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OVERLAND FLOW IN MOUNTAINOUS AREAS

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ABSTRACT

Runoff in mountainous regions results from rainfall, snowmelt and glacier-melt. The different components of runoff are generally considered to be surface run off, sub-surface runoff and ground water runoff. Surface runoff consists of overland flow and channel flow. Overland flow is that part of surface runoff which flows directly over the land surface towards the stream channel.

Overland flow is known to occur as thin sheet flow, before surface irregularities cause a gathering of runoff into discrete stream channels. The primary distinguishing characteristics of overland flow is its shallow depth relative to roughness elements. The overland flow is an unsteady free surface flow and most dynamic part of response of watershed due to excess precipitation.

Overland flow is important from the point of view of the quantity of water transported, but more so from the point of view of its interaction with land surface and consequent contribution to the total surface runoff. It is also an important factor from the view of land-use practices as large scale erosion takes place because of the overland flow.

The overland flow from a mountainous watershed is recognised as a non-linear process. In general, there are two non-linear approaches which are used in analysing watershed response; system approach and hydrodynamic approach. System approach develops input-output relationships without making any explicit assumptions regarding the internal structure of the system. The approach requires the assumption that certain general laws of physics hold and further requires a geometrical abstraction of the real-world phenomenon. It is, therefore, the hydrodynamic approach which has been mostly used for overland flow modelling by several investigators.

The various steps in applying the models based on hydrodynamic approach are:(i) to decide upon the model geometry wherein the catchment may be represented by simple geometric elements such as combination of planes and channels or linearly converging and diverging sections. (ii) to decide upon the form of resistance law and infiltration equation, and (iii) to solve the hydrodynamic equations.

Non-linear behaviour of overland flow models poses the difficulty in solving the hydrodynamic equations. Therefore, two simplified approaches namely Horton-Izzard approach and kinematic wave approximation are used to solve the hydrodynamic equations.

The review indicated that the kinematic wave approximation to the hydraulics of overland flow is better for rough and steep slopes. Several investigators emphasised that the approximation is valid for almost all cases of overland flow.

Various investigators developed both analytical and numerical solutions to kinematic wave equation. Analytical solutions to the kinematic wave equations provide answers for a simplified class of problems while problem of a more general type are handled with numerical solutions through attendent discritisation of the solution domain. The assumption leading to the analytical solutions are restrictive and as such their practical utility is greatly diminished, when compared to numerical solutions of kinematic wave equations. The numerical solutions are also far from being elementary, as the stability and convergence criteria need to be respected. Furthermore, numerical schemes may result in 'kinematic shocks' which need to be modelled properly.

Future research needs to be oriented towards finding more accurate estimate of rainfall excess and soil-data, which is important in calculating infiltration rate in a watershed. The quantification of errors due to geometric simplification and the effect of different physiographic features on resulting overland flow hydrograph may help generalise the extent of geometric simplification of a watershed.

1.0 INTRODUCTION

The water resources of our country are generated from rainfall and melting of snow from high mountain peaks. Development of water resources projects play an important role in the agricultural based economy of our country. These projects require the estimation of peak magnitude of floods for different hydraulic structures which includes the estimation of design flood for spillways, flood control structures, cross-drainage works and bridges.

Estimation of flood in mountainous areas requires a thorough understanding of runoff process in these areas. The surface runoff in mountainous regions consists of three components, viz. overland flow as thin sheet of water, small stream flow, and river flow.

An important problem in mountainous regions is the siltation due to overland flow, the main cause of erosion and transportation of soil particles. In order to understand the problems and arrive at solutions for them, study of overland flow is necessary.

The overland flow is of hydrologic importance for several reasons: it moves quickly to stream channels, thereby causing the sharp flood peaks. It is only slightly subjected to evaporation because of its short time in transit, and sometimes a greater proportion of overland flow than of subsurface flow contributes to streamflow and by virtue of its velocity detaches soil particles from the land surface and is therefore an important agent in impairing water quality in streams by increased turbidity. The velocity of overland flow largely determines its flood and erosion potential. Water flows more rapidly down steep slopes over smooth surfaces and inconcentrated channels. Vegetation which increases surface roughness, debris from landslides and other obstructions slow down the velocity of overland flow and discourage concedntration in rills and gullies.

Some of the recent studies use the equation of motion and their solution (particularly with Kinematic flow approximation) for describing the hydrodynamics of overland flow. A review of overland flow modelling based on equations of motion and the analytical and numerical solutions adopted by various investigators is made in this report.

2.0 REVIEW

The rainfall-runoff process of a catchment is a very complicated phenomena, comprising of two stages:(a) the generation of an amount of excess water in surface, sub-surface and ground water zones, and (b) the way in which this excess water flowing as surface runoff, sub-surface runoff and ground water runoff appears as the total runoff at the catchment outlet.

The surface runoff is that part of the runoff which travels over the ground surface and through channels to reach the basin outlet. Thus, surface runoff consists of both overland flow and channel flow. The part of the surface runoff that flows over the land surface towards stream channel is called overland flow.

Runoff processes in mountainous areas differ from those in plain areas primarily because of the differences in meteorological and physiographic factors of the two areas.

2.1 Runoff Process in Mountainous Areas

The rain and snowmelt runoff processes in rugged mountainous catchments is a relatively complex phenomenon than in plain areas. The meteorological parameters like rain, snow, temperature and physiographic factors like soil, rocks and their composition in a watershed are highly variable at different elevation levels in the watershed.

In mountainous regions, precipitation occurs more frequently and sometimes with high intensities for longer duations. The surface is highly irregular which increase the resistance to surface runoff. Also, since these areas are characterised with steep slopes and with well defined boundaries, more often hydrographs with steep rising limbs are noted. These areas are most prone to flash floods, which occur due to heavy rainfall, snowmelt or a combination of the two. Steep gradients in hilly and foothill regions allow the overland flow to move more quickly downslope, thereby causing the flash flood peaks.

Because of some of the above characteristics of mountainous watersheds, flow in mountainous areas differs from those in plain areas significantly. Some other points of differences may be summarised as follows:

(i) Frequently heavy rainfall and low temperature gives soil a low moisture deficit resulting in larger streamflows;

(ii) Forests, vegetation and small surface depressions are more common in mountainous catchments, which intercept the rainfall;

(iii) Well defined streams with efficient cross-sections and hardly any flood plain resulting in higher magnitude of flood;

(iv) Due to thin soil mantle, most of the rainfall drains off with little and no ground water storage. This results in steep recession limbs.

2.1.1 Hillslope flow process

Various components of runoff viz.surface runoff, sub-surface runoff and ground water runoff may arrive at the stream by several routes. The path by water (Fig.1) determine many of the characteristics of the land slope, the use to which the land can be put and the strategies adopted for land management.

The excess rainfall which appears as overland flow follows path No.1 in Fig.1.

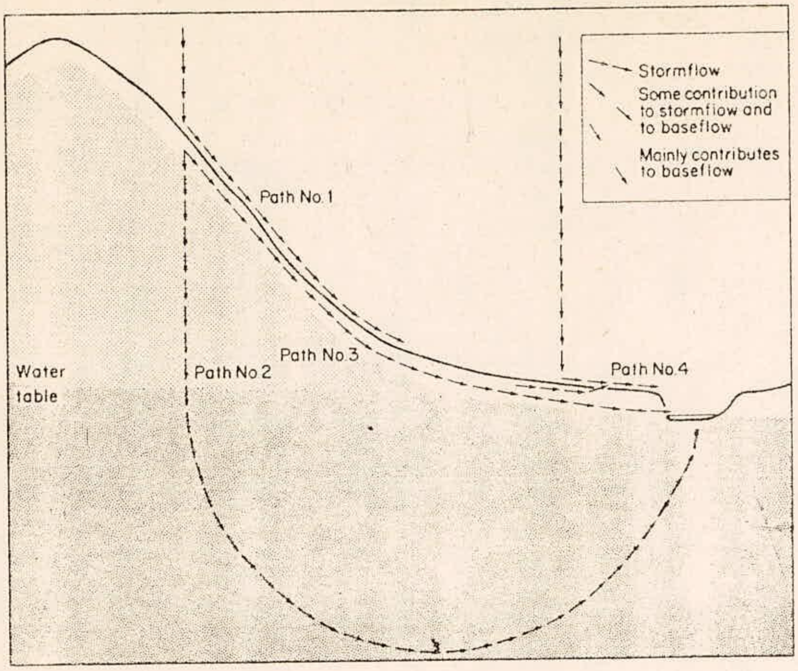

Fig.1: Possible flow paths of water moving downhill (reproduced from Dunne, 1978)

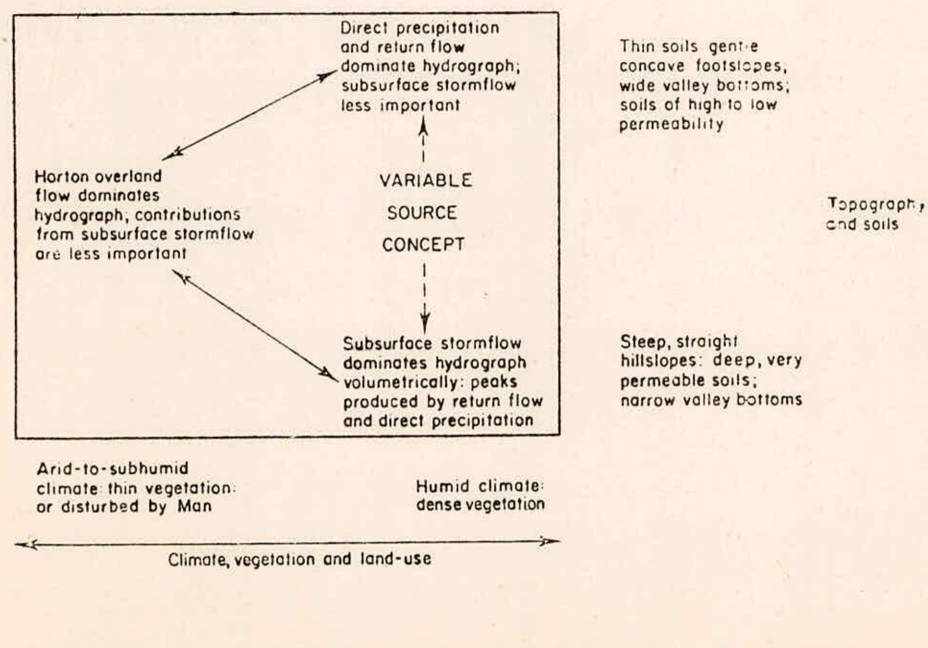

Fig.2: Schematic illustration of the occurance of various runoff process in relation to their major controls(reproduced from Dunne, 1978).

If the precipitation is arrested by soil (which is deep and of uniform permeability), the arrested subsurface water moves vertically to the zone of saturation and thence follows a curving path to the nearest stream channel (Path No 2 in Fig.1). This is referred to as 'ground water flow' and contributes to the baseflow of the stream. However, the infiltrated rainfall can reach the stream channel by shorter route(path No.3 in Fig.1) along the slope if the depth of the soil is shallow and the soil permeability decreases with increasing depth. The flow through this path is classified as 'sub-surface flow'. Depending upon the condition of saturation of the soil, the subsurface flow may be classified as saturated or unsaturated subsurface flow. The sub-surface water reaches the channel more quickly than the ground water. When entire depth becomes saturated due to percolation, some of the sub surface water emerges from the soil surface and reach the stream channel as overland flow. Such water is referred to as return flow (Musgrave and Holton, 1964). Rainfall onto the saturated area can not infiltrate, but runs over the surface. This contribution termed 'direct precipitation onto saturated areas' is difficult to be identified seperately from return flow. Storm runoff from these two sources as classified together as 'saturated overland flow' (Path NO.4 in Fig.1). Runoff from this source contributes to storm runoff hydrograph because of its ability to reach stream channels during the course of a rainstorm.

Each process has a different response to the rainfall and contribute differently to the volume peak rates and timing of the storm runoff. The process that determine the movement of stormflow, its volumes and timing of their contributions are controlled by climate, geology, physiography, soil characteristic, vegetation and land-use. Fig.2 adopted from Dunne (1978), summarizes the environmental controls on the various mechanisms of streamflow generation.

2.1.2 Runoff process in mountainous areas of India

India has about 30% of its land mass covered by mountains. The important mountain regions of the country are the HImalayas in the North, the Vindhyas of Central India and the Western and eastern ghats in Peninsular India.

2.1.2.1 Himalayan region

Himalayas are one of the worlds largest mountain systems, having 14 mountain peaks over 8000 m(asl) and hundredsover 7000(asl). It spreads over a length of 2500 kms in the east-west direction and a width varying from 200-400 kms. in the north-south direction.

The mean annual rainfall over Himalayan region varies from 50 to 250 cm with less of the rainfall occuring around the foothills of Himalayas. As one goes higher, the rainfall has tendency to increase. Towards east, the rainfall increases in Nepal and Darjeeling Himalayas. The south-west monsoon is the principal rainy season, contributing about 50% to 70% of the annual rainfall in the region. The western disturbances occuring in winter months(Nov.-Feb.) also bring copious amounts of precipitation over the region which is mostly in the form of snowfall and contributes to the snowmelt runoff during subsequent spring season.

The main source of Himalaya waters are snow, snow and rain at the snow-fields, monsoon rains, glacier melt and return flow from soil after the cessation of monsoon. The effectiveness of various sources of flow from Himalayas is briefly described as follows:

(a) Snow

A good percentage of Himalayan waters is derived from the snows and glaciers which constitute a potential reservoirs. Winter precipitation which occurs in the form of snow goes on accumulating till the cessation of winter. As the season advances, the accumulated snow melts and releases water into streams. Before the onset of monsoon, the contribution from these snow accmulations is significant from the point of view of irrigation and hydroelectric power.

(i) The northwest Himalayas

In northwest Himalayas, the period of snowmelt runoff is set at April-July with inclination, because of high altitude, to include August also. The study made by A.N.Khosala in his 'Rainfall and Runoff' in 1942 representing the Chenab river, shows a wide monthly discord between weighted rainfall and measured runoff. Only in the annual total do the precipitation and runoff agree and long experience indicates that the net runoff from intermittent rains may even be only one-fourth of the runoff from an equivalent snow cover. However, in north-west Himalayas, if delayed snowmelt from November through March and accelerated snowmelt from April through September are accepted as a basis of analysis, most of the discrepancy may not be noticed.

Considering the role of snowmelt runoff on the hydrology of Punjab rivers, it was found that snowmelt contributes a significant proportion of annual flow.

