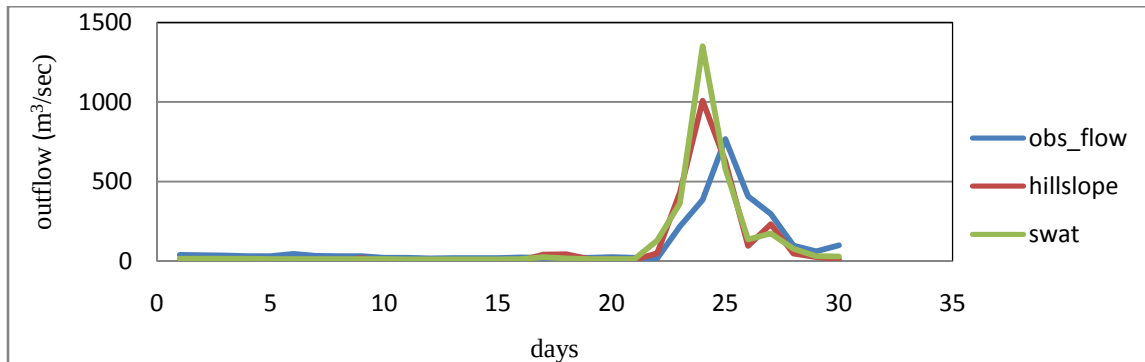


Fig.1: Comparison of runoff hydrograph (Calibration)

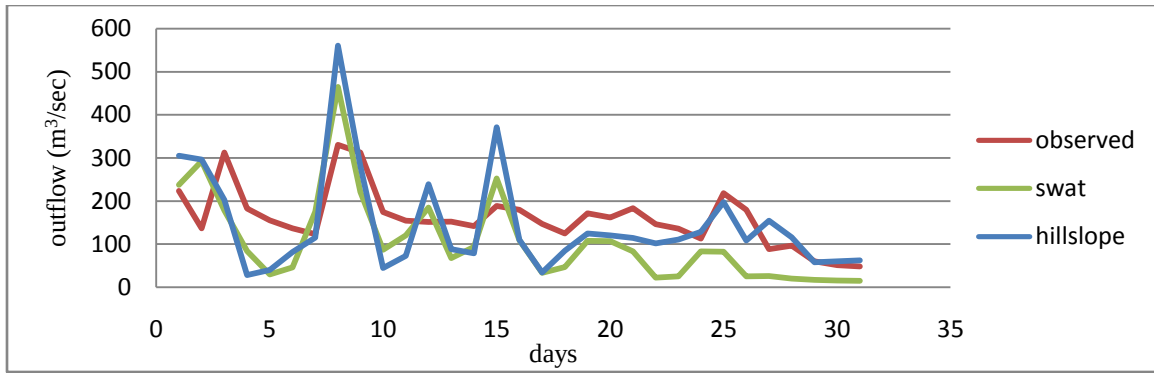


Fig.2: Comparison of runoff hydrograph (validation)

The model was run with macroporosity 0.003 and microporosity 0.485. The hydrograph obtained using the above macroporosity parameter are compared with observed hydrograph and SWAT simulated hydrograph (fig.1) The timings of hydrograph in terms of occurrence of the peaks are well reproduced.

The hydrograph of outflow obtained by hillslope while properly accounting for the sequence of arrival of flows, do not provide for the storage properties of the

catchment. To overcome the deficiency, a linear reservoir is hypothetically availed at the outlet to provide the requisite attenuation. Hillslope simulated output passed through a linear reservoir as inflow and achieved outflow is compared with observed outflow hydrograph. For time interval 24 hours and storage-time constant 35.26 (approx 36 hours) outflow is estimated. This attenuated result shows better agreement with observed flow at outlet of catchment area (fig.3).

