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HYDROLOGICAL ASPECTS OF WATERSHED DEVELOPMENT

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1.0 Introduction

A Watershed is the natural base for studying and modelling the terrestrial system, because the inputs and outputs are defined and quantified, and second the integrated system responses are determinant (Swift and Cunningham, 1986). Watershed , which is the locus of those points from which runoff, reaches the outlet of the stream, is a natural geographical unit with a certain extent of homogeneity and uniformity. This natural unit is easily visualised in a mountain setting whose boundaries for precipitation, evaporation, and subsurface flow are clearly defined by topography. Also, it is an open physical system in terms of inputs of precipitation and solar radiation and outputs of discharge, evaporation and re-radiation. The inter-dependent nature of land and water resources thus necessitates the consideration of watershed as the basic unit in developing planning and the reasons for that include, (i) from the ridge lines everything runs downhill, (ii) this not only include water, soil and pollutants, but also most generally includes transportation route like roads, railroads, and, of course, rivers, (iii) one of the few thing which generally moves uphill is the population. As population density increases and as land resources become scarce the population expand into the upper parts of the watershed (but remains within the watershed boundaries), (iv) historically cities have grown up around intersection of rivers and river mouths where they spill into bays and oceans, (v) watershed are contiguous and therefore will aggregate to larger units.

1.1 Watershed

A watershed is a drainage basin enclosed by a ridge line or divide line. It is an area from which runoff flows past a single point into a stream. Land, water and vegetation are the important natural resources in a watershed. The basic unit for development of water, fuel, fodder, livestock and all associated components is a watershed, which is a manageable hydrological unit. The deterioration of natural resources can be contained and the total resources can be properly developed only by adopting the watershed approach. In this approach, development is not confined just to agricultural land alone, but covers the starting from the ridge line to the outlet of the nalah or the natural streams, All types of lands namely agriculture, forests and waste lands are treated as per need with appropriate measures combined with erosion and water storage structures.

The concept of watershed as a planning unit for development of land and water resources is available since long but the watershed approach has gained importance since 1974 when the Ministry of Agriculture, Government of India initiated the programmes of Soil and water Conservation, Drought Mitigation Measures, Dry Farming, Flood Control and Hill Area Development etc. on watershed as a planning unit. Presently watersheds form the basis of presenting natural resources data for effective planning and optimum development of land and water resources. Planning of watershed development depends on their scientific delineation. The All India Soil and Land Use Survey has prepared Watershed Atlas of India. The entire country has been divided into 6 major water resources regions namely (i) rivers falling into Arabian Sea except Indus System, (ii) The Indus Basin in India, (iii) rivers falling into Bay of Bengal other than the Ganga and Brahmaputra Systems, (iv) The Ganga System, (v) The Brahmaputra System and Rajasthan), 35 river basins (mean size 50,000 Km^2 plus minus 50%), 112 catchments, 500 subcatchments and 3237 watersheds (mean size 500)

1.2 Need of Watershed Development

On the hill side, erosion selectively removes the clay particles and organic materials which are the constituents that store nutrients in a form available to plants. In addition to removal of plant nutrients, the removal of loose topsoil, which has good infiltration, water holding and rooting characteristics, is damaging. The total cost of accelerated soil erosion, either in monetary terms or in human suffering, has never been calculated and probably could never be (Dunne and Leopold,1978). Soil erosion has been recognised as a, (i) major threat to the continued productivity of the land, (ii) source of water pollution, (iii) cause of non-availability of water in subhumid tropical region.

Many watershed development programme have been launched in our country to

- prevent premature siltation of the reservoir,
- restore degraded catchment,
- improve status of land productivity,
- improve the soil moisture regime and enhanced ground water recharge,
- moderate peak flow and runoff volume of watershed, and
- control water pollution.

The effects of soil erosion are not only felt on site but also on downstream. Deposition of eroded sediment in reservoirs and harbours incurs heavy cost's for maintenance; sedimentation within the stream channel damages fish life and can ruin their spawning habitats; the conveyance capacity of the channel can also be reduced temporarily by this deposition, with increased frequency of over bank flooding.

In many regions of the world, the soil erosion problems have cropped up due to growing population. Every available piece of land is used to produce food. Limited remnants of forest on steep slope of important catchments are being invaded by agriculture, which soon generates rapid sheet and gully erosion. In an analysis made in 1983 by Dhruva Narayanan and Ram Babu (Narayana et.al, 1990), it was estimated that about 5333 million tonnes of soil is detached annually, and of this about 20% is carried away by the rivers into the sea. Nearly 10% of it is being deposited in our surface reservoirs resulting in a loss of 1 to 2% of the storage capacity. According to Singh et al. (1990), out of the total eroded materials from Indian river catchments nearly 1572 million tonnes are being washed into sea while 480 million tonnes are getting deposited in various reservoirs in India.

1.3 Hydrology of Small Watersheds

Estimation of runoff and sediment from a watershed requires modelling larger components if not the entire hydrological cycle. The variables which describe the physical state of a watershed system are (i) watershed size,(ii) slope and roughness characteristics, (iii) erodibility and (iv) texture of soil. These are known as system parameters. The variables which affect the state of the watershed system are (i) temperature, (ii) radiation and (ii) vegetation cover. These are known as state variables.

Rain, and litter contributions are the input variables. The response of the system is hydrograph and pollutograph comprising of water, sediment and nutrients. Zones that produce storm runoff also yield sediments, plant nutrients, bacteria and other pollutants. An understanding of the storm runoff production indicates the process by which these components reaches stream and also directs the management practices that might be used to regulate the discharge of these materials. To understand the basis of erosion process, it is necessary to know the various modes of surface runoff generation. In nature , surface runoff is generated by a variety of surface and near surface flow process.

1.4 Soil and Water Conservation Measures

Cultivation on steep slopes in humid regions without protection measures often causes serious watershed problems. The results are not only deterioration of the productivity of land 'on site' by water erosion but also aggravation of the silting and flood damage 'off site'. The problem is further compounded as the cultivators of steep slopes are mostly poor small farmers. The dilemma is always there; on one side resettlement and changing of land use may not be feasible from socioeconomic stand point; on the other side land and water resources of the hilly region are under constant threat by such cultivation.