(ii) Southeast Himlayas-the Kosi basins

In the south-eastern Himalayas, the snowmelt beings on 1st March. The period of snowmelt may end by July, but the presence of snow at higher elevation may prolong the period. The relative importance of snow does not differ much throughout the Himalayas, though greater supplies of monsoon water occur in the south-east.

The effect of monsoon in JUne can be considered small, and the April-June runoff, mainly snowmelt, in the Sutlej is 24 percent of the annual and March-June runoff in Kosi is 17.9 percent. The April-August runoff in Sutlej is 73.7 percent of the annual while in Kosi it is 62.8 per cent. (Dhir and Singh, 1956). If some reduction from these percentages is made for the effect of monsoon, then also, it is found that snow cover has substantial effect on runoff during snowmelt period.

(b) Rain

When the effectiveness of rain during the snowmelt season is considered, the value of rainfall is found to be small when compared to equivalent amount of snowmelt. However, Dhir and Singh (1956) have analysed the runoff figures of Sutlej basin in North-west Himalayas and of the Kosi and Tista basins in South-east Himalayas to study the effectiveness of monsoon rain contribution to runoff.

(c) Glaciers

When the seasonal and accumulated snow have melted sufficiently to leave the surface of glaciers bare, the later will come into action through direct exposure to melting. This activity starts only when the snowmelt is well on wane and continues until the freezing sets in. According to Dhir and Singh(1956), September-October seems to be the probable period of Himalaya Glacier melting.

2.1.2.2 Ghats in Peninsular India

The Central Indian and Peninsular rivers derive their flows from rainfall only, and most of them are, therefore, seasonal with very little flow in the non-monsoon season.

The Western Ghats oriented north-south lies between 9°N and 21°N in Peninsular India. They have an average height of 900 metres and run in an unbroken range of hills from Maharashtra to South Kerala. South-west monsoon is the main source of water supply for the western Ghats, specially on the windward side.

Subrahmanuyam and Parthasarathi (1980) evolved runoff coefficients based on the soil type, slope and vegetation cover to convert water surplus into runoff. Ali (1982) modified the coefficients to suit physical characteristics of Godavari basin. Ram Mohan and Nair (1986) adopted these modified coefficients (table 1) to study the water balance of the western ghats on an annual and seasonal basins.

The runoff coefficient of a station is the product of runoff factors for station slope, soil type and vegetation.

Table 1: RUNOFF COEFFICIENTS BASED ON SOIL TYPE SLOPE AND VEGETATION COVER FOR WESTERN GHATS

	Parameter	Runoff factor	Detention factor
	STATION SLOPE		
(i)	10 m/km(Gentle)	0.70	0.30
(ii)	10-20 m/km(Moderate)	0.85	0.15
(ii)	20 m/km(steep)	1.00	0.00
	SOIL TYPE		
(i)	Sandy (High permeability)	0.70	0.30
(ii)	Silt(medium permeability)	0.85	0.15
(iii)	Clay (Low permeability)	1.00	0.0
	VEGETATION		
(i)	Tropical rain forest (Low Flow)	0.70	0.30
(ii)	Monsoon forest (Medium flow)	0.85	0.15
(iii)	Open Jungle (High flow)	1.00	0.0

Ram Mohan and Nair(1986) developed runoff and detention map on seasonal and annual basis. The runoff map reveals that on the western side of Ghats, runoff values upto 240 cm are noted in the region around Honavar and Mercara. Runoff values more than 400 cms are seen at Mahabaleswer. On the lee side of Ghats runoff is non-existent on an annual basis. In general, the isolines of runoff follow isohyets. The runoff factors of 1.00 is unlikely under natural conditions.

On seasonal basis, runoff values during the pre-monsoon season range from 1 cm to 5 cm over the region. Higher values are noted around Alleppey (10 cm) and Kodaikanal(15 cm). In the south-west monsoon season, runoff is increased and the values range from 50 cm to 150 cm. Maximum values are around Mahabaleswar (500 cm) and Merecara(200 cm). During the post monsoon season, runoff values decrease to the range of 10 cm to 40 cm. In the winter season, runoff again decreases to the range of 5 cm to 20 cm, values generally increasing towards south.

2.2 Factors Affecting Overland Flow in Mountainous Areas

In general, the factors that affect the overland flow in mountainous areas may be classified into three categories. These are: (i) Meteorological factors, (ii) Geomorphological factors, and (iii) other factors.

2.2.1 Meteorological factors.

Rainfall, snowmelt and temperature effects come under this category. Rainfall is directly related to the overland flow and is the principal cause of overland flow generation. The rainfall characteristic which affect the overland flow are: Intensity of rainfall, its duration and the impact of raindrops. The effect of rain drop impact on the sheetflow is reviewed in later sections (Art.2.7.1.2)

Mountainous catchments receive rainfall more frequently and with a longer duration. Due to shorter time interval between storm spells there is less time for soils to drain and so soil moisture content remains high. Therefore, mountainous catchments tend to have a lower soil moisture deficit to replenish before significant subsurface flow occurs. Besides, steeper slopes in mountainous catchments promote faster overland flow.

Runoff process during snowmelt also affects the overland flow. In India, the mountainous areas covered by snow is about 80% of total areas of Himalayas. The Western part of the Himalayas get more snowfall than the eastern parts. The onset of spring exposes the snow to intense radiation causing the rapid melt. Snowmelt runoff is strongly influenced by non-uniform characteristics of snow accumulation, ground frost, saturation of soils and radiation as modified by topography and cover. The contrbituion of these factors cause the area contributing runoff to be dynamic in the sense that it varies during and between the days. (Partial area concept as discussed by Dunne and Black, 1971).

Dunne and Black (1971) conducted an experimental study and found that almost one-half of the snowmelt water left the plot as overland flow because of the reduction in infiltration rate due to the presence of thin layer of frost in the top soil. The response of subsurface flow during melting was heavily damped by storage and transmission of water in the soil. Combined hydrographs (of surface and subsurface flow) were dominated by overland flow. Comparison of such hydrographs with concurrent stream channel hydrographs from basin suggest that overland flow was also a major control of the diurinal fluctuation of streamflow. They also conclude that even on parts of the watershed not covered by frost, complete saturation of soil was responsible for overland flow on some areas of river basins in humid areas.

Temperature is an important parameter in the study of snow and glacier melt. There are very few observatories which measure temperature at higher elevations. Some investigators have adopted lapse rate of 6.5 degrees per 1000 meters of elevation for the Beas valley in Himachal Pradesh. In recent years, the use of remote sensing techniques to gather information for watershed modelling has assumed great importance to assess snow cover in relatively inaccessible and hazardous regions.

2.2.2 Geomorphological factors

Various factors which affect the runoff are physiographic characteristics (size, shape, slope, orientation, elevation, stream density etc.) physical characteristics (surface condition, soil type), geological conditions such as permeability and capacity of ground water formations, topographical conditions such as presence of lakes, swamps, artificial drainage etc.) and channel characteristics (size and shape of cross-section, roughness) and length and overland flow.

Soil influence contributing area to overland flow generation through their infiltration rate and thickness of their permeable horizons. Slope gradients influence the rate of overland flow, subsurface flow and hence distribution of saturated soil and "saturation overland flow". The effect of local bottom slope and roughness coefficients variations on overland flows, over a plane, using Kinematic wave theory, has been investigated by Hager (1984). He found that the effect of local bottom slope and roughness coefficient variation is significant on the resulting surface profile but could be ignored regarding discharge characteristic, provided valleys are not flat in the upper and steep in the lower zones. He also concluded that the local effect of roughness coefficient needed to be accounted for when surfaces are significantly rougher at the upper than at the lower zones of catchment area.

The meteorological and geomorphological factors do not affect the small and large basins alike. In case of small catchments, the overland flow is predominant when one considers a small time scale like daily runoff. Also, the response of small catchments is quick to high rainfall intensities and sensitive to landuse changes. However, in large basins, the channel storage is very much dominant with the result the other responses become relatively insignificant. Sometime, two basins of nearly same size may have different runoff phenomenon as guided by their catchment behaviour.

2.2.3 Other factors-vegetation, forests and land uses

Studies concerning the relationship of land use to water yield and also the hydrologic behaviour of forest lands and range lands are necessary to understand as to how forests and land use affect the hydrologic functions of mountainous watersheds.

Rashtriya Barg Ayog (India) reports listed six major factors that contribute to the high rate of runoff and sediment discharge from the upper catchments. These are (1) Shifting cultivation, (ii) Grazing, (iii) People's right and privileges, (iv) Forest fires, (v) Surface mining and (vi) Land studies and slips. These factors are discussed below:

Vegetation cover is directly related to the maintenance of infiltration capacity, whenever the precipitation occurs. The functions of vegetation cover are breaking of the impact of rainfall (which, otherwise, tends to 'disturb' the overland flow), dissipation of soil moisture by evapotranspiration, and building of soil against erosion. The vegetation cover develops more open soil structure by building up and maintaining a partial and complete cover of unde composed or partly decomposed organic matter at or near the surface of the soil. This causes the water to move more slowly and therefore affords much more time for continued infiltration. The net result is to increase infiltration and to reduce overland flow, finally resulting in less erosion of soil and less formation of gullies.

The most noteworthy effects of vegetation cover are found in undisturbed forest stands. The soil here is home of much animal life. Many animal including most of rodents and insectivores, dwell or burrow in the soil, thus giving passage to water. In undisturbed forests, the dead and decaying root systems affect the structure of soil profile and create important fissures for free water conduction, mainly in vertical direction.

Land use, while highly interrelated with vegetation cover, may have effects independent of cover. Adverse land-use practices, which include overgrazing by sheep and cattle, repeated burning of litter and humus layers on the forest floor, and top soil loss by accelerated erosional process, have great effects on infiltration and production of overland flow and as such, studies should be conducted on sites to understand the hydrologic relation of land use and runoff.

A major factor influencing infiltration is the degree, the surface soil is compacted. Under wet condition, when the soil is compacted either by repeated ploughing process or by some other means (say, grazing), the noncapillary pore spaces are reduced, and infiltration rates become much lower, thus enhancing the runoff. Sub-surface stormflow has been shown over 'plough-pans' created by repeated ploughing compaction(Minshall and Jamison, 1965). Crop residue below the depth of mechanical disturbances, however, can improve soil structure and macroporosity, increasing inherent permeability of deeper zones. Where the soils are undisturbed by mechanical cultivation, the dead and decayaing plant roots contribute to the establishment of macro-porosity in the depths at which root penetration occurs.

Storey et al (1964) presented methods of hydrologic analyses to evaluate land treatment effects on streamflow. The hydrologic evaluation of land treatment depends on the particular hydrologic process that are operating in the watershed under study. In general, all the methods use a procedure which includes, (1) the survey of the soil, vegetation, use and condition of the watershed, (2) Estimation of future trend of these complexes with and without land treatment programme in effect, and (3) Estimation of streamflow with and without the land treatment programme. The difference between the streamflow for the two conditions evaluates the effect of land treatment.

Patric and Reinhart(1971) in their studies evaluated the hydrologic effects of deforesting two mountain watersheds in West Virginea. They have shown how the water yield; the duration of flows and instantaneous peak flows etc. are increased due to forest cutting in mountainous areas. They deforested the watersheds in two stages and studied hydrologic effects in growing and dormant seasons. The augmented flows mostly occured in growing seasons(May through October) whereas during the dormant season (November through April) the stormflows were little influenced. The study reinforces conclusion reached by Hornbeck et al (1970) in their study in England who observed sizeable increase in annual water yield, most of which occured in growing season and more important during critical low flow periods in later summer and early fall. Rothacher (1965) in his analysis also found considerable augmentation in flows of later summer and early fall.

By studying the effects of reforestation, McGuineess and Harold(1971) concluded that reforestation reduces both low flows and intermediate flows, and also decreases highflows but not significantly. Reforestation has also resulted in reduction of maximum annual flow volumes for all durations of one day and greater and in a significant delay in onset of dormant season flow. Lull and Sopper (1966) also evaluated the influence of various climatic, topographic and land-use variable to streamflow in the north-east and concluded that forest areas were more common on lands where greater runoff was natural i.e.steep slopes, shallow soils etc. The percentage of watershed area in forest cover was, however, correlated positively with runoff.

2.3 Mechanism of Overland Flow Generation in Mountainous Areas

Overland flow is the flow of water over the land surface toward a stream channel and is the initial phase of surface runoff. Nearly all the surface runoff starts as the overland flow in the upper reaches of the watershed and travels atleast a short distance before it reaches a rivulet or channel. After the flow enters a channel, it becomes channel flow.

The overland flow on a hillslope is the primary source of the lateral inflows that create peak flows during storm runoff events. Overland flow is generated at a point on a hill slope only after surface ponding takes places. Ponding takes place only after surface soil layers become saturated. Surface saturation can occur because of two quite distinct mechanisms. These mechanisms are:

(i) Horton Mechanism

(ii) Dunne Mechanism

2.3.1 Horton Mechanism

This mechanism was first espoused by Horton (1933) and placed in a more scientific framework by Rubin and Steinhardt (1963). According to this mechanism, the overland flow is generated when the rainfall intensity is in excess of the infiltration capacity of the soil so that excess rainfall appears as overland flow. As illustrated in Fig.3, a moisture content versus depth profile during such a rainfall event will show moisture contents that increase at the surface as a function of time. It may be seen from fig.3a, that at some point in time t^3 the surface becomes saturated and an inverted zone of saturaration begining to propagate downward into the soil. It is at this time (Fig.3c) that the infiltration rate drops below the rainfall rate and the overland flow is generated. The time t^3 is called the ponding time. Thus, the necessary conditions for the generation of overland flow by the Horton mechanism are: (1) the rainfall rate greater than the saturated hydraulic conductivity of the soil, and (2) the rainfall duration longer than the required ponding time for a given initial moisture profile.