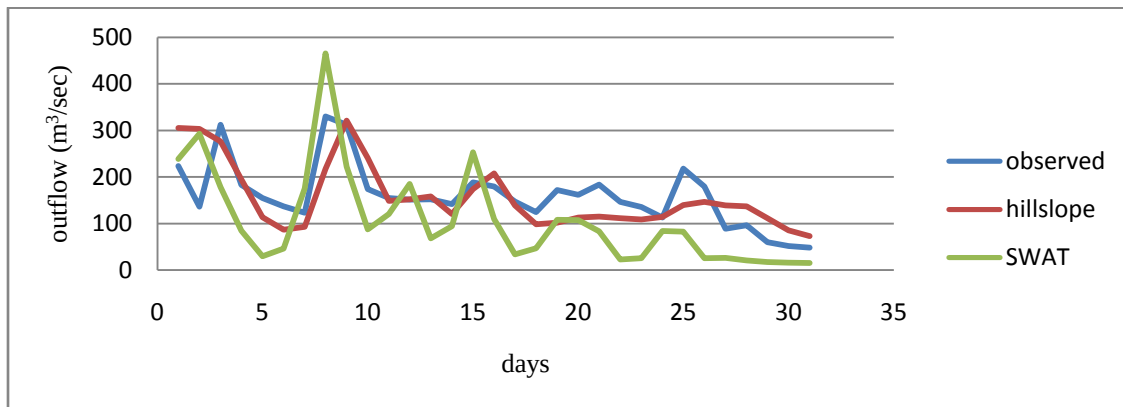


Fig.3: Linear reservoir outflow vs. observed outflow and SWAT

Model evaluations show coefficient correlation and R^2 value are better in Hillslope model as compare to SWAT model output. PBIAS value is near to 0 in hillslope model but SWAT output is more biased as

value is 0.325. NSE check in SWAT model output computed negative value, which is not acceptable. Hillslope model computed NSE value 0.34 which is viewed as acceptable (table 2).

Table 2: Comparison between hillslope model output with SWAT output.

Check	Hillslope model Vs. Observed data	SWAT Vs Observed data
R^2	0.4814	0.45
Coefficient of correlation	0.698	0.67
PBIAS	0.026	0.325
NSE	0.34	-0.86

5.2. Comparison of cumulative discharge

The model is also used to simulate subsurface flow occurring within and through the soil matrix in hillslope. The cumulated discharge was computed using

the Hillslope model and compared with the cumulated discharge using SWAT with respect to observed cumulative discharge. The results obtained by the

hillslope model are in good agreement with observed cumulative discharge (Fig.4).