By applying terracing and protected waterways, the steep slopes can be cultivated safely and profitably. There are essentially four types of bench terraces i.e., level, outward sloped, conservation bench, and reversed sloped. The outward slopped terraces and conservation benches are for arid and semi-arid regions. Reverse slopped terraces are suitable for slopes between 70 to 300 in humid regions. Six types of reversed slope terraces have been suggested (Sheng, 1977, vide FAO conservation guide, 1986). These are (1) bench terraces, (2) hill side ditches, (3) individual basins (4) orchard terraces, (5) mini-convertible terraces, and (6) and hexagons.

The treatment measures on agricultural land usually consist of bunding, terracing, levelling, contour cultivation and improved moisture conservation. For Non-agrictiltural lands afforestation, development of pasture and grassland are done.

Various types of water harvesting structures, percolation ponds, silt detention dams, check dams, nalla plugging and gully control structures are integral part of agricultural and Non-agricultural land treatment (Singh et al., 1990)

1.3 Objective of the present study

The objective of the present report is to describe various watershed models in details including data requirement, input, output, various physical process and governing equation. The suitability of particular model to Indian condition is also have been highlighted in this report.

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2.0 Watershed components

Land and water are the basic component of a watershed and for optimum utilisation of land and water resources in any area, an integrated watershed development approach is considered to be the most ideal as it helps in maintaining the ecological balance (Sahai, 1988). The micro-level assessment and monitoring of resources, identification of constraints, ecological problems and adoption of effective management practices are important for integrated sustainable development of land and water resources and for watershed management (Dhruvnarayan et. al.,1990). In an integrated watershed development approach, rainfall, runoff, soil erosion and sediment yield are various hydrological components of watershed to be processed. In areas where there is soil erosion and sediment yield problem resulting from excessive rainfall, a quantitative information on these hydrological aspects are often not available. Numerous models have been developed to predict runoff, erosion, and sediment from field and watershed under various condition. The integrated use of GIS, Remote sensing and various watershed models is an emerging trend, for assessing not only a quantitative information on theses hydrological aspects but also in making effective planning and in optimum development of land and water resources in a sustainable manner.

2.1 Watershed Characteristic

Watershed or Drainage basin may be defined as the area which contributes water to a channel or set of channels. It is the source area of the precipitation eventually provided to the stream channel by various paths. It provides a limited unit of the earth surface within which basic climatic quantities like temperature, humidity, net radiation, wind velocity and hydrologic quantities like rainfall, runoff, soil erosion, soil moisture, evaporation can be measured and their effect on Watershed Characteristics can be determined. It can be expressed as.

$F = f(p.m)\ dt$
f = Behaviour of watershed
p = Process occurring on Watershed
m = Materials present in watershed
dt = Change with respect to time

The following are major watershed characteristics of great significance (i) Size of area of the drainage basin, (2) Shape of the drainage basin, (3) Length of the drainage channel, (4) Slope of the drainage channel and (5) Soil cover complex.

The larger size of the basin, the greater the amount of rain it intercepts and higher the peak discharge that results. The rational formula of predicting runoff rate is

$q = .0028\ CiA$
C = runoff coefficient depending upon soil cover & hydrologic conditions
i = rainfall intensity in mm/hr
A = watershed area in ha

q = runoff rate in m^3/sec.

Size or Area of the Drainage Basin :

The area of the drainage basin is its most important physical characteristics because it directly affects the size of the storm hydrograph and magnitude of runoff . The area is actually the horizontal projection of the land surface from which runoff into the channels occurs. Topographic maps, aerial photographs are used for determining the size of a watershed. Those area which are not contributing runoff to a watershed must be omitted from the area for which sometime field reconnaissance is necessary. The size of the drainage area is generally expressed in acres, hectares, sq. miles or sq. kilometres. The relationship between various unit are.

1 Square Kilometre = 0.386 square miles
1 Square Kilometre = 100.0 hectares
1 Square Kilometre = 247.1 acres
1 hectare = 2.471 acres

Schulz (1976) described the following methods for the determination of the area of a drainage basin from the available toposheets of the basin, (a) Estimation, (b) Planimeter, (c) Dot Grid, (d) Strip sub division, (e) Geometric subdivision, (f) Analog to digital converter.

Shape of the Drainage Basin :

The shape or outline form of a drainage basin, as it is projected upon the horizontal datums plane of a map may, to a large extent, affect stream discharge characteristics. Long narrow watersheds are likely to have lower runoff rates than more compact watersheds of the same size. The runoff from the long narrow watershed does not concentrate, as quickly as it does from the compact areas and long watershed are less likely to be covered uniformly by intense storms. When the long axis of a watershed is parallel to the storm path, storms moving upstream cause a lower peak runoff rate than storms moving downstream. For storms moving upstream runoff from the lower end of the watershed is diminished before the peak- contributes from the headwaters arrives at the outlet. However a storm moving downstream cause a high runoff from the lower portions coincident with high runoff arriving from the headwaters.

The shape of the drainage basin can be expressed in terms of shape index, defined as the ratio of the basin length to the square root of the basin area,

$$S_i = \frac{L}{\sqrt{A}} = \frac{L^2}{A} = \frac{L}{W}$$

where

Si = Shape index,
L = Length of the watershed along the main stream, and

W = average width of the watershed or A/L

The most commonly used basin shape factor is LC_a often defined as the distance along the main drainage channel from the point of interest to a point opposite the computed centre of gravity of the drainage area. In other words, LC is the length measured up the stream channel from the base of the drainage are to a point corresponding to the centroid of the area. For most basins LC_a = 0.5L i a good approximation.