Horton emphasised that the overland flows in mountainous areas create the peak flows during storm runoff events. Although much emphasis was placed on overland flow (rainfall intensity-infiltration rate) as the origin of storm hydrograph peaks, very little was said about the inability to commonly observe this phenomen, particularly on veget-

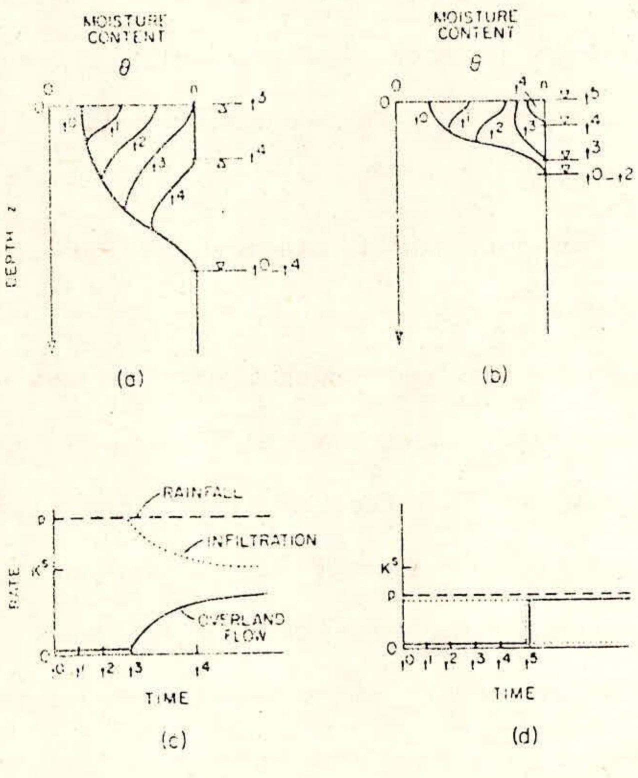

Fig. 3 Moisture content versus depth profiles for:
(a) the Horton mechanism, and
(b) the Dunne Mechanism, Overland flow generation for
(c) the Horton Mechanism, and
(d)the Dunne Mechanism

(Reproduced from Freeze, 1980)

ated and soil-covered slopes. The sequence of events when rainfall intensity exceeds the infiltration rate were listed by Cook (1946) as under:

(1) A thin layer forms on the surface and downslope surface flow is initiated.

(2) The flowing water accumulates in surface depressions.

(3) When full, these depressions begin to overflow.

(4) Overland flow enters micro-channels, which coalesce to form rills, which combine to form rivulets, which, in turn discharge into small gullies, this being continued until discharge into major channels occurs.

(5) Along each collecting channel, lateral inflow from the land surface takes place.

Cook(1946), however, pointed towards two serious deficiencies in Horton's approach; firstly, that the calculation of surface runoff from rainfall intensity and infiltration rate only holds good for very small areas where time of transit can be virtually ignored and secondly that some surface runoff has existed for some time as sub-surface flow which was returned to the stream. Observations by Kirkham (1947) on an experimental hillslope plot in Iowa led to the view that during intense precipitation, water infiltrated downwards near the top of the hill, horizontally outwards over the middle of the slope and vertically upwards near the hillslope base due to 'artesian pressure' developed by downward seepage over the higher part of the slope. Kirkby (1969 a and 1969b) also pointed out that this type of flow will occur instantaneously over a basin only if it is small and has a really homogeneous soil, soil-moisture, interception, depression storage and infiltration conditions. This type of overland flow is most common phenomenon in arid and semi-arid climatic condition, but is relatively rare in humid and humid-temperature conditions. However, the Horton overland flow can occur in humid areas also where the original vegetation and soil structure have been destroyed. Horton overland flow is very much influenced by vegetation which increases the initial depression storage due to increased open pores and high permeability and hence the infiltration. Hence, where dense vegetation cover is established, Horton overland flow is very unusual. (Kirkby and Chorley, 1967). The other important controls of Horton overland flow are: rainfall characteristic (intensity, duration and drop size), soil characteristic(texture, structure, depth, initial moisture-content, clay minerology, condition of soil surface, before rainfall) and land use.

Haggett and Chorley (1969) concluded that many storms might be expected to produce overland flow from limited contributing areas at much lower rainfall intensities than are required to exceed the infiltration capacities over the whole basin so as to produce universal Hortonian overland flow. Betson (1964) used the term ' partial area concept' for his view of the storm runoff generating process and concluded that only part of the catchment may be expected to contribute to direct runoff.

2.3.2 Dunne Mechanism

The second mechanism, as described by Dunne (1978) is illustrated in figures 3b and 3d. In this case the precipitation rate P is less than the saturated hydraulic conductivity K^s of the soil and the initial water table is shallow. Surface saturation occurs because of rising water table, ponding and overland flow occur at time t^5 when no further soil moisture storage is available.

The Horton mechanism is more common on upslope areas. The Dunne mechanism is more common on near channel wetlands. Horton overland flow is generated from partial areas of hillslope where surface hydraulic conductivities are lowest. Dunne overland flow is generated from partial areas of the hillslope where water tables are shallowest. Both mechanisms lead to variable source areas that expand and contract through wet and dry periods.

2.4 Quantitative Description of Overland Flow

Overland flow follows a system of downslope flow paths from the drainage divide to the nearest stream channel. The flow net comprises of a family of streams, of different stream orders, with respect to topographic contours. Horton (1945) defined 'length of overland flow' as the length of flow path, projected to the horizontal, of non-channel flow from a point on the drainage divide to a point on the adjacent stream channel. Horton noted that 'length of the overland flow' is one of the most important independent variables affecting both the hydrologic and physiographic development of drainage basin.

Horton evaluated the average length of overland flow, L_o as half the reciprocal of the drainage density:

$$L_o = \frac{1}{2D_d} \qquad \ldots(1)$$

where, the drainage density, D_d, is defined as the ratio of total channel segment lengths cumulated for all orders within a basin to the basin area (projected to the horizontal):

$$D_d = \frac{\Sigma L_s}{A} \qquad \ldots(2)$$

where L_s is the sum of the stream-lengths for the watershed and A is the drainage area. The drainage density is an important indicator of linear scale of land form elements in stream eroded topography and expresses the closeness of spacing of channels.

Thus, if the length of all the channels that are fed directly by overland flow can be measured, it is possible to estimate the average length of overland flow. ;Drainage density is measured from a map with the planimeter and the chartometer.

When overland flow occurs on a natural slope, the areas of sully turbulent flow are interspersed with areas of laminar flow, indicating a condition of mixed flow. For either turbulent or laminar flow, the depth of the flow may be estimated by the equation (Emmett, 1978).

$$q = KD^{M} \qquad \ldots(3)$$

where, q is the unit discharge expressed as m^3/sec/m and D is the mean depth in meter. K is a constant depending upon the parameters like resistance coefficient(Manning's n) and slope gradient, etc. M is the exponent of depth, which reflects, in part, the degree of turbulence. For turbulent flow, when the depth is estimated by combining the continuity equation.

$$q = DV \qquad \ldots(4)$$

and the Manning's equation

$$V = \frac{1}{n} D^{0.67} S^{0.50} \qquad \ldots(5)$$

where, V is the mean velocity,

The exponent M comes out to be 1.67. For laminar flow, a form of Poiseuille formula could be used to estimate the mean depth of flow, which gives M, a value of 3. Thus the value of M varies from 1.67 for fully turbulent flow to 3.0 for fully laminar flow. The values of M would range between these two extremes, for mixed flow condition. The depth, at a selected downslope point, or for a given value of discharge can be calculated using equation (3).

2.5 Hydraulics of Overland Flow in Mountainous Areas

Overland flows are the result of complex interaction regarding precipitation, infiltration, evaporation and storage effects. One should consider the interaction between overland flow and infiltration as both the process occur simultaneously. During overland flow, water held in detension storage remains available for infiltration. The infiltration capacity varies with time and is controlled by several factors including intensity and duration of rainfall, surface conditions slope of the surface etc.

The term 'Overland Flow' is frequently used in references to very shallow flow over plane surface. It is sometimes referred to as 'sheet flow' because the water is visualised as moving as a sheet downslope over a plane surface to the nearest concentration point or channel. Woolhiser (1977) considered all such flows which fit into abstraction of his model as overland flows. It may include thin sheet flow over plane surfaces and may also include flows over rilled and irregular surface or flow in small channels. He did not precisely define the boundary between overland flow and channel flow and considered such a seperation as purely operational. Emmett (1978) restricted use of the term 'sheet flow' to certain form of overland flow.

In order to understand the dynamics of overland flow in mountainous areas, it is necessary to determine the flow off the plane at the downstream end for given physical conditions and a given pattern of lateral inflow along the plane. The equation of spatially varied unsteady flow over a plane describe many of the important aspect of

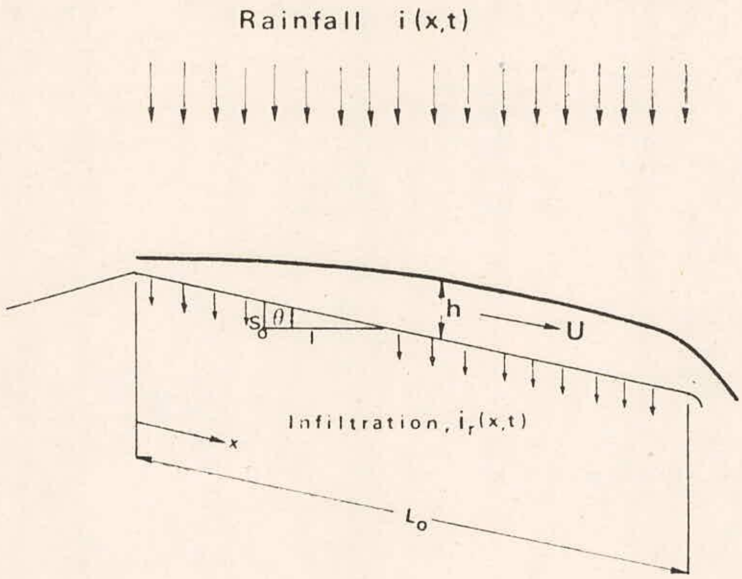

Fig.4: Definition sketch of overland flow on a plane
(Reproduced from Woolhiser, 1977)

overland flow. The problem under consideration is is shown in Figure 4. A plane of unit width, length L_o and slope S_o receives rainfall at a rate of $i(x,t)$ per unit area. Water infiltrates at a rate $i_r(x,t)$. Flow is assumed to be one dimensional. The dependent quantities are the local velocity, u, and local depth, h. The independent variables are the space-time coordinates, x and t respectively. The continuity equation for the overland flow can be written as:

$$\frac{\partial h}{\partial t} + u \frac{\partial h}{\partial x} + h \frac{\partial u}{\partial x} = q(x,t) \qquad \ldots(6)$$

and the momentum equation is

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + g \frac{\partial u}{\partial x} = g(S_o - S_f) - \frac{u}{h} q(x,t) \qquad \ldots(7)$$

where,

$h=h(x,t)$=Depth of overland flow(L)

$u=u(x,t)$= Flow Velocity (L/T)

$q=q(x,t)$=The net rate of lateral inflow(L/T)

$= i(x,t) - i_r(x,t)$

g= Acceleration due to gravity(L/T^2)

S_f= Friction slope (L/L)

For the derivation of continuity and momentum equations, collectively referred to as shallow water equations, paper of Kibler and Woohiser(1970) may be consulted.

2.6 Different Approaches for the Solution of Overland Flow Equations.

The equations of hydraulics of overland flow is one in which non-linear effects are quite marked. Since the solution of equations of unsteady flow for this case is quite difficult, simplified approaches need to be used to the study of overland flow. One such approach is based on the replacement of momentum equation by assumption of a power relationship between the outflow at the downstream end and the total storage on the surface. This method was proposed by Horton (1938) for overland flow on natural catchment and later used by Izzard (1946) for paved surfaces. The second approach, the kinematic wave solution, also assumes a power relationship between discharge and depth, but in this case, the assumption is that of a relationship between the discharge and the depth at every point. The problem of description of non-linear conceptual models was discussed by Dooge (1977). The above two approaches considered by various investigators for the solution of over flow equations are discussed below.

2.6.1 Horton-Izzard method

The solution of equations of unsteady flow is done by an assumed relationship between outflow and storage. It is noted that when the equilibrium runoff of a number of experimental plots was plotted against the average surface detention at equilibrium on log-log paper, the experimental points fell approximately along a straight line. An exact linear relationship on logarithmic paper would indicate that equilibrium outflow at the downstream end and the equilibrium storage were connected as below:

$$Q\ (L,\ te\ ) = Q_e = a\ S_e^c \qquad \ldots(8)$$

where

Qe was the discharge at the downstream end of the plane under equilibrium conditions,

S_e was the total surface storage at equilibrium conditions, and

a & c are parameters.

The assumption is made that such a power relationship holds not only at equilibrium but also at any time during the rising hydrograph or during the recession. Using this assumption one can write:

$$Q(L,t) = Q_L = a\ S^c \qquad \ldots(9)$$

where, Q_L is the discharge at the downstream end at any time and S is the corresponding total storage on the surface of the plane of overland flow. The equation of continuity (equation 6) can be written in the hydrologic form as:

$$qL - Q_L = \frac{dS}{dt} \qquad \ldots(10)$$

It can be written for the assumption already made as:

$$Q_e - aS^c = \frac{dS}{dt} \qquad \ldots(11)$$

or

$$adt = \frac{dS}{S_e^c - S^c} \qquad \ldots(12)$$

The solution of equation (12) is:

$$t = \frac{1}{aS_e^{\,c-1}} \int \frac{d(S/S_e)}{1-(S/S_e)^c} \qquad \ldots(13)$$

Horton (1938) solved the equation for rising hydrograph due to step function input for the case of C=2 which he described as 'mixed flow' since the value of C is intermediate between the value of 5/3 for turbulent flow and and the value of 3 for laminar flow. Horton's solution may be written as:

$$\frac{Q}{Q_e} = \tan h^2 \; (t/Ke) \qquad \ldots(14)$$

where $Ke = \frac{Se}{qe}$

Since the system is non-linear, the time parameter K will depend on intensity of inflow. Izzard (1944) presented the solution for C=3 (i.e. for laminar flow) in the form of dimensionless rising hydrograph.

The conceptual model based on Horton-Izzard solution clearly assumes that the whole system can be lumped together and treated as a single non-linear reservoir whose outflow storage relationship is given by equation (9). Even though this conceptual model is extremely simple in form, the fact it is non-linear makes it less easy to handle than some of the apparently complex conceptual models used to simulate linear or linearised systems.

2.6.2 Kinematic wave approximation

Kinematic wave approximation is one of the approaches which has proven to be a very useful tool in overland flow modelling. Many of the numerical problems could be overcome with the use of this simplified approach. As will be seen later in this section, this method assumes a power relationship between discharge and depth at every point and thus constitutes a distributed type of relation. The kinematic wave approach is equivalent to the use of a cascade of large number of very small equal non-linear reservoirs.