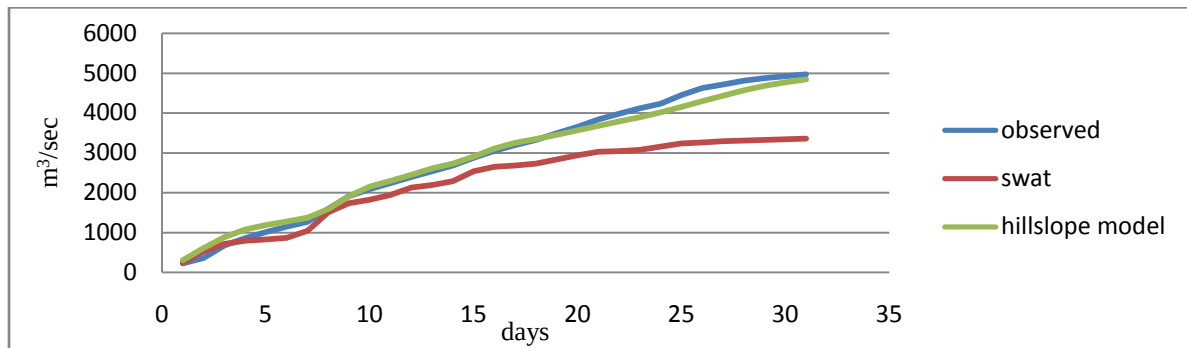


Fig.4: Cumulative outflow comparison

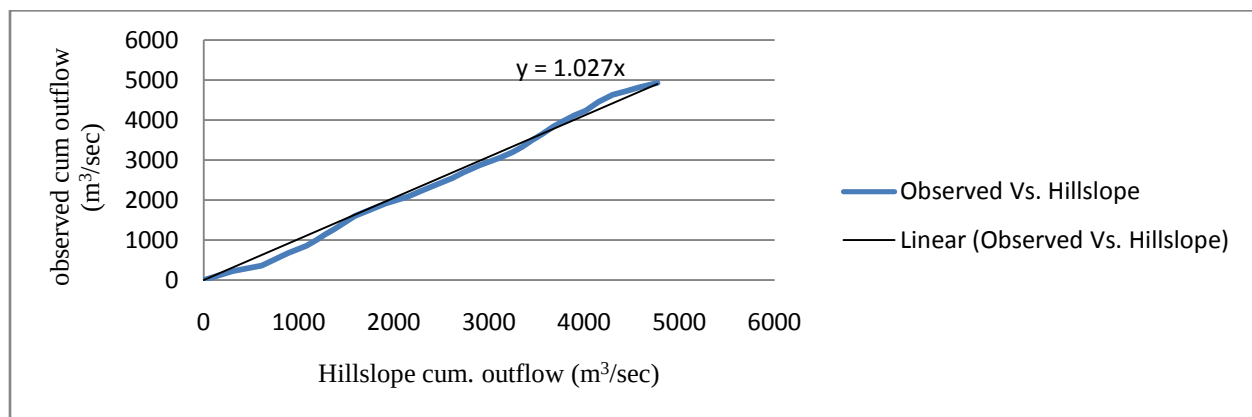


Fig.5: Observed cumulative flow vs. hillslope cumulative flow

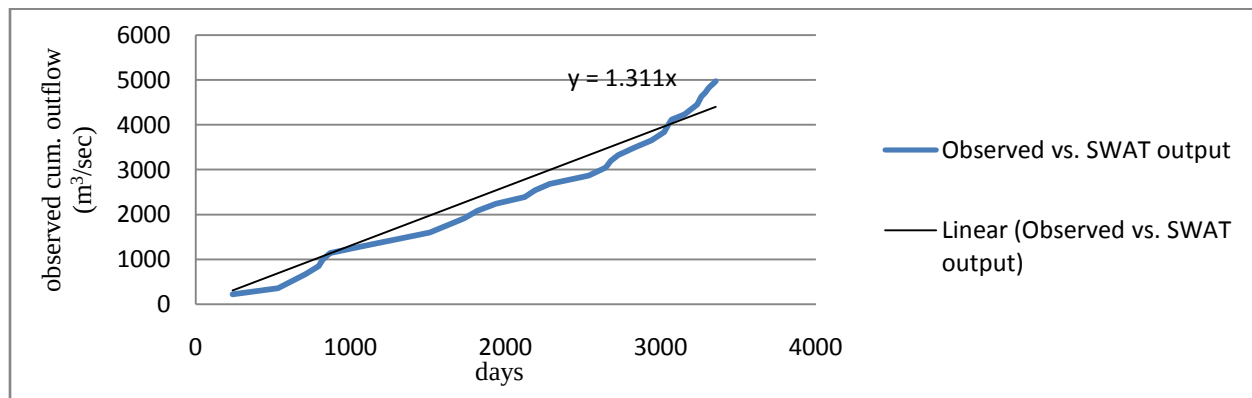


Fig.6 observed cumulative flow vs. SWAT model output

To compare the incremental discharge of SWAT simulated output and hillslope simulated output with respect to observed flow, a comparison graph is plotted between hillslope outflow and observed outflow (Fig.5) and compare it with graph between observed outflow and SWAT outflow (Fig.6). According to results shown here, hillslope model is in good consent with observed outflow, as the trend line is closer to 'Y=X' line than SWAT simulated outflow. The various model

parameters are determined by observed rainfall-runoff data. It lacks the ability to estimate model parameter from the physical properties of the soil and the geometry of the slope. In this study parameters are estimated by physical properties of soil. Assumptions of homogeneous soil type and constant slope are made but this module has to be added in SWAT. After addition module can be performed for all HRU's in different

segment consisting different characteristics and results can be improved.

6. Conclusion:

The study has identified the physical processes connected with the runoff process on a hillslope based on field observation. Hillslope model is based on two domain concept, which has been recognized as an appropriate method in modeling such hillslope soil system.

The hillslope model ran for calibration and validation for the study area has assumed a homogeneous soil system which contains single type soil, constant average hillslope angle and uniform depth throughout the hillslope length.

The results of the model have been compared with the observed hydrograph and SWAT simulated hydrograph. It is concluded that the hillslope model performs reasonably well as mentioned in results in compare with SWAT simulated output. Comparison suggests the suitability of model in simulating the runoff processes on hillslope, involving preferential flow. Both Horton and Dunn's variable source area generation mechanism are explicitly incorporated in the model.

The following conclusion can be drawn from this study-

1. The model reasonably predicts water movement in unsaturated soil with and without macropore.
2. Maximum macropore size, minimum macropore size and macroporosity define the capacity of infiltrated and percolated water that can be retained in soil matrix.
3. The results shows coefficient of correlation, coefficient of determination and percent bias (PBIAS) values are better for hillslope model than SWAT model.
4. Hillslope model and SWAT model, both are estimating higher peak than observed data due to the occurrence of rapid peak of observed hydrograph. But results are satisfactory for gradual peak of hydrograph.
5. The hydrograph of outflow obtained by hillslope while properly accounting for the sequence of arrival of flows, do not provide for the storage properties of the catchment. To overcome the deficiency, a linear reservoir to be hypothetically available at the outlet to provide the requisite attenuation.

Finally, the results of hillslope model simulation suggests that porous soils have to be categorized in terms of macroporosity along with other soil water characteristics so that the saturated hydraulic conductivity of matrix can be estimated with the help of observed saturated hydraulic conductivities of existing soils. These parameters enable to hillslope model flow mechanism of such soils for which classical single domain approach is inappropriate.

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