Miller (1954) introduced basin circulatory ratio and defined it as the ratio the basin area to the area of a circle having a circumference equal to the perimeter of the basin, i.e.

$$R_c = \frac{Ab}{Ac}$$

where

R = Circulatory ratio
Ab = Area of the basin, and
Ac = Area of circle having the same length of perimeter as the basin

This expression has a value of unity for a circular basin while for two basin the same size, the runoff will be more for the one with the smallest circulatory ratio.

Schumm (1954) used an elongation ratio, R_e defined as the ratio of diameter of a circle of the same area as the basin to the maximum basin length The value of the elongation ratio approaches one as the shape of a drainage basin approaches a circle. Systematic description of the geometry of a drainage basin and its stream channel system requires measurement of linear aspects of the drainage network areal aspects of the drainage basin and gradient aspects of channel network an contributing ground slopes.

2.1.1 Linear aspects of the drainage network

Stream orders:

The first step in drainage basin analysis is the designation of stream orders which is a measure of the position of a stream in the hierarchy of tributaries. Hortan (1945) introduced a classification system in which the first order streams are those which have no tributaries whereas the largest channel in a basin was assigned highest stream order. The second order streams are those whose tributaries are only of first order, whereas third order streams receive both first and second order tributaries and it also is considered to extend headward to the end of the longest tributary as shown in Fig.2.1. Strahler (1964) also adopted the same scheme for ordering streams. The main disadvantage of this system is that it violates the distributive law, in that the entry of a lower order tributary stream does not always increase the order of the main stream. Shreve (1966) has proposed a simple remedy for this by dividing the network into separate link at each junction and allowing the magnitude of each

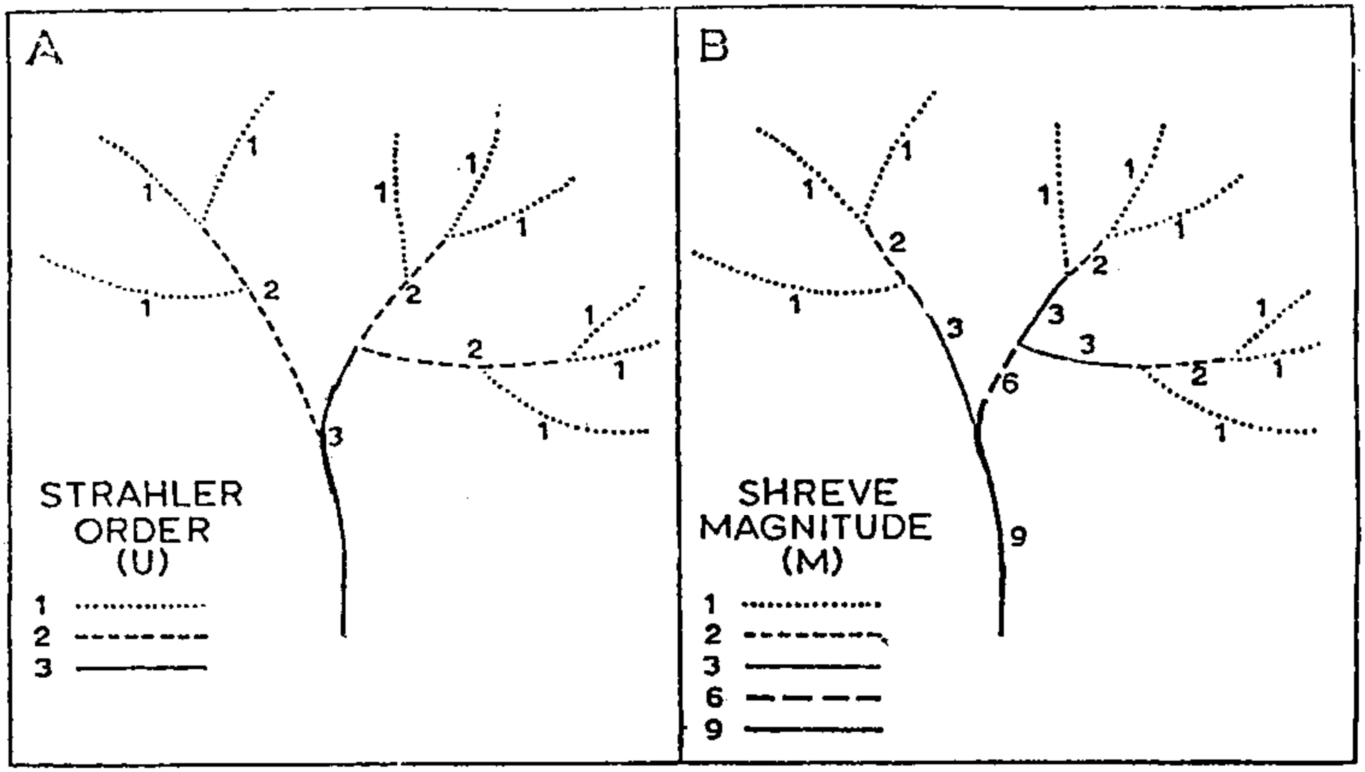


Figure 2.1 : Stream order as proposed by Strahler and Sherve

link to reflect the number. of first-order streams ultimately feeding it.

Bifurcation ratio :

The ratio of number of segments of a given order Nu to the number of segments of higher order. Nu+ 1 is termed as Bifurcation ratio, Rb

$$Rb = \frac{Nu}{Nu+1}$$

The bifurcation ratio will not be the same from one order to the next because of variation in watershed geometry but tend to be a constant through the series. This observation is the basis of Horton's law of stream numbers which slates that the number of stream segments of each order form an inverse geometric sequence with order number

$$N_u = Rb^{k-u}$$

where k = the order of trunk segment

The bifurcation ratio provides some measure of stream segments tendency to divide. If it is assumed that the precipitation and other controlling factors are same throughout, then the elongated basin with high bifurcation ratio would yield a low but extended peak flow and the round basin with low bifurcation ratio would produce a sharp peak as shown in Fig.2.2. Bifurcation ratio characteristically range between 3.0 and 5.0 for watershed in which the geologic structures do not distort the drainage pattern. The theoretical minimum possible value of 2 is rarely approached under natural conditions.