Kinematic wave occurs whenever a balance between gravitational and frictional forces is achieved. Under such circumstances the dynamic terms in the momentum equation (terms $\frac{\partial u}{\partial t}$, $u \frac{\partial u}{\partial h}$, $g \frac{\partial h}{\partial x}$ and $\frac{u}{h} q$ 9 x,t) in equation 7) -

become negligible in comparison with gravity and friction effects. The momentum equation (equation 7) reduces to the following form:

$$S_o = S_f \qquad \ldots(15)$$

The hydraulic conditions required by this assumption have been examined by Lighthill and Whitham (1955), Henderson (1963) and by Woolhiser and Liggett(1967). The application of shallow water equations, or their kinematic approximation to overland flow generation was pioneered by Henderson and Wooding (1964), Morgali and Linseley (1965) and Brakensiek (1966). The most complete and rigorous analysis is that of Woolhiser and Liggett (1967). Since then, the kinematic wave approximation has come to be widely used.

With the kinematic wave approximation, the mechanism of flow is now described by equations (6) and (15). Flow is assumed to occur as sheet flow rather than rectangular channel. The width B. on the sheet flow plane is assumed to be unity (i.e.,B=1) and as such:

$$Q = B\,u\,h = uh \qquad \ldots(16)$$

The friction slope, S_f, in equation (15) is defined by a stage discharge relationship such as Manning's equation or Chezy equation. The hydraulic radius, R, is calculated for B h so that R=h. Thus for sheetflow, Manning equation becomes:

$$u = \frac{1}{n} h^{2/3} S_f^{1/2} \qquad \ldots(17)$$

where, n is Mannings resistance coefficient. Substituting from equation (15) for S_f into equation (17):

$$u = \frac{1}{n} S_o^{1/2} h^{2/3} \qquad \ldots(18)$$

If slope, S_o, and roughness parameter, n for a given condition, is assumed to be constant, equation(18) can be rewritten as:

$$u = \alpha h^{N-1} \qquad \text{...(19)}$$

in which, $\alpha = \sqrt{S_o}/n$ and N=5/3 for Manning equation and $\alpha = C\sqrt{S}$ and N=3/2 for Chezy equation, where C is the Chezy roughness coefficient.

Substituting for u in equation (16):

$$Q = \alpha h^N \qquad \text{....(20)}$$

Equation (20) is outcome of momentum equation under Kinematic flow approximation. Equation (6) the continuity equation can be put in the form:

$$\frac{\partial h}{\partial t} + \frac{\partial (uh)}{\partial x} = q(x,t) \qquad \text{...(21)}$$

or

$$\frac{\partial h}{\partial t} + \frac{\partial Q}{\partial x} = q\ (x,t) \qquad \text{...(22)}$$

Combining equations (22) and (20), we obtain:

$$\frac{\partial h}{\partial t} + \frac{\partial}{\partial x} (\alpha\ h^N) = q(x,t) \qquad \text{...(23)}$$

or

$$\frac{\partial h}{\partial t} + \alpha N h^{N-1} \frac{\partial h}{\partial x} = q,\ (x,t) \qquad \text{...(24)}$$

Equation(24) is a partial differential equation having a single family of characteristics. The solution of equation (24) in conjunction with appropriate initial and boundary conditions will completely characterise the outflow hydrograph.

Procedures for kinematic wave computations are either analytical or numerical. Analytical solutions provide answers for a simplified class of problems while problem of a more general type are handled with numerical solution through attendent discretisation of the solution domain.

2.6.2.1 Analytical solutions

Parsen (1949) used the kinematic approach in describing the rising hydrograph of small runoff experimental plots. Lighthill and Whithamn (1955) developed the mathematical theory of kinematic waves including the mathematical phenomenon of kinematic shock. Iwagaki (1955) used the kinematic wave method incorporating a continuous lateral inflow to analyse in detail the hydrograph of overland flow and streamflow. Henderson and Wooding (1964) applied the kinematic wave technique to flow over a sloping plane. They obtained the solutions to the Kinematic wave equations for simple plane and channel geometries. They analysed the problem and developed the equation for rising hydrograph and falling hydrograph by arguments used on the method of characteristcs They also compared their results to data with a good reproduction of observations.

Wooding (1964a, 1965b, and 1966) discussed analytical and numerical solutions for overland flow problem. He obtained the analytical solutions by the method of characteristic firstly for flow over a plane v-shaped catchment under a constant uniformly distributed rainfall of finite duration and secondly for the stream outflow arising from the catchment discharge. Woolhiser and Liggett (1967) reported an analytical solution of the overland flow problem for a specified zone of the characteristic plane for an initially dry surface neglecting the momentum of the rain. The slope of the energy gradient was approximated using Chezy formula. Theypresented the solution for the rising hydrograph for a wide range of value of kinematic flow number. Computations were completed using method of characteristic described by Liggett and Woolhiser (1967).

Kibler and Woolhiser (1970) obtained the Kinematic wave solutions by three rectangular method and method of characteristics. Their dimensionless hydrographs (Fig.6) compares the solutions by method of characteristic and three rectangular grid method. The analysis by Henderson and Wooding (1964) and Wooding (1965a, 1965b, 1966) was followed closely by Eagleson (1970) in analysing overland flow problem. Lane et al (1975) solved the kinematic wave equations for pulse and impulse input. They first define the characteristic in x-t plane, so as to identify the nature of the flow whether laminar or turbulent and then use the equation to find out the overland flow hydrograph for plane and parabolic overland flow surfaces.

Singh and Woolhiser (1976) also proposed the analytical and numerical solutions to the dimensionless shallow water equations derived for a linearly converging section of a cone to represent the complex watersheds. Woolhiser (1977) gave the analytical solution of the kinematic wave equations for simple geometries. Singh and Agiralioglu (1981a) utilised the kinematic wave theory to investigate the diverging overland flow and derived explicit analytical solutions to the problem based on the method of characteristics.

The partial difference equation, representing the kinematic approximation to overland flow can be transformed into the characteristic form in the following manner.

Recalling the kinematic wave equation:

$$\frac{\partial h}{\partial t} + \frac{\partial}{\partial x} (\alpha h^N) = q(x,t) \qquad ..(25)$$

or

$$\frac{\partial h}{\partial t} + \alpha \frac{\partial}{\partial x} h^N = q(x,t) \qquad ...(26)$$

Along the solution surface, the following expression for the total derivative holds.

$$\partial h = \frac{\partial h}{\partial x} dx + \frac{\partial h}{\partial t} dt \qquad ...(27)$$

Both equations (26) and (27) must hold simultaneously so as in matrix notation we have:

$$\begin{bmatrix} 1 & \alpha N h^{N-1} \\ dt & dx \end{bmatrix} \begin{bmatrix} \frac{\partial h}{\partial t} \\ \frac{\partial h}{\partial x} \end{bmatrix} = \begin{bmatrix} q\ (x, t) \\ \partial h \end{bmatrix} \qquad \ldots(28)$$

By equation the square matrix on the left side to zero, we obtain the equation of the characteristic ground curve.

$$\frac{\partial x}{\partial t} = \alpha N h^{N-1} \qquad \ldots(29)$$

The compatability condition yields:

$$\frac{\partial h}{\partial t} = q\ (x,t) \qquad \ldots(30)$$

The above two equations can be solved to obtain the rising and the recession hydrograph by providing appropriate initial and boundary conditions.

2.6.2.2 Numerical solutions

Since the assumptions leading to analytical solutions are somewhat restrictive their practical utility is greatly diminished. Numerical or hybrid solutions of the kinematic wave equations were therefore evolved by several investigators.

In a series of three papers, Wooding (1965a, 1965b and 1966) extended the theory of kinematic flow approximation to a V-shaped watershed model, discussed numerical solutions and compared results with observed data. A solution was obtained for the problem where the rainfall varies arbirtarily with time over the catchment. He examined the effects of varying rainfall over the outflow hydrographs and also investigated the effect of variation in infiltration on possible modification in the catchment outflow hydrograph.

Margali and Linsley (1965) and Schaakey (1965) used the numerical solution of the kinematic wave equation to describe surface runoff from rural and urban watersheds. Brakensiek (1966) found the numerical solution of the kinematic wave equation to describe surface runoff from rural watershed.

Woolhiser and Liggett (1967) found that the kinematic wave approximation yielded results comparable to those determined by more general approaches such as Horton-Izzard approach provided Froud no. F_o is always below 2 and kinematic wave number $K = \frac{S_o L_o}{H_o F_o^2} > 10$, in which S_o is slope of the channel, L_o is length of the channel, H_o is normal depth at the lower end of the plane and F_o is the Froud number for normal flow depth H_o. The parameter K is an index representing the magnitude of slope and friction effects and may be interpreted as the product of the ratio of typical elevation differences $(S_o L_o)$ between lowest and highest point of a reach and flow depth times the inverse Froud number. The first term accounts for the shallowness of the flow while the second, F_o, reflects dynamical effects. The analysis of kinematic flow no.'K' shows that the kinematic approximation is best for rough, steep slopes with low rates of lateral inflow. It is valid on almost all overland flow planes.

Kibler and Woolhiser (1970) obtained the solutions of kinematic wave equation in the presence of kinematic shocks by three rectangular difference schemes and compared the results with the one obtained by the method of characteristic(Fig.6). They have also given the stability calculations for the three methods. The methods and the stability criteria have been listed in tabular form also (Table 2).

Agiralioglu and Singh (1980) used Lax-Wendroff scheme to solve kinematic wave equations successfully. Singh and Agiralioglue (1981b) again used the Lax-Wendroff scheme (Houghton and Kasahara, 1968) to give numerical solution to kinematic wave theory applied to diverging overland flow problem.

Ponce et al (1978) in their study of examining the applicability of kinematic and diffusion models in open channel flow concluded that most overland flow problems can be modelled as kinematic flow. Although their model does give considerable insight into the behaviour of these models, it does not include the relevant boundary conditions for overland flow. Therefore, it seems appropriate to utilize the approach of Woolhiser and Liggett (1967) and compare dimensionless overland flow hydrographs to develop approximate criteria. Morris and Woolhiser (1980) commenting on kinematic flow number 'K' (Woolhiser and Liggest, 1967) showed that the additional criteria $S_o L_o / H_o > 5$ is also required. Hager and Hager (1985) also examined the application limits for the kinematic wave approximaotion and established the application criteria for the kinematic wave approximation as:

(i) Maximum Froud no.F_o, be smaller than unity or according to (Harger, 1985):

$F_o^2 = (K\sqrt{S_o})^{9/5}/g < 1$ Corresponding to $K\sqrt{S_o} < 3$

where; $K = \frac{1}{n}$ is roughness coefficient, S_o is the bed slope g is acceleration due to gravity and F_o is the typical Froud number, and

(ii) $PK^3\sqrt{S_o}/g^2 < 0.07$ on any subreach of a watershed, where p is the difference of intensity of lateral inflow p_i and lateral outflow p_o $(p=p_i-p_o)$. They, however, concluded that in practice, overland flow is always governed by kinematic wave approach, while flow in small streams have to be examined more carefully regarding the above applicability criteria.

Various numerical schemes which have been frequently utilised to solve the kinematic wave equation are:

(i) Upstream finite differencing schemes,

(ii) Crank-Nicholsen scheme,

(iii) Breakensick scheme, and

(iv) Single-step Lax-Wendroff scheme.

Equation (24) is non-linear partial differential equation and for these equations convergence and stability conditions are not yet established, except for some simplified cases. An alternative approach is to linearize the non-linear equations and then perform the analysis. After linearizing the equation (24), the equation becomes:

$$\frac{\partial h}{\partial t} + (\alpha N \bar{h}^{-N-1})\frac{\partial h}{\partial x} = q\ (x,t) \qquad \ldots(31)$$

where, $\bar{h}$ is a constant. Let $a = N\bar{h}^{-N-1}$. It will be seen that the analytical treatment of step error remains unaffected (since q(x,t) is always known) making equation (31) homogeneous. The homogeneous form of equation may be written as:

$$\frac{\partial h}{\partial t} + a\frac{\partial h}{\partial x} = 0 \qquad \ldots(32)$$

The formula for each scheme to solve the equation(32) is given as

(i) Upstream finite differencing scheme

This scheme approximated equation(32) as:

$$h_{i\ (n+1)} = h_{i,n} - \frac{\Delta t}{2\Delta x}[h_{i,n} - h_{(i-1).n}] \qquad \ldots(33)$$

(ii) Grank-Nicholson scheme

Equation (32) can be approximated as:

$$h_{i(n+1)} = h_{i,n} - a\frac{\Delta t}{2\Delta x}[h_{i,n} - h_{(i-1),n} + h_{i,(n+1)} - h_{(i-1)(n+1)}]$$

$$\ldots(34)$$

(iii) Breakensiek scheme

This is four point implicit scheme. Equation (32) can be approximated by this scheme as:

$$\frac{1}{2\Delta t}\left[h_{(i+1),(n+1)}-h_{(i+1),n}+h_{i(n+1)}-h_{i,n}\right] = -\frac{a}{2\Delta x}\left[h_{(i+1),(n+1)}-h_{i(n+1)}+h_{(i+1),n}-h_{i,n}\right] \quad ...(35)$$

(iv) Single step Lax Wendroff scheme

This scheme is most popular. Equation (32) is approximated by using this scheme as:

$$h_{i,(n+1)} = h_{i,n}+\frac{\Delta t}{\Delta x}\left[-\frac{a}{2}\left(h_{(i+1),n}-h_{(i-1),n}\right)\right] + \left(\frac{\Delta t}{\Delta x}\right)^2\frac{a^2}{2}\left[h_{(i+1),n}-2h_{i,n}+h_{(i-1),n}\right] \quad ...(36)$$

As has been discussed earlier, Kibler and Woolhiser (1970) have used the three rectangular finite differencing schemes to solve the kinematic wave equations numerically. These three schemes are: Single step Lax-Wendroff scheme; Upstream finite differencing schemes; and Breakensiek's four point implicit scheme. They did not linearize the kinematic wave equation and made it homogeneous and gave the formuale for each scheme directly for equation (24). These formulae, their order of approximation and the linear stability criteria have been reproduced here in table 2. The definition sketch of the notation in table 2, has been shown in figure 5.

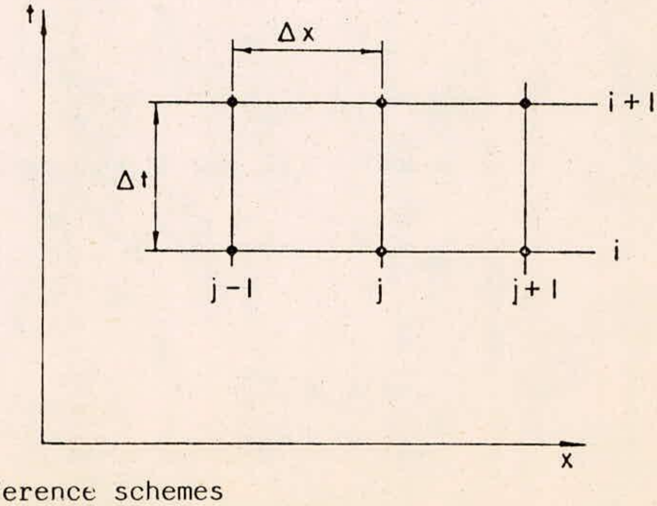

Fig.5 Notation for finite-difference schemes (reproduced from Kibler and Woolhiser, 1970)

Table No 2 : RECTANGULAR GRID FINITE DIFFERENCE SCHEMES
(Reproduced from Kibler and Woolhiser, 1970)

Method	Finite Difference Equation	Order of Approximation	Linear Stability Criterion
Single-Step Lax-Wendroff	$h_j^{i+1} = h_j^i - \Delta t \frac{k}{n} \left[\frac{\left(h_{j+1}^{i^N} - h_{j-1}^{i^N} \right)}{2\Delta x} - \frac{1}{2} \left(q_{j+1}^i + q_{j-1}^i \right) \right] +$ $\frac{\Delta t^2 Nk}{4n\Delta x} \left\{ \left(h_{j+1}^{i^{N-1}} + h_j^{i^{N-1}} \right) \left[\frac{k}{n} \frac{\left(h_{j+1}^{i^N} - h_j^{i^N} \right)}{\Delta x} - \frac{1}{2} \left(q_{j+1}^i + q_j^i \right) \right] - \right.$ $\left. - \left(h_j^{i^{N-1}} + h_{j-1}^{i^{N-1}} \right) \left[\frac{k}{n} \frac{\left(h_j^{i^N} - h_{j-1}^{i^N} \right)}{\Delta x} - \frac{1}{2} \left(q_j^i + q_{j-1}^i \right) \right] + \frac{2n\Delta x}{Nk\Delta t} \left(q_j^{i+1} - q_j^i \right) \right\}$	$0(\Delta x)^2$	$\frac{\Delta t}{\Delta x} \leq \frac{n}{Nk\bar{h}^{N-1}}$
Upstream Differencing	$h_j^{i+1} = h_j^i - \frac{Nk}{n} \frac{\Delta t}{\Delta x} \left(h_j^{i^N} - h_{j-1}^{i^N} \right) + q_j^i \Delta t$	$0(\Delta x)$	$\frac{\Delta t}{\Delta x} \leq \frac{n}{2.75kNh^{N-1}}$
Brakensiek's Four Point Implicit	$\frac{h_j^{i+1} - h_j^i + h_{j-1}^{i+1} - h_j^i}{2\Delta t} + \frac{k}{n\Delta x} \left(h_j^{i+1^N} - h_{j-1}^{i+1^N} \right)$ $- \frac{1}{4} \left(q_{j-1}^{i+1} + q_j^{i+1} + q_{j-1}^i + q_j^i \right) = 0$	$0(\Delta x)$	Unconditionally stable

All of these methods have been used successfully. The single step Lax-Wendroff scheme has second order accuracy and will have the smallest errors of approximation for a given Δx and Δt. This partly explains the popularity of this scheme. The four point implicit method is unconditionally stable so may save some computation time if larger time steps are used. Singh (1976) has developed the step error of these schemes and he has also shown that for convergent and stable schemes, the production of step error of one scheme may not be the same as that of another. He found that the step error of Lax Wendroff scheme is least and that of Breakensiek 4 point scheme is highest. This points out that Breakensick 4 point implicit method should not be recommended for use under all circumstances. Thus the important point is that the stability and step error of a numerical scheme must be considered simultaneously. Stability is one of the properties of a difference scheme that is required before convergence is gauranteed. In an unstable scheme small numerical errors introduced in the computational method are amplified and eventually dominate the solution. Stability analysis and step error computations identify the suitability of the application of different numerical schemes and also determine the appropriate step lengths for conditionally stable scheme.

Kibler and Woolhiser(1970) observed that the development of shock-wave phenomena, an undesirable feature of kinematic cascade model, is the property of mathematical approach rather than observable feature of hydrodynamic process. The dimensionless hydrograph computed by three methods and by method of characteristics are shown in figure 6. Shock is visible in solution obtained by method of characteristics. The input pulse duration is equal to the time to equilibrium of the 2-plane cascade The smoothening effect of all three numerical schemes in the shock effected regions is clearly visible and the second order Lax-Wendroff method does give the best approximation. In general, the peak response is delayed and reduced by as much as 20% for the first order schemes.

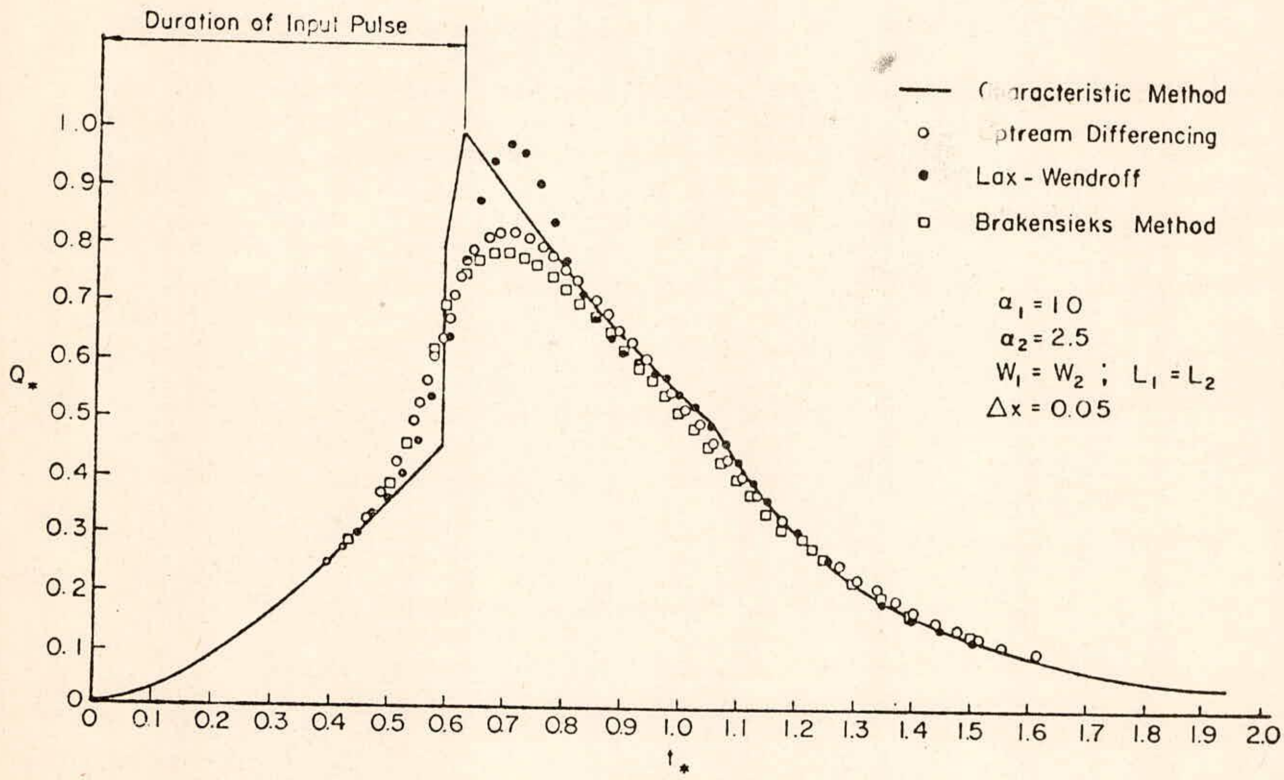

Fig.6. Comparison of finite difference methods (reproduced from Kibler and Woolhiser, 1970)

2.7 Modelling of Overland Flow in Mountainous Areas

The hydrological modelling of overland flow in a watershed is usually based on hydrodynamic flow equations. This requires a full description of flow process which is far from being simple and may involve some empirical relations. For example, the turbulence characteristics of these flows are usually accounted for empirically such as by the Manning formula and the effects of surface tension for overland flows are ignored.

General procedure of overland flow modelling and some mathematical models of overland flow are reviewed in this section.

2.7.1 General procedure

The basic assumption underlying the simplifying approach to hydrologic modelling is that the complex geometry and topography of natural catchments can be replaced by large number of simple elements. In order to apply equations describing overland flow to watersheds with geometrical complexities, to better understand watershed response or to make predictions, the following decisions are to be made.

i) regarding the method of spatial representation of the watershed,

ii) on the form of hydrulic resistance law, infiltration law and several key parameters,

Also the user has to selecte appropriate numerical methods for solving the equations. Various analytical and numerical schemes for solving the equations of overland flow have already been described.

2.7.1.1 Methods of spatial representation of the watersheds

The response of a watershed to rainfall is a very complex natural process. No theoretical model of a natural watershed could be conceived of which could account for all the variables and their inter-relationship that affect the runoff process. The objective of any mathematical model is to make simplifying assumptions and to transform natural geometry into a simpler one and yet retain the most important characteristic of the physical system.

One geometrical abstraction which has been made use of by several investigators is that a watershed may be represented by a network of overland flow planes and channels. Woolhiser and Liggett (1967) have shown that the simplified hydrodynamic approach based on kinematic wave theory is applicable to most hydrologically significant cases of overland flow. Since its development (Lighthill and Whitham, 1955) several investigators have used the kinematic wave theory to model surface runoff from natural watersheds(Wooding, 1965a, 1965b, 1966) Brakensiek, 1967a, 1967b, Kibler and Woolhiser, 1970, Eagleson, 1972, Singh, 1974). Most recognised that natural drainage system had such complex surface configuration that it was necessary to transform the complex configuration into a simpler one with a similar hydrologic response. Several alternate geometric representations (Wooding, 1965a; Brakensiek, 1967b, Herley et al, 1970) have been hypothesized involving varying degree of abstraction. Rovey, Woolhiser and Smith (1977) also used a network composed of planes and channels to represent watershed Geometry. They used kinematic routing as was used by Kibler and Woolhiser (1970) but Harley, Perkins and Eagleson (1970) included an option of the linear response function to the complete equations for flows not dominated by lateral inflow.

A triangular grid representation of a watershed has certain appealing features in that it would confirm more closely to watershed topography. The other ways of representing watersheds is in the term of converging sections (Woolhiser, 1969; Singh and Woolhiser, 1976) and diverging section (Singh and Agiralioglu, 1981a and b). All these methods of representation of natural watersheds have been examined and discussed later.

2.7.1.2 Parameter estimation and form of resistance equation

Once the decision regarding the method of spatial representation of a watershed has been made, the user has to decide on the form of a hydraulic resistance law and estimate several key parameters.

For simplifying watershed geometry by cascade of planes and channels approximation, the information regarding slope and slope length etc. is required. One way of estimating the slope of each plane is by deriving a least square estimate of slope by fitting a plane to coordinate data from topographic maps. Hobson (1967) has taken such an approach in trying to describe surface shape in topographic sense. But, the channel characteristics are poorly defined at the map scale normally available. Machmeier and Larson (1968) used stream hydraulic geometry relations to define stream characteristics in numerical studies of watershed response usitlising a physically based model.

(a) Resistance to overland flow:

Resistance to rainfall-induced overland flow over natural and man-made surfaces may be influenced by several factors. Boundary roughness is frequently much greater than that encountered in ordinary hydrulic structures. These factors are:

i) Rates of flow,

ii) Raindrop impact

(i) Effect of rate of flow :

At low rate of flow, the roughness elements protrude through the free water surface, and at high rates of flow they may change in time and distance because of erosion or because the vegetation is bent over by flowing water. On vegetated surfaces, the plant leaves and stems may offer more resistance to flow than the soil roughness.

(ii) Effect of raindrop impact :

Raindrop impact has retarding effect on shallow flows. Keulegan (1944) has reported the retarding effect to be small but other investigators (Izzard, 1944: Parson, 1949; Yoon and Wenzel, 1971: Shen and Li, 1973) have reported that the effects may be significant. It was also shown that the values of friction factor increased due failling rain and this increase is dependent on rainfall intensity. Most investigators also reported an increase in the value of friction factor with an increase in flume slope. Emmett (1978) concluded that the isolated effect of aritificial rainfall used in his investigations almost doubled the friction factor over that for flows without rainfall.

(b) Form of resistance equation

The relationship between Darcy-Weisbach friction factor f and the dimensionless Reynolds No Re, is well established for pipes and smooth channels (Chow, 1959) and laboratory experiments and theoretical analyses since 1930 have shown that a similar relationship holds good for shallow flow over a plane bed with either a smooth or rough surface, provided that the surface is completely submerged by the flow (e.g.Horton et al, 1934; Woo and Brater, 1961; Emmett, 1970; Yoon and Wensel, 1971; Shen and Li, 1973; Phelps, 1975; Savat, 1980). Under such conditions, the shape of f-Re relation is a function of the state of flow: the relation has a slope of -1.0 where the flow is liminar and slope close to -0.2 where the flow is turbulent (.e.gHorton et al, 1934, Emmett, 1970, Morgali, 1970, Yoon and Wenzel, 1971, Shen and Li, 1973). However, the situation is less clear where flow is transitional.

The form of f-Re relation is of fundamental importance to the mathematical modelling of overland flow in mountainous areas. Whether a model is based on Saint-Venant equations (Woolhiser and Liggett, 1967; Woolhiser,1975) or employs the kinematic wave approximation (e.g. Henderson and Wooding, 1964; Woolhiser and Liggett, 1967, Foster et al, 1968, Lane and Woolhiser, 1977, Dunne and Dietrich, 1980, Moore, 1985), it needs to take into account the resistance of the hilslope surface to flow. In the past this has usually been done by incorporating into the model a relation between f and Re(or surrogates thereof), the most widely used relation being the conventional one for shallow flow over a plane bed. The relation generally has an adjustable parameter, such as intercept of the laminar flow portion of the relation. In some cases the value of intercept has been estimated from experimental data (e.g.Dunne and Dietrich, 1980), whereas in other it has been obtained by optimization (e.g.Woolhiser et al, 1970, Woolhiser, 1975, Lane and Woolhiser, 1977). Studies have shown that computed overland flow hydrograph is very sensitive to the value of the intercept (e.g.Woolhiser 1975, Dunne and Dietrich, 1980) and it stands to reason that it is even more sensitive to the shape of f-Re relation.

In desert hillslopes, virtually all runoff from hillslope occurs in the form of overland flow. But, according to Ambrahams et al (1986) conventional f-Re relation for shallow flow over a plane bed does not apply to desert hillslopes and may not be employed in mathematical models of overland flow on such hillslopes. They examined the relation between the Darcy-Weisbach friction factor f and Reynolds number, Re, for overland flow on six runoff plots in semi-arid southern Arizona and found that f-Re relations for desert hillslopes have two basic shapes: Convex upward and negatively sloping. They gave reasons for these shapes and expressed the urgent need for additional field and laboratory investigations of the f-Relation, so that models of overland flow can be based on more realistic relations and better simulate runoff hydrographs.