Average Stream Length :

The mean length of channel Lu of order u is the ratio of the total length divided by the number of segment Nu of that order, thus

$$L_u = \sum_{i=1}^{N} \frac{L_u}{N_u}$$

Horton (1945) postulated that the length ratio (RL) which is the ratio of mean length Lu of segments of order u to mean length of segments of the next lower order, Lu-1, tends to be constant throughout the successive orders of a watershed He was therefore able to state the law of stream lengths, which states that the average lengths of streams of each of the different orders tend to approximate a direct geometric series in which the first term is L, such that

$$L_u = L_1 R_L^{u-1}$$

where

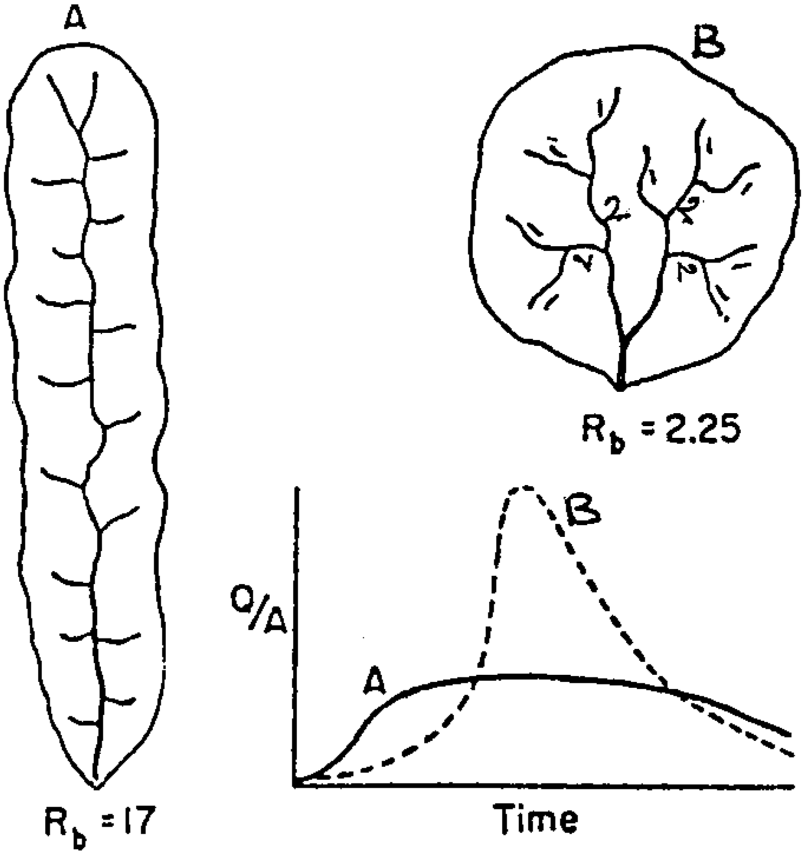


Figure 2.2 : Elongated basin (A) with high Rb value will yield a low but extended peak flow as compared to Round basin (B) with low Rb value having sharp peak.

L_1 = average length of first order streams
Lu = average length of stream of order u
RL = constant called the stream length ratio

Total length of Channel :

Horton (1945) was the first to use the total length of all channels as morphometric measure, as it is related to channel storage. He observed that law of stream numbers & lengths can be combined as a product to yield an equation for the total length of channels of a given order **u**, knowing the bifurcation and length ratio and the mean length L_1 of the first order channel segments.

$$\sum_{i=1}^{N} L_u = L_1\ R_b^{\,k-u}\ R_L^{\,u-1}$$

Total length of all channels is computed by summing the lengths of all stream reaches.

Length of overland flow :

Length of overland flow is one of the most important independent variables affecting both the hydrologic and physiographic development of drainage basins. Horton (1945) defined length of overland flow, Lg, as the length of flow path of nonchannel flow from a point on the drainage divide to a point on the adjacent stream channel. Because the number of starting points; on a basin perimeter, is infinite, the choice of flow path represent the length of overland flow must be specified. An average length can be computed from measurement of a number of paths emanating from points uniformly spaced around the entire basin perimeter. A maximum length can be obtained for any given first order basin by taking the longest possible flow path contributing to the tip of the first order channel. This parameter is approximately one half the reciprocal of the drainage density i.e. $L_g = 1/2D$.

Interbasin Length :

The maximum horizontal length measured from the basin mouth to the most distant point on perimeter is termed as interbasin length, L0.

$$\sum_{i=1}^{N} \frac{HN}{N}$$

Drainage density:

The drainage density, D is simply the ratio of total channel segment lengths cumulated for all orders within a basin to the basin area

$$\sum_{i=1}^{K}\ \sum_{i=1}^{N}\ \frac{L_u}{A_u}$$

Dimensionally this ratio reduces to the inverse of length. It may be thought of as an expression of the closeness of spacing of channels. In general, low drainage density is favoured in regions of highly resistant or highly permeable subsoil materials, under dense vegetative cover and where relief is low. High drainage density is favoured in regions of weak or impermeable subsurface , materials, sparse vegetation and mountainous relief. Drainage density is a textural measure of a basin which is generally independent of basin size. It is considered to be function of climate, lithology & stage of development. Numerically this ratio expresses the number of miles of channel maintained by a sq. mile of drainage area,

Constant of Channel Maintenance :

Schumm (1954) introduced constant of channel maintenance as the ratio between the area of a drainage basin and total length of all the channels.

$$C = \frac{1}{D}$$

or it is equal to the drainage density. The importance of this constant is that it provides a quantitative expression of the minimum, limiting area required for the development of a length of channel.

Channel frequency :

Horton defined the channel segment frequency as the number of streams per unit area in a drainage basin or

$$F = \sum_{i=1}^{K} \frac{N_u}{Ak}$$

where $\sum_{i=1}^{k} N_u$ is the total number of segments of all orders within the given basin of order K & Ak is the area of that basin in square miles.