Emmett (1978) in his labratory test studied the effect of roughness and flume slope on depth. He concluded that effect of roughness on value of depth is both general and complex. Because of the additional resistance to flow, roughness increases the depth of flow for a given discharge. The maximum influence of roughness appears near the transition from laminar to turbulent flow. In this region, the depths on the rough surfaces are from 15% greater(for less steep slopes) to 30% greater (for the steeper slopes) than depths on the smooth surfaces. Resistance to flow expressed in his study as Darvy-Weisbach friction factor and Manning's resistance coefficient described bulk resistance to flow rather than resistance attributable to grain roughness alone.

In most of the laboratory and field investigations, the most common approach has been to assume that the Darcy-Weisbach equation is the appropriate form and then to relate the friction factor f to hydraulic and geometric variables. The Darcy-Weisback equation is:

$$u = \sqrt{\frac{8g}{8} \; S_o R} \qquad \ldots(37)$$

Here, u= velocity, g=Accl. due to gravity, f=friction.

factor, S_o= Bed slope, R=Hydraulic radius

It has been observed that overland flow behaves initially as if it were laminar. However, the turbulence may generate by raindrop impact. For laminar flow, the theoretical relationship between the friction factor and Reynolds number is:

$$f = \frac{K}{R_e} \qquad \ldots(38)$$

where, R_e is Reynolds number and K is the constant. For laminar flow over a smooth surface(without raindrop impact), K=24. For laminar flow over rough surfaces, K is greater than 24. The parameter K is related to the characteristic of surface and can be very large(40,000) for dense turf(Woolhiser, 1975 and 1977). With the raindrop impact, the parameter K can be approximated by: (Woolhiser, 1975 and (1977)

$$K = K_o + A\, i^b \qquad \ldots(39)$$

where K_o is a parameter without rainfall and A and b are empirical parameters. If the surface is hydraulically smooth, the resistance effect of raindrop is significant. However, it become insignificant for vegetated surfaces.

Set of values for K_o and parameters A and b have been reported by Woolhiser for different surface characteristics.

The Manning and Chezy formulas are frequently used as the resistance law for turbulent flow cases. The tabulated Mannings 'n' in handbooks are suitable for most channels. But for shallow overland flow or flow in grass waterways, it has been found that values change substantially with Reynolds number.Emmett (1978) have plotted the values of Mannings'n' as a function of Reynolds number and the average depth of flow.

(C) Infiltration models and storage models

Horton (1933) was the first to outline in full the classical models of hillslope hydrology in terms of his infiltration theory of runoff. Rainfall in excess of the infiltration capacity runs off as overland flow. As water infiltrates into the soil, the infiltration capacity is reduced. It is commonly expressed as a function of time elapsed, or of total amount infiltrated during the storm. The former expression is analytically simpler but is less adaptable to the conditions of variable rainfall intensity than the latter type of expression.

The storage model of surfac runoff does not limit rainfall intensity but only the available volume for cumulative infiltration. Infiltration of rainfall is predicted until this storage is filled. Subsequent rainfall, even at low intensities, is predicted to produce overland flow. Storage may be depleted by downward percolation and or by lateral downslope flow.

Infiltration models which required detailed numerical solution of the partial differential equation of unsaturated flow need too much computer time and soil related data such as moisture content, saturated and unsaturated conductivity etc. for practical use. Approaches based on simplifications of those equations or the model presented by Smith and Parlange (1978) and Morel-Seytoux (1978) appear to be the best at the moment.

A simple storage model is most useful under such conditions when rainfall intensities are generally less than infiltration capacities. Whereas, a simple infiltration model, is closest to reality when rainfall intensities commonly exceed infiltration capacities. In general, however, a combined model is preferable.

2.7.2 Some Overland flow models

In article 2.7.1 general procedure for modelling overland flows have been reviewed. The need to transform the complex geometries into the simpler one having a similar hydrologic response is also discussed thereon.

Depending upon the geometric complexity natural watersheds may be represented by a combination of four geometric elements, (i) plane, (ii) converging section, (iii) diverging section, and (v) channel. These elements can be grouped in such a way as to provide an almost perfect representation of a given watershed regardless of its geometric complexity. Some of the mathematical models based upon such simplifications have been reviewed in this section.

2.7.2.1 Kinematic cascade model

In order to bring overland flow simulations closer to reality, it is necessary to attempt simulations on planes that are not restricted to a single slope. The most advanced approach of this type is that of a kinematic cascade, which is defined as a sequence of n discrete overland flow planes or channel segments in which the kinematic wave equations are used to describe the unsteady flow. The kinematic wave flow equations are derived for flow over a hydraulically smooth plane, but the same form can be used for irregular surfaces where the mean flux per unit width is proportional to the storage in an incremental area.

Henderson and Wooding (1964) and Wooding (1965a, 1965b and 1966) had restricted their study of overland flow to a single plane. Brakensick (1967a) made the essential steps from Wooding's V-shaped model to the kinematic cascade model. This step is fundamental because rather than a single plane discharging into a channel- a lumped non-linear model- Brakensiek broke the lateral flow portion into a sequential series(cascade) of planes. This extension was to let each plane have different characteristic resulting in a distributed model. Thus Brakensiek is credited to have introduced the concept of kinematic cascade which transformed an upland watershed into a cascade of planes discharging into a single channel. His transformation technique was based on preservation of hypsometric curve and contour length-elevation curve for watershed. Brakensiek has also described the basic application of kinematic flood routing method and also the properties of kinematic technique within the context of hydraulic and hydrologic flood routing procedure (Brakensiek, 1966, and 1967b). In order to minimize the discrepancy between observed and computed hydrographs, Brakensiek tried to adjust the Mannings roughness in his applcation of kinematic cascade to the watershed.

Harley et al (1970) and Singh(1974) applied kinematic cascade model to urban and rural agricultural watersheds. Kibler and Woolhiser (1970) provided most complete analysis of kinematic cascade system. Their analysis and some of the results are discussed later in this section. Smith and Woolhiser (1971a and 1971b) combined overland flow model in the form of a kinematic cascade, to an infiltration model to represent overland flow on infiltrating surfaces.

The kinematic cascade model used by Jeyaseelan(1984 and 1985) was originally developed by Woolhiser (1969). Later Smith et al (1970) developed parametric infiltration model and Rovey et al (1977) combined two models and presented what, they called a 'KINGEN' model.

Lane et al (1975) used kinematic cascade model in order to simulate complex surfaces and compared the results obtained by cascade of plane approximation to these for convex and concave surfaces. They summarised the modelling procedure by showing how watershed geometry could be combined with kinematic wave theory in the kinematic cascade model (figure 7).

An n-plane cascade receiving lateral inflow and discharging into a channel segment is shown in figure 8.

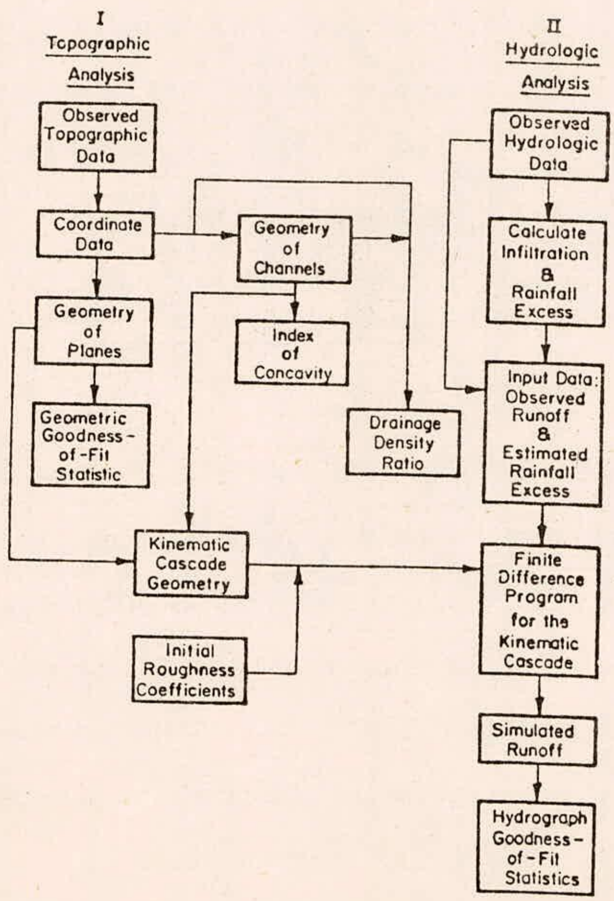

Fig.7 Summary of modelling procedure(reproduced from Lane et al, 1975)

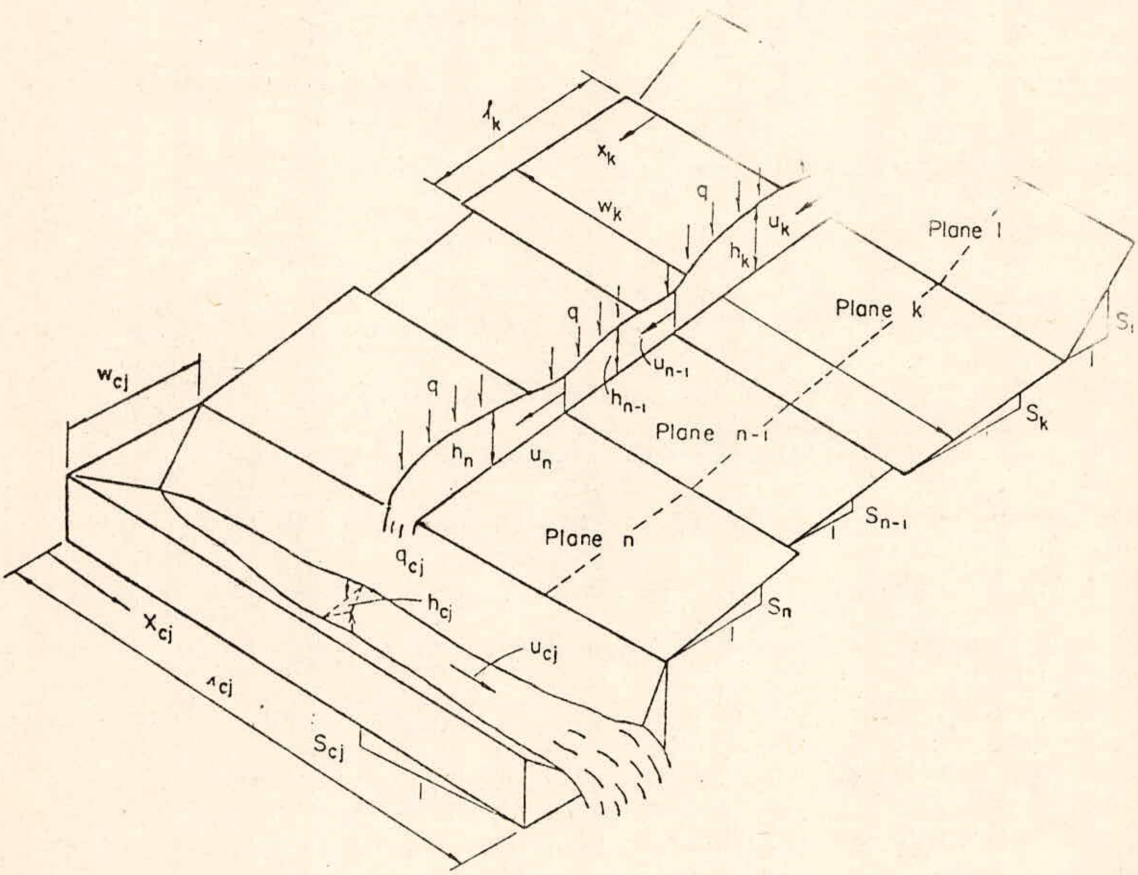

Fig.8: Cascade of n-plane discharging into j^{th} channel section (Reproduced from Kibler and Woolhiser, 1970)

Kibler and Woolhiser(1970) developed the dimensionless characteristics equations for the K-th plane as:

$$\frac{\partial h_*}{\partial t} + \beta h_*^{N-1} \frac{\partial h_*}{\partial x_*} = q_* \qquad ...(40)$$

where, the asterik indicates that the terms are dimensionless. The terms q_* and β can be defined as follows:

q_* = The dimensionless lateral inflow

$$= \frac{q}{I_k} \qquad ...(41)$$

where, I_k is the normalising lateral inflow given by:

$$I_k = \frac{1}{T_K} \left(\frac{Q_K}{X_k}\right)^{\frac{1}{N}} = \frac{Q_k}{L_k} \qquad ...(42)$$

and $$\beta = \frac{\alpha_k{}^N T_k}{\sum_{i=1}^{n} li} \left(\frac{Q_k}{\alpha k}\right)^{\frac{N-1}{N}} = \frac{NL_k}{\sum_{i=1}^{n} l_i} \qquad ...(43)$$

The recession part of the hydrograph can be described by th same equation (40) by putting the lateral inflow rate $q_*=0$.

Ki r and Woolhiser (1970) solved these equations by method of characteristic and also by three rectangular grid finite difference schemes. In the kinematic cascade approach, the equation of flow are solved independently for each plane and at each time step.