Metton (1958) analyzed in detail the relationship between drainage density and stream frequency. As shown in Fig.2.3. It is possible to construct two hypothetical drainage basins having same drainage density but different channel frequency, and on the other hand, it is possible to have two basins of the same frequency but different density. Melton tested this possible range of variation by plotting F versus D curve for 156 drainage basins covering a vast range in scale, climate, surface cover and geologic type, as shown in Fig.2.4. The relationship of density to frequency tends to be conserved as a constant in Nature. He derived the dimensionally correct equation and from this dimensionless number F/D^2.

$$F = 0.694\ D^2$$

which tends to approach the constant value 0.694, despite

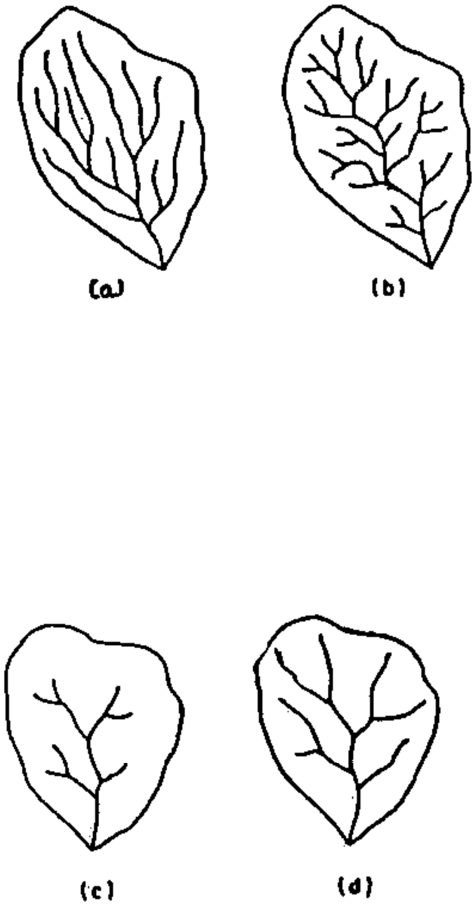


Figure 2·3: Hypothetical basins a and b have the same drainage densities but different stream frequencies; basins c and d have the same frequencies but different drainage densities. (Relationship between Drainage Density and Stream frequency).

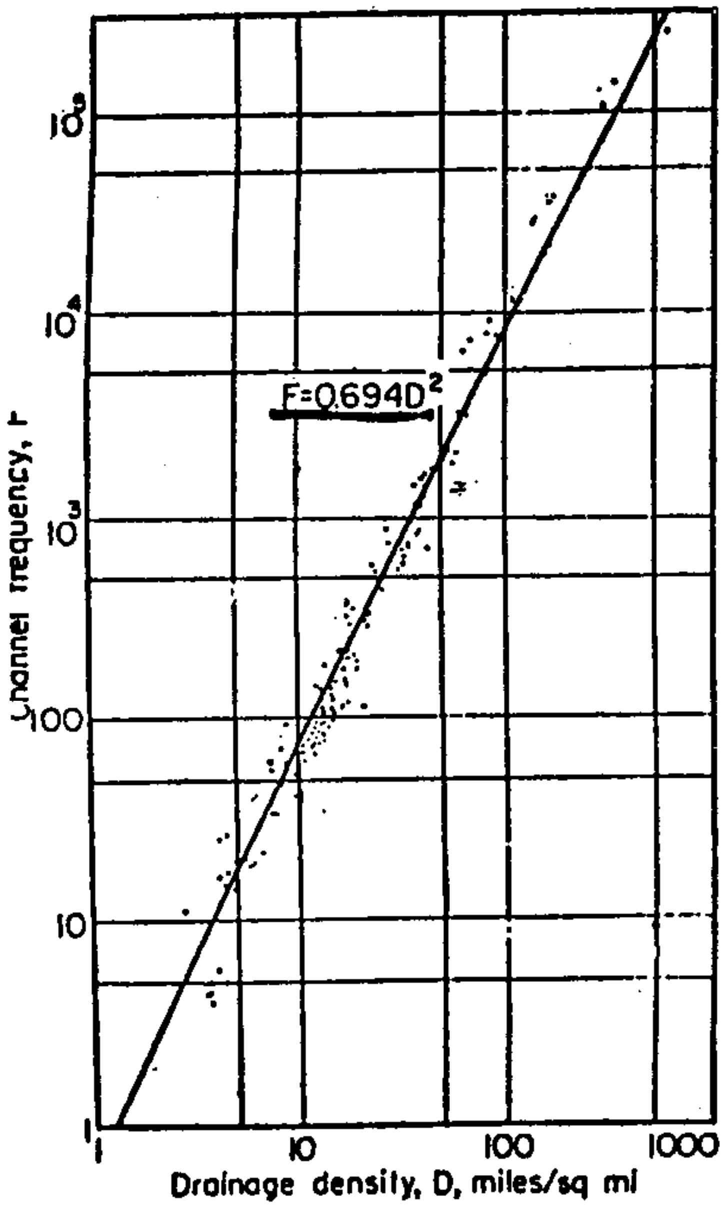


Figure 2.4 : F Vs D for 156 Drainage Basins (Melton 1958)

vast variations in linear scale.

2.1.2 Relief (Gradient) Aspect of Drainage Basins & Channel

The elevation difference between two points in a watershed or along a stream is a very significant variable in the hydraulics of the flow of water from the watershed. The slope is related to rate at which the potential energy of the water at. high elevation in the headwaters of the catchment is converted to kinetic energy. Losses in various forms occur in the process. Water is held in storage and the travel time in the hydrologic system is in general inversely related to the slope.

The average watershed slope in percent may be determined from topographic map by the following equation:

$$S = \frac{MN}{A} X\ 100$$

where

M Total length of contours within the watershed, ft
N Contour interval in feet
A Size of the watershed, ft^2
S Mean basin slope

The mean basin slope influences like form of hydrograph.