An undesirable feature of kinematic cascade model of overland flow is the development of shock wave phenomena in the solutions. According to Kibler and Woolhiser (1970):"while the shock-wave phenomenon may arise under certain highly selective physical circumstances it is looked upon in this study as the property of mathematical equations used to explore the overland flow problem rather than the observable feature of this hydrodynamic process". Kibler and Woolhiser(1970) applied the kinematic cascade to complex watershed and concluded that kinematic cascade effectively reduces geometric complexity and accura-

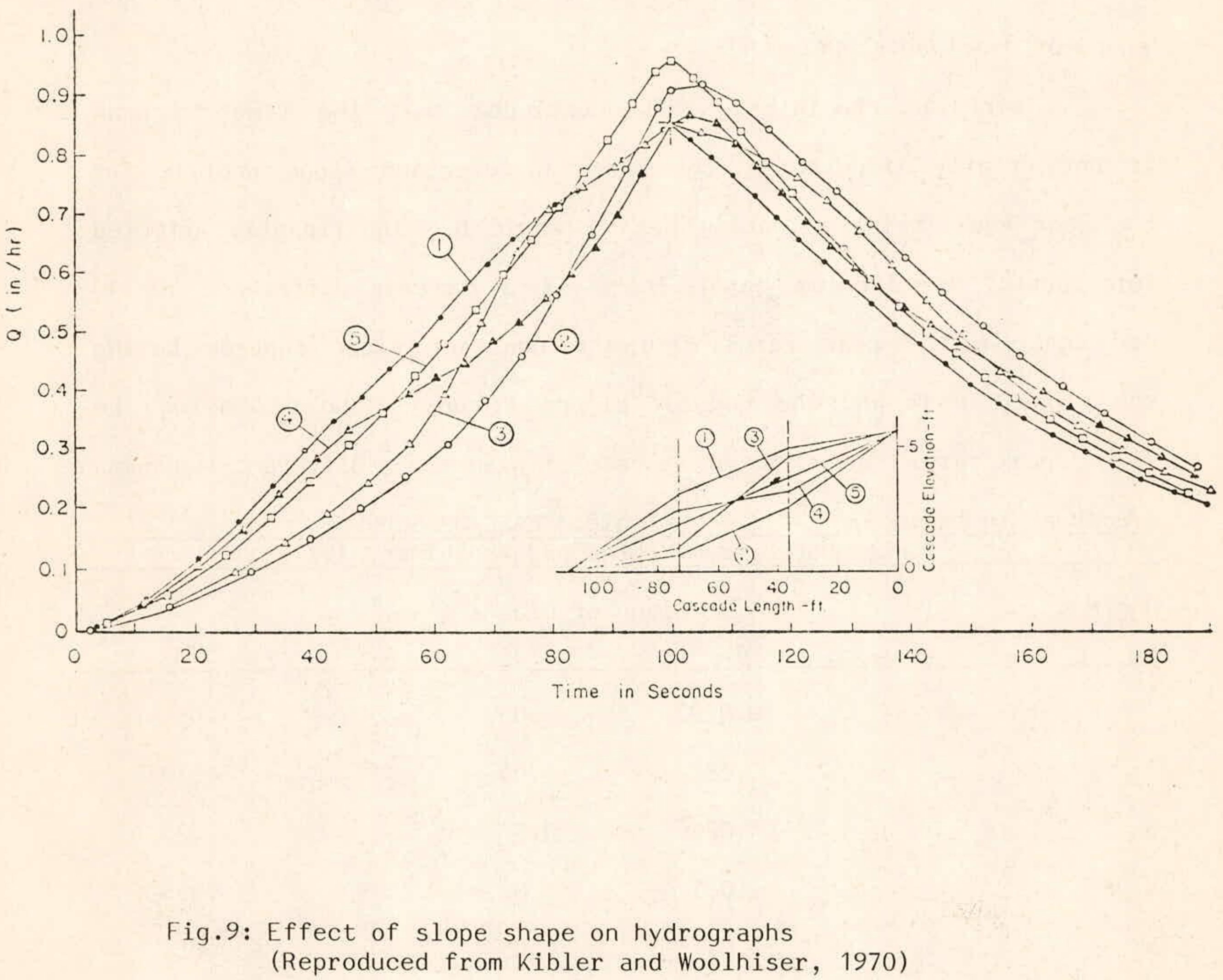

Fig.9: Effect of slope shape on hydrographs
(Reproduced from Kibler and Woolhiser, 1970)

tely simulates overland flow derived from complex watershed surfaces. The effect of changing overland slope on the outflow from the kinematic cascade was also investigated which revealed a strong correlation between the general shape of the rising hydrograph and the profile of overland slope for the cascade. The results of the computation are shown in figure 9 for a unit rain rate of 1 in/hr applied for 100 Secs. The general shape of the rising hydrograph is the same as the shape of overland slope.

Kibler and Woolhiser (1970) concluded that the time to peak is not greatly affected by the shape of overland slope profile for the near equilibrium situation but it would be significantly affected for partial equilibrium case. There is a maximum difference of 10 per cent in the peak rates with the constant slope cascade having the highest peak and the complex slopes (runs 3 and 4) having the lowest peak rate. The slope of cascade of planes for different run numbers are shown in table 3.

Table:3 CASCADE SLOPES
(Reproduced from Kibler and Woolhiser, 1970)

Run No.	Slope of Planes S_1	S_2	S_3
1	0.0197	.05	.08
2	.08	.05	.0197
3	.025	0.1	.025
4	.065	.02	.065
5	.05	.05	.05

2.7.2.2 Converging overland flow models

The second approach of simplifying the geometric complexities is to consider a converging section as suggested by Woolhiser(1969).

According to him, the converging geometry might be a useful abstraction of a watershed regardless of its complexity. He obtained exact solutions for kinematic flow on converging surface. he derived the characteristic equation for converging overland flow based on kinematic flow approximation and has put them in dimensionless form. He introduced a parameter, γ , which defines the degree of convergence exhibited by a section- a small value of γ indicates high flow convergence. As γ approaches unity the convergence of flow tends towards that of a plane rectangular surface.

Kibler and Woolhiser (1970) compared kinematic cascade solution with kinematic solution for overland flow on a converging watershed surface. The replaced a converging overland surface by a series of rectangular planes with decreasing width, while a complex continuous overland slope was represented by a series of discrete planes with individually uniform slopes. Sherman and Singh(1976a and 1976b) and Singh (1976b and 1976c) also dealt with converging overland flow in their study.

Singh and Woolhiser (1976) presented analytical and numerical solutions for the surface runoff hydrographs from a linearly converging section with kinematic flow to test its usefulness as a model for predicting peak discharge.

For the geometry of the converging section shown in Figure 10, the continuity equation has been written by Veal(1966). From this figure, apparently the converging section has four geometric parameters L_o , γ and S_o, where L_o is length of the section; S_o is the slope, γ is parameter related to the degree of convergence and θ is interior angle. Because of radial symmetry, θ does not affect the relative response characteristics, only the watershed area must be preserved and is, therefore, dependent on L_o and γ.

Some of the interesting features of the converging section are:

(1) Its discrete analog is a system composed of a cascade of unequal non-linear reservoirs (a system view)

(2) Its response is similar to that of a cascade of planes of decreasing size.

(3) The convergence may account for the concentration of runoff at the mouth of natural watersheds.

The continuity equation for the converging geometry shown in figure 10 can be written as:

$$\frac{\partial h}{\partial t} + \frac{\partial (uh)}{\partial x} = q\ (x,t) + \frac{uh}{L_o - x} \qquad \ldots(44)$$

and the kinematic approximation to the momentum equation:

$$Q = \alpha\ h^N \qquad \ldots(45)$$

where, h= local depth of flow, u=local mean velocity, Q=rate of outflow per unit width, q(x,t)=rate of lateral inflow, x and t are space and time co-ordinates respectively and N and α are kinematic wave function relationship parameters. Singh and Woolhiser (1976) have introduced normalizing quantities to make equations dimensionless. After substituting dimensionless variable (Singh and Woolhiser, 1976), the above two equations reduce to:

$$\frac{\partial h^*}{\partial t^*} + U^* \frac{\partial h^*}{\partial x^*} + h^* \frac{\partial u^*}{\partial x^*} = q^*(x,t) + \frac{(1-\gamma)u^*h^*}{1-(1-\gamma)x^*} \qquad \ldots(46)$$

and

$$Q^* = h^{*N} \qquad \ldots(47)$$

And the following kinematic wave equation is obtained after substituting equation (47) into (46)

$$\frac{\partial h^*}{\partial t^*} + Nh^{*N-1} \frac{\partial h^*}{\partial x^*} = q^*(x,t) + \frac{(1-\gamma)h^{*N}}{1-(1-\gamma)x^*} \qquad \ldots(48)$$

Singh and Woolhiser presented analytical and numerical solution to the above equation. They calculated rainfall excess based on Philip's (Philip, 1957) infiltration equation.

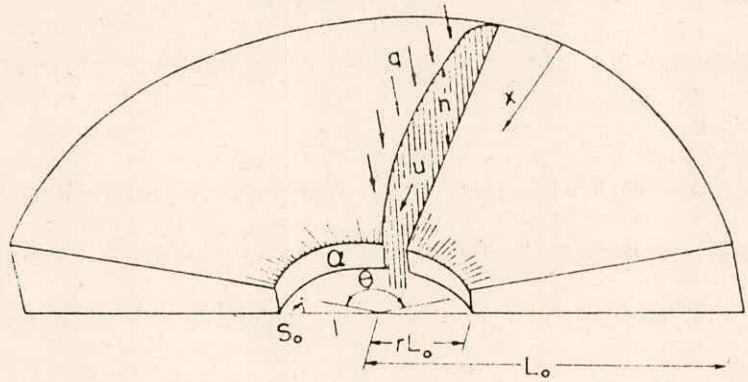

Fig.10. Geometry of Converging section (reproduced from Singh and Woolhiser, 1976)

2.7.2.3 Diverging overland flow models

There are many watersheds in nature which diverge in shape. These have an appearance converse of that of converging watersheds. The flow on these watersheds is radially outwards, converse of that on converging section. There are also many watersheds whose upland portions diverge and lower portions converge. If the watershed is diverging and converging then coupling of diverging section with a converging section may be desirable to represent it. However, if, in a complex watershed, a portion is diverging, then it would be desirable to include the diverging section of a network model to represent it.

The diverging overland flow does not appear to have been investigated before 1981 when Singh and Agiralioglu (1981a and 1981b) in a sequence of two papers, presented the analytical solutions for a diverging geometry for two cases: (1) when infiltration is considered through rainfall excess, and (2) when infiltration s treated concurrently with runoff. They utilised the kinematic wave theory to investigate the diverging overland flow. The important features of diverging overland flow which leads to the application of kinematic wave theory are:

(1) Its discrete analog is a system composed of a cascade of unequal non-linear reservoirs (a system view)

(2) Its response is similar to that of a cascade of planes of increasing size.

Singh and Agiralioglu used the diverging geometry in order to transform the geometric complexity of the natural watersheds into a simpler one and tested its hydrologic response. The diverging geometry

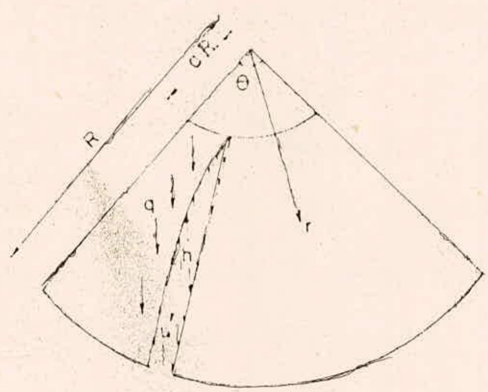

Fig.11 : Diverging Geometry(Reproduced from Singh and Agiralioglu, 1981)

is shown in figure 11, where R denotes the length of the section a. The parameter related to the degree of divergence, θ , the interior angle and S_o the ground slope. Therefore R(1-a) is the length of flow. Because of radial symmetry θ does not affect the relative response characteristics, only the watershed area must be preserved. It is therefore, dependent on R and a.

For unsteady non-uniform flow over a diverging surface, the equations of continuity and momentum (Singh and Agiralioglu, 1980 and 1981) on a unit width basis are:

Continuing equation:

$$\frac{\partial h}{\partial t} + u\frac{\partial h}{\partial r} + h\frac{\partial u}{\partial r} + \frac{uh}{r} = q(r,t) - f(r,t) \qquad \ldots(49)$$

and the kinematic approximation to the momemtum equation:

$$Q = (r, h)\, h^N \qquad \ldots(50)$$

where,

h = local mean depth of flow

u = local mean velocity

Q = rate of outflow per unit width

q(r,t)= rate of lateral inflow or rainfall

f(r,t) = rate of infiltration

r and t = space and time coordinates respectively and N and

α = Kinematic friction relationship parameters.

Combining equations (49) and (50) with constt.

$$\frac{\partial h}{\partial t} + N\,\alpha h^{N-1}\frac{\partial h}{\partial r} = q(r,t) - f(r,t) - \frac{\alpha h^N}{R} \qquad \ldots(51)$$

Equation (51) is the basic governing equation.

Singh and Agiralioglu (1981a) derived explicit analytical solution to the above equation of diverging overland flow. They also compared diverging and converging overland flow models by using the experimental data of Langford and Turner (1973) which were observed on a rectangular plane 4.572 m wide and 22.86 m long. It has impervious bitumen paved surface with a slope S_o=0.01. The rainfall intensity was 0.06 m/hr. and equilibirum discharge of 1742 cm^3/sec. For this data, the diverging

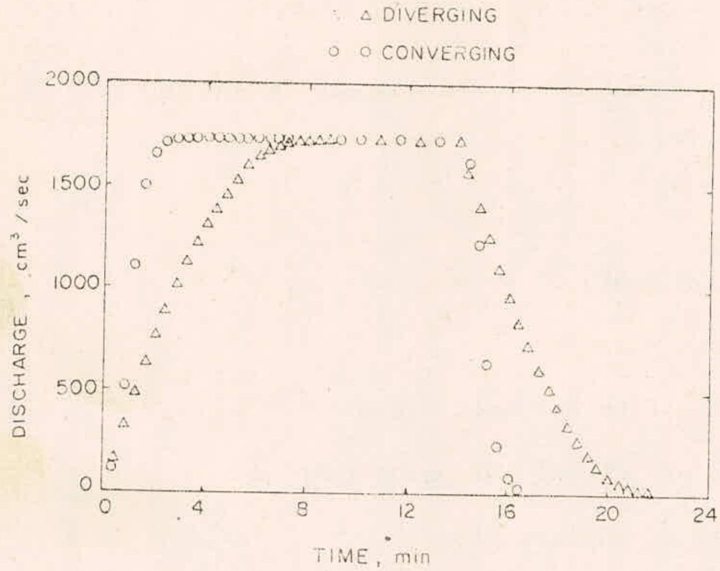

Fig.12: Comparison of diverging and converging overland flow models (Reproduced from Singh and Agiralioglu, 1981)

and converging overland flows are shown in figure 12. It is clearly visible that the time of concentration for diverging overland flow is more. Also, the diverging model recedes slower than does the converging model. These differences are compatible with geometric differences.

Singh and Agiralioglu (1981b) applied the above model to several natural watersheds and examined its ability to predict surface runoff from these watersheds. They used the Lax-Wendroff scheme to obtain numerical solutions. The diverging geometry is specified from watershed topography. Rainfall excess was determined using Philips equation (Philip, 1957). Their diverging overland flow model has only one parameter, which was estimated using the modified Rosenbrock algorithm. From the comparison of observed and computed hydrographs it is seen that on the whole, the relative error stays within 35% in prediction of hydrograph peak and within 35% in prediction of hydrograph peak time. They concluded that the model is potentially promising and deserves further investigation.