Basin Relief (H):

Is the elevation difference between basin mouth and the highest point on the basin perimeter. The total relief of a basin is a measure of the potential energy available to move water and sediment down slope,

Relief Ratio:

It is the ratio between the basin relief and the basin length. It gives the overall steepness of a drainage basin and is an indicator of the intensity of erosion processes operating on slopes of the basin. Possibility of a close correlation between relief ratio and hydrology characteristics of a basin is suggested by Schumm (1956), who found that sediment loss per unit area is closely correlated with relief ratio, as shown in Fig.2.5. The significant regression with small scatter suggest that relief ratio may prove useful in estimating sediment yield if the appropriate parameters for a give climatic conditions are established.

Relative Relief:

Was introduced by Melton (1957) as the ratio of the basin expressed in units of miles, to the length of the perimeter or

100 H

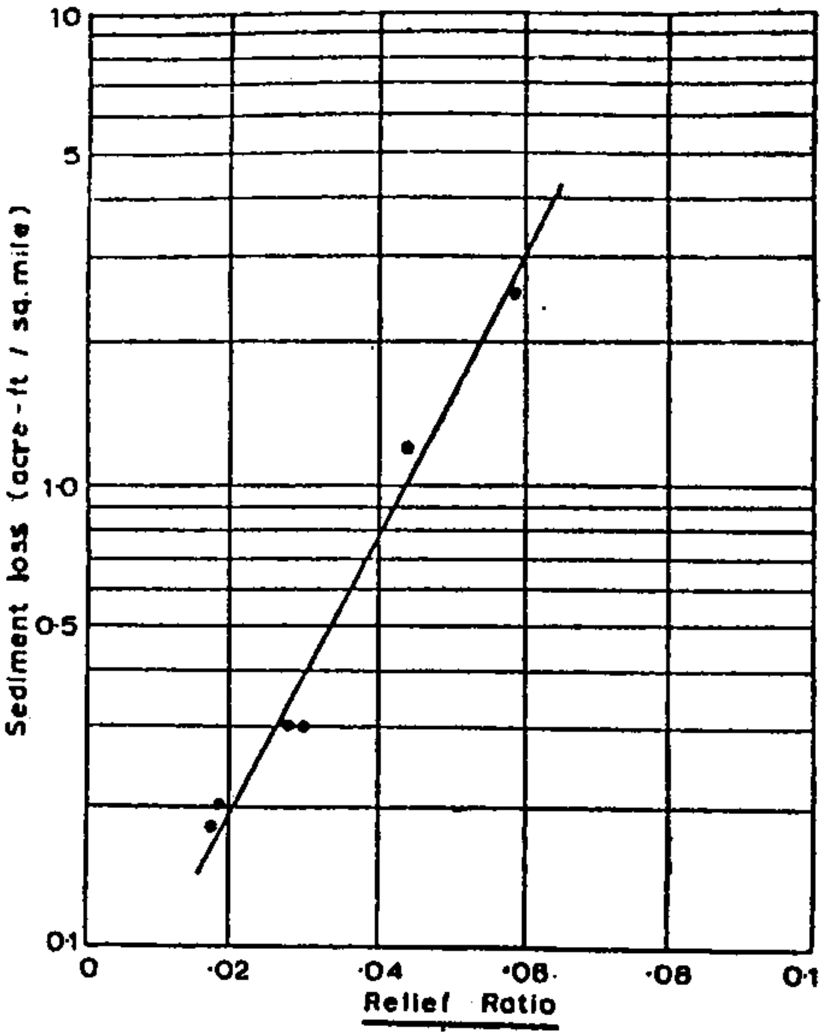


Figure 2·5 : Relation of Sediment loss to relief ratio for six small drainage basins in the Colorado.

Rhp = ------
5280 P

where

H Max. basin belief in feet
P Basin perimeter in miles
Rhp Relative relief in percent

It has an advantage over the relief ratio in that it is not dependent on the basin length which is questionable Parameter in oddly shaped basins.

Ruggedness number:

To combine the qualities of slope steepness and length, a dimensionless ruggedness number HD is defined which is the product of relief H and drainage density D where both terms are in the same unit. Extremely high values of the ruggedness number occur when both variables are large, that is when slopes are not only steep but long as well.

2.1.3 Time of Concentration

The time of concentration of a watershed is the time required for water to flow from the most remote point of the area to the outlet once the soil has become saturated and minor depression filled. One of the most widely accepted method of computing the time of concentration, Tc was developed by Kirpich (1 940).

$$T_c = 0.0195\, L^{0.77}\, S^{-.385}$$

where
Tc = time of concentration in Min
L = max length of flow in meters
S = watershed gradient in m/m

2.1.4 Hydrologic Soil Cover Complexes

The soils and vegetative covers of a watershed are generally classified separately, A combination of a specific soil and a specific cover is referred to as a soil cover complex and a measure of this complex can be used as a watershed parameter in estimating runoff.

Soils :

The hydrologic properties of a soil or a group of soils are an essential factor in the hydrologic analysis of watershed data. Soils can be classified according to their hydrologic properties if considered independently of watershed slope and cover. Four major soil groups are recognized for the primary classification of watershed soils as shown in table 1

Cover :

Essentially cover is any material, usually vegetation, covering the soils an providing protection from the impact of rainfall. Under ordinary conditions detailed information about the cover such as plant density and height, root density and depth extant of plant cover is required. The various type of land use or cover, their hydrologic soil group, treatment or practice adopted & hydrologic condition is given in Table 2.

Table 1 -Major soil groups based on SCS method

Soil group	Description	Final infiltration rate (mmf h)
A	Lovvest Runoff Potential. Includes deep sandswith very little silt and clay, also deep, rapidly permeable losses	8-12
B	Moderately Low Runoff Potential. Mostly sandy soils less deep than A, and loss less deep or less aggregated than A, but the group as a whole has above-average infiltration after thorough wetting.	4-8
C	Moderately High Runoff Potential. Comprises shallow soils and soils containing considerable clay and colloids, though less than those of group D. The group has below average infiltration after presaturation.	1-4
D	Highest Runoff Potential. Includes mostly clays of high swelling percent, but the group also includes some shallow soils with nearly impermeable subhorizons near the surface.	0-1

Source: US Soil Conservation Service, National Engineering Handbook, Hydrology, Section 4(1972) and U.S, Dept. Agr. ARS 41-172 (1970).

Table 2. Runoff Curve Numbers of Hydrologic Soil Cover Complexes for Antecedent Rainfall Condition II and I =0.25

Land Use Group or Cover	Treatment or Practice	Hydrologic Condition	Hydrologic Soil			
			A	B	C	D
1	2	3	4	5	6	7
Fallow	Straight row	-	77	86	91	94
Row crops	Straight row	Poor	72	81	88	91
	Straight row	Good	67	78	85	89
	Contoured	Poor	70	79	84	88
	Contoured	Good	65	75	82	86
	Terraced	Poor	66	74	80	82
	Terraced	Poor	62	71	78	81
Small grain	Straight row	Poor	65	76	84	88
	Straight row	Good	63	75	83	87
	Contoured	Poor	63	74	82	85
	Contoured	Good	61	73	81	84
	Terraced	Poor	61	72	79	82
	Terraced	Good	59	70	78	81
Close seeded legumes or rotation meadow	Straight row	Poor	66	77	85	89
	Straight row	Good	58	72	81	85
	Contoured	Poor	64	75	83	85
	Contoured	Poor	55	69	78	83
	Contoured	Good	55	69	78	83
	Terraced	Poor	63	73	80	83
	Terraced	Good	51	67	76	80
Pasture or range		Poor	68	79	86	89
		Fair	49	69	79	84
		Good	39	61	74	80
	Contoured	Poor	47	67	81	88
	Contoured	Fair	25	59	75	83
	Contoured	Good	6	35	70	79
Meadow (permanent)		Good	30	58	71	78
Woods (farm wood lots)		Poor	45	66	77	83
		Fair	36	60	73	79
		Good	25	55	70	77
Farmseeds		-	59	74	82	86
Roads and right-of-way (hard surface)		-	74	84	90	92

Source: US Soil Conservation Service, National Engineering Handbook, Hydrology, Section 4(1972) and U.S, Dept. Agr. ARS 41-172 (1970).

2.2 Watershed parameters

2.2.1 Precipitation

Precipitation is defined as liquid or solid water that reaches the surface of the earth. It denotes all form of water that reach the earth from the atmosphere. The usual forms are rainfall, snowfall, hail, frost and dew. Of all these only the first two constitute significant amount of water. The magnitude of precipitation varies in space and time. For precipitation to form (1) the atmosphere must have moisture (2) there must be sufficient nuclei present to aid condensation (3) weather condition must be good for condensation of water vapour to take place, and (4) the product of condensation must reach the earth. The form of precipitation can be one of the following type:

a) Rain

It is the principal form of precipitation in India. The term rainfall used to describe precipitation in the form of water drops of size larger than 0.5mm. The maximum size of drop is about 6mm. On the basis of intensity, rainfall is classified as :

1.	Light Rain	Intensity upto 2.5mm/h
2.	Moderate Rain	Intensity 2.5mm/h to 7.5mm/h
3.	Heavy Rain	Intensity > 7.5mm/h

b) Snow

Snow consists of ice crystal which usually combine to form flakes. When new snow has an initial density varying from 0.06 to $0.15 g/cm^3$.

c) Drizzle

A fine sprinkle of numerous water droplets of size less than 0.5mm and intensity less than 1mm/h is know as drizzle. In this the drop are so small that they appear to float in the air.

d) Glaze

When rain or drizzle come in contact with cold ground at around zero degree celcious, the water drops freeze to form an ice coating called glaze or freezing rain.

e) Sleet

It is frozen raindrop of transparent grains which form when rain falls through air at subfreezing temperature.

f) Hail

It is a showery precipitation in the form of irregular pellets or lumps of ice of size more than 8mm. Hails occur in violent thunderstorms in which vertical currents are very strong.

Some of the term and hydrological process connected with weather system associated with precipitation are given below:

- Cyclonic Precipitation
- Orographic Precipitation
- Frontal Precipitation
- Convective Precipitation
- Monsoon, in India

2.2.2 Interception

Interception is precipitation which collects on the plant canopy. It ultimately evaporates back into the atmosphere and is generally lost as far as surface runoff is concerned. However, it represents an abstraction from precipitation and must ultimately be quantified. The four primary factors which influence the amount of interception are: species of vegetation, growth stage of vegetation, season of year and wind velocity briefly the amount of water inception is a function of:

- storm characteristics;
- the species, age and density of prevailing plants and trees and
- the season of the year.

The interception loss is more at the beginning of rainfall and it gradually reduces to a constant value equal to evaporation loss during the storm period. Percentage of interception loss is more for smaller amount of rainfall. A general equation for estimating such losses is not available since most studies have been related to particular species or experimental plots strongly associated with a given locality. In average a well developed tree retention may be of 20 drops per leaves. For light shower where $P < 0.01$ inch, 100% interception may occur. Where for shower $P > 0.04$ inch, losses occur in the range of 10 to 40%.

2.2.3 Surface Retention

This is water retained on the ground surface in micro-depression. At the end of the storm, this water will either evaporates or infiltrate into the soil profile. There is small probability that some surface retention will become surface runoff if, in the process of infiltration, it becomes interflow water as it moves through the soil profile. Factor which control the amount of surface retention are micro-topography and surface macro-slope. The primary physical factor influencing the magnitude of surface retention is the surface micro-relief of the area and any factor which have a bearing on that micro-relief.

2.2.4 Surface Detention

This is water temporarily detained on the surface that is necessary required for surface runoff to occur. Therefore, it could logically be considered as an integral part of the surface runoff component rather than a separate process. The most significant factors controlling surface detention include: surface micro-relief, vegetation, surface macro-slope, rainfall excess distribution and the general topography of a catchment.