2.7.2.4 Some other models

Smith and Woolhiser (1971a and 1971b) combined the infiltration models with the kinematic equation of overland flow in form of kinematic cascade, with interacting boundary conditions at the soil surface to provide a mathematical model of the generation of overland flow from rainfall on an infiltrating surface. They tested their model both in laboratory and in field. Figure 13 shows two numerically simulated hydrographs compared with data taken from a 40 ft.laboratory soil flume. Simulated and measured hydrographs match quite impressively. The only discrepancy can be seen in figure 13

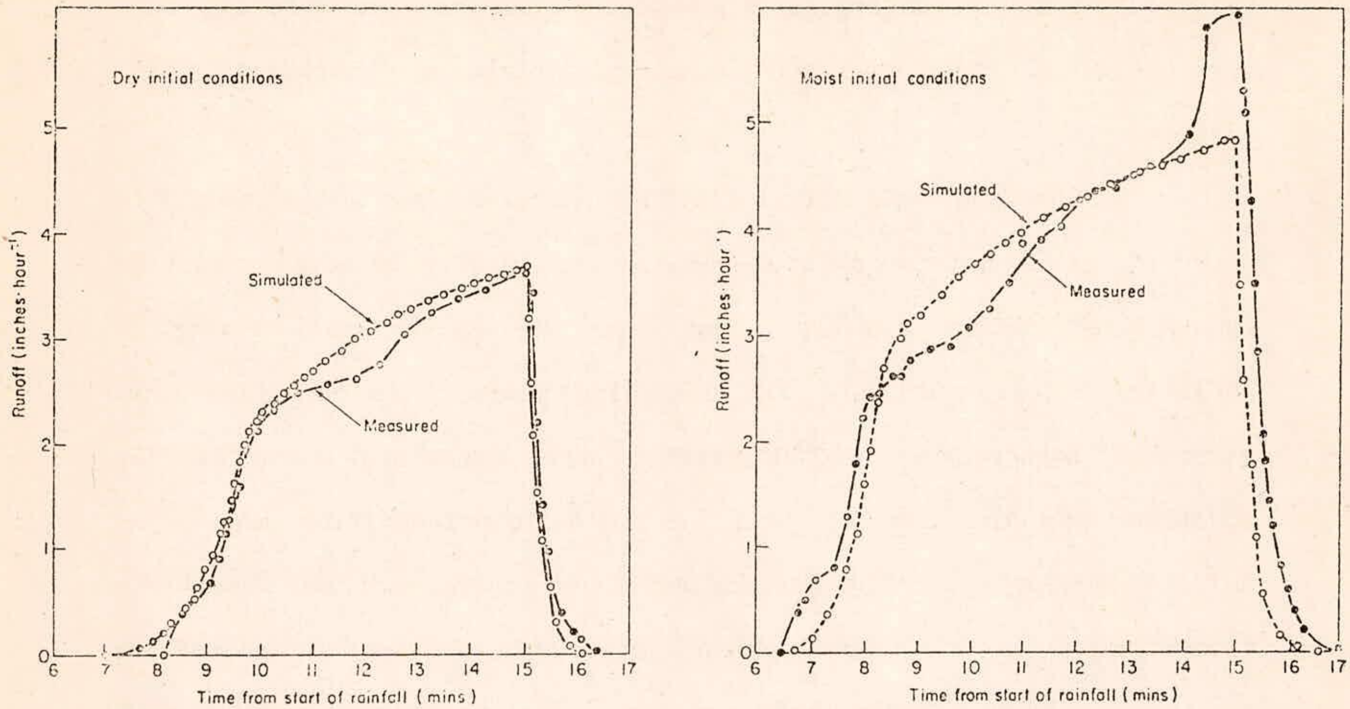

Fig.13: Measured and simulated overland flow hydrographs for laboratory prototype infiltrating slope
(Reproduced from Smith and Woolhiser, 1971b)

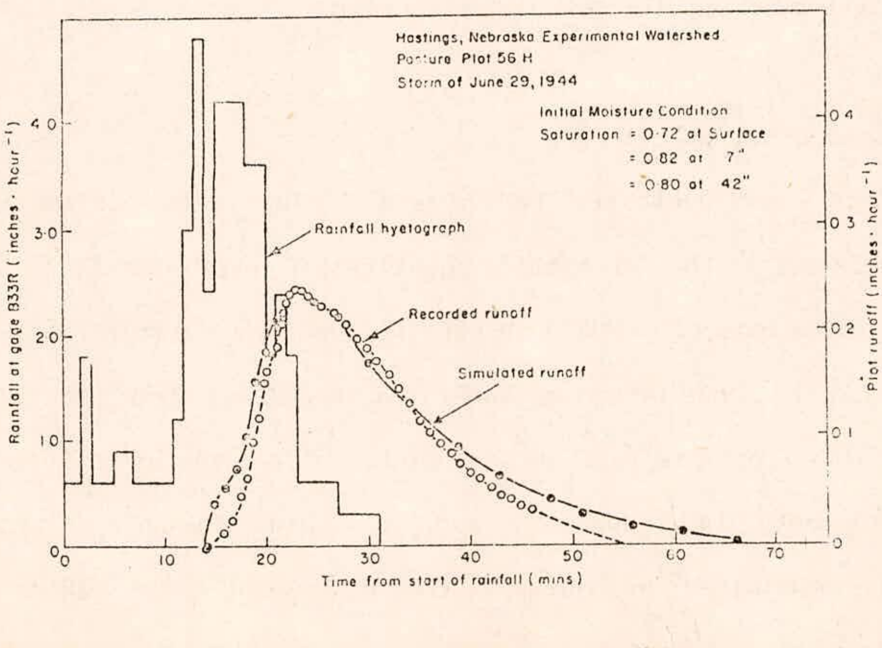

Fig.14: Measured and simulated overland flow hydrographs for a field plot in an experimental watersheds
(Reproduced from Smith and Woolhiser, 1971b)

in runoff near the end of the rainfall event in moist case. The discrepancy may be because of the air entrepment, a phenomenon not accounted for in the model.

The model was also tested against published rainfall-runoff records from field plots in an experimental watershed in Nebraska and simple result is shown in figure 14. The match seems to be quite impressive for field data also.

Lane et al (1975) have examined the effect of non-uniform slope-shape upon overland flow. The arbitrary surface of parabolic nature like convex and concave surfaces are used for an impulse input, which is defined as an input of finite depth occuring instantaneously and is most powerful in detecting the influence of slope shape. The proposed goodness of fit statistics shows that effect of slope shape upon peak rate of runoff is more pronounced for laminar flow. When cascade of plane approximation is used to examine the complex slope shape upon overland flow, it is found that for convex surfaces, two planes are sufficient to duplicate the discharge from parabolic surfaces but the hydrographs are not well reproduced. However, for concave surfaces, the peak discharges come closer to the theoretical values as the number of planes in the cascade is increased. They also extended the model to field datas to study the influence of slope shape upon overland flow and concluded that the concave watersheds produced a more delayed response when compared with convex watersheds but the peak discharges were not significantly affected.

Lane et al (1975) also investigated the effect of distortion in some of the characteristic which are impossible to be preserved in models, like stream order, drainage density, topographic roughness etc. (see fig.15 and 16). The drainage density and geometric simpli-

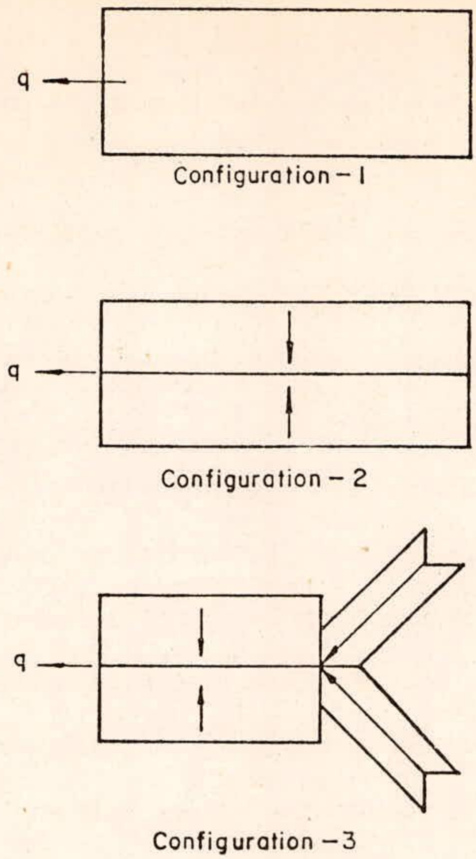

Fig.15:Example configurations for simulation study of the effects of distortions in drainage density.(Reproduced from Lane et al, 1975)

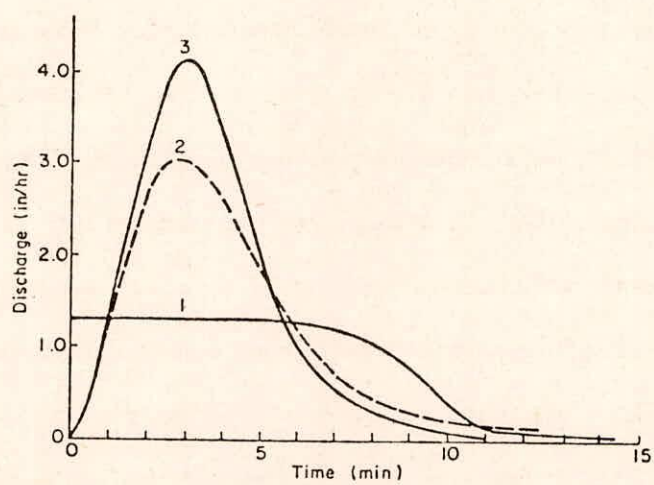

Fig.16:Impulse responses for the three test configurations at shown in Fig.15. (Reproduced from lane et al, 1975)

fication of figure 15 are shown in Table 4.

Table 4. Geometric Simplification and drainage density corresponding to three test configuration shown in Fig.15.

Test Configuration No.	Geometric Simplification	Drainage Density ft/ft^2
1	Single plane	0.00
2	Two planes and one channel (wooding model)	0.005
3	Six planes and three channels	0.007

They concluded that in modelling watersheds, if the drainage density is underestimated then the lag time and the peak discharge will be overestimated.

Numerous investigators have examined the influence of drainage density upon surface runoff. Some of them related lag time to area, slope and drainage density.

Datta(1979) studied the effect of steepness of slope and initial soil moisture on the peak discharge and overland flow hydrograph. He found that for catchments having same length and same initial soil moisture under same intensity and duration of rainfall, the catchment having steeper slopes has higher overland flow. The rate of increase in the rising stage and the rate of decrease of discharge in the recession stage of hydrograph for catchment having steeper slopes is more than that for catchment having milder slope. Peak discharge is more for catchment having steeper slope, when time of rainfall, tr, is less than time of concentration, te.

Freeze (1980) utilised a stochastic conceptual mathematical model of hydrologic process on a hillslope to investigate the influence of spatial stochastic properties of the hillslope parameters on the statistical properties of resulting runoff events. The model used in this analysis is conceptual because it utilizes a set of physically based equations to route rainfall events through a hillslope. It is stochastic because the rainfall events and the hillslope parameters are defined by a set of stochastic processes. The model utilizes a stochastic rainfall generator and allows the generation of overland flow by both the Horton mechanism and Dunne Mechanism.

3.0 REMARKS

In the past few years, considerable progress has been made in the understanding of the mechanism by which precipitation in mountains regions is delivered to stream channels. Overland flow is the first phase of surface runoff generation. The overland flow is both unsteady and spatially varied as it is mainly fed by rain and depleted by infiltration neither of which are constant in time and space. The flow may be either laminar or turbulent or a combination of these two conditions and the depth of flow may be either below or above critical or the depth may change from sub-critical to super critical. The physical laws required in hydrodynamic approach to overland flow modelling are the equations of continuity and momentum. The main problem associated with this approach is the difficulty in solving the equations of motion because of its non-linear behaviour. There has been significant progress in the development of substantial simplification of flow equations namely the kinematic wave approximation. By now it is well established that the approximation can be made under almost all conditions of overland flow.

To apply the kinematic wave equation to practical situations, one need to decide on the method of spatial representation of watershed and an appropriate model for infiltration. Also, appropriate parameter for hydraulic resistance and porous media characteristic needed to be established. Stable and consistent numberical scheme is essential for the solution of kinematic wave equation.

The review reveals that the kinematic wave approximation is best for rough and steep slopes. But it is found that the slope encountered in most of the overland flow models is not more than 0.1. The lack of application of models to the Indian mountainous watersheds is also felt. Jayaseelan (1984, 1985) applied kinematic cascade model to Wirpen Nulla, a tributary of Wardha river in Godavari basin, wherein land slope is only 0.03.

The description of overland flow on natural hillslopes is beset with many problems primarily since the hydraulic parameters vary rapidly over time and space. The mathematical models could be made to perform better if more objective technique are developed to describe the variation in hydraulic parameters and topographic features.

For this purpose, further research needs to be oriented towards:

(i) Obtaining better timing relationships between rainfall, rainfall excess and runoff;

(ii) Obtaining more accurate rainfall excess estimates, particularly with respect to initial abstractions and temporal variations caused by the action of different processes varying in space;

(iii) Collecting data associated with soil properties; and

(iv) Development of émpirical relationships between geometry and hydrograph characteristics.

These studies would help in generalization of hydraulic flow parameters. Laboratory experiments may also be conducted to generalise the effect of geomorphological and land cover parameters on overland flow. An infiltration function wherein a block of rainfall divided into infiltration and rainfall excess provides input to a routing model is an oversimplification. One infiltration equation may be necessary during rainfall when the entire area is active and another after rainfall when the rills and microrills are still active but the interrill areas of overland flow are not. The procedure may be a logical starting point.

In any event, if the errors due to distortions in geometric simplification can be quantified, then it may be fruitful to begin quantifying the errors due to oversimplification in estimated rainfall excess. A second step in attacking the problem might be via a calibrated simulation model. Also, since drainage density is a measure of all channels in area, it may prove to be an important parameter in studying rill infiltration, as suggested by Foster and others.

Data collection on experimental watersheds should be oriented towards the hydraulic soil properties important in infiltration, rather than the traditional description as given by soil chemists and agronomists. The analyses of soil shall aim at developing relations between moisture tension, saturation, and unsaturated conductivity. Field measurements of saturated conductivity are also very important and remote sensing offers ample hope for the future, by which surface and near surface saturations could be obtained on a large scale. Such models incorporating current knowledge of the physical processes involved could be applied to study the overland flow component of watershed surface runoff.

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