2.2.5 Infiltration

Infiltration is defined as the entry of water from the surface into the soil profile. Infiltration is the key process at the land surface which must be carefully considered in the models for describing the hydrology of the watershed. Water may infiltrate immediately from rainfall into the soil profile or it may flow into the temporary storage and infiltrate later. Storage in the soil profile is large but direct into this storage occurs at relatively low rates. Delayed infiltration complements direct infiltration and occur when waterflows into temporary storage of limited capacity, such as surface depressions and soil fissures. This water will later infiltrates or evaporates. Hortan (1931) defined infiltration capacity as the maximum rate at which a given soil in a given condition can be absorb rain as it falls. It is the infiltration capacity of the soil that determines for a given storm, the amount and the time distribution of rainfall excess that is available or runoff and surface storage. In watershed, infiltration is the most important hydrological component . The major controlling factors are :

(i) Soil Properties

The influence of shapes of soil and the hydraulic conductivity on infiltration was studies by Hanks and Bowers (1963). They showed that variation in the soil water diffusivity at low water content had negligible effect on infiltration from a pounded water surface. However, variation in either the diffusivity or soil water characteristics at water contents near saturation have a very strong influence on predicted infiltration. See fig 2.6. and 2.7.

(ii) Initial Water Content

This is one of the important factor that influences infiltration of water into the soil profile. Infiltration rates are high for drier initial condition but the dependence on initial water content decreases with time. Infiltration rates are higher at low initial water content because of higher hydraulic gradients and more available storage volumes. If infiltration is allowed to continue indefinitely,, the infiltration rate will eventually approach K_s regardless of the initial water content. The higher the initial water content, the lower the initial infiltration rate and the more quickly the rate approaches the asymptote K_s. In other words, high initial water contents reduce the effective porosity and the range of pore sizes available for infiltrating water. Phillips(1957) showed that for all times during infiltration the wetting front advances more rapidly for higher initial water Content. The figure 2.8 shows different infiltration rate curves depending on initial soil moisture content.

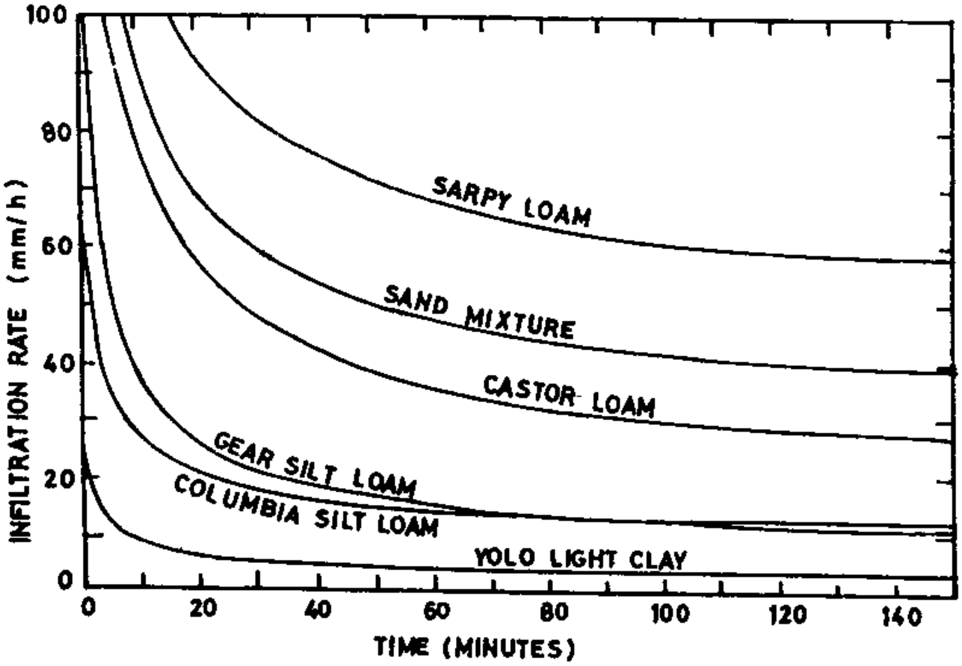


FIG. 2·6 INFILTRATION RATE CURVE OF SOME SOILS
(Adopted from Hann 'Small Catchment Hydrology')

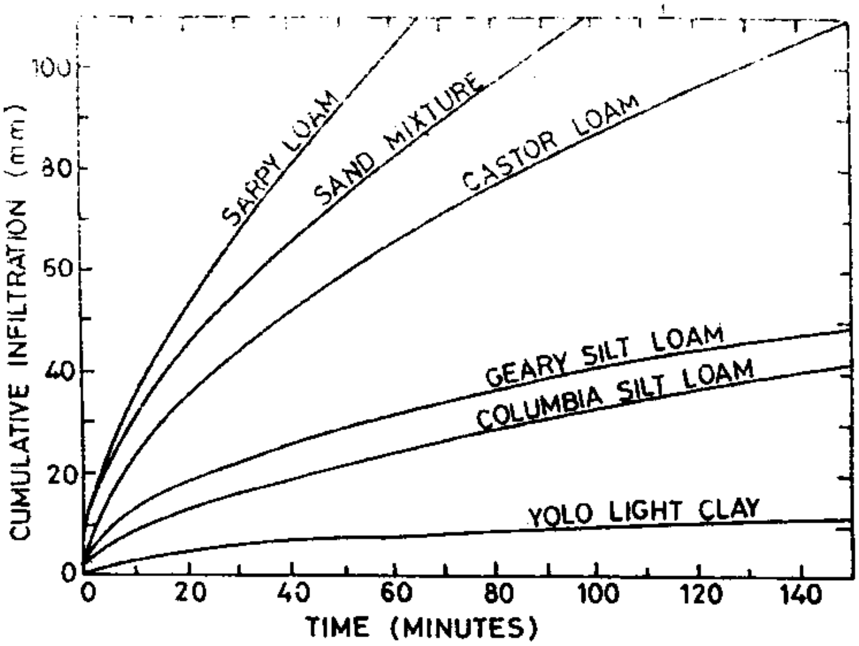


FIG. 2·2 CUMULATIVE INFILTRATION RELATIONSHIP FOR THE SOILS (Adopted from Hann 'Small Catchment Hydrology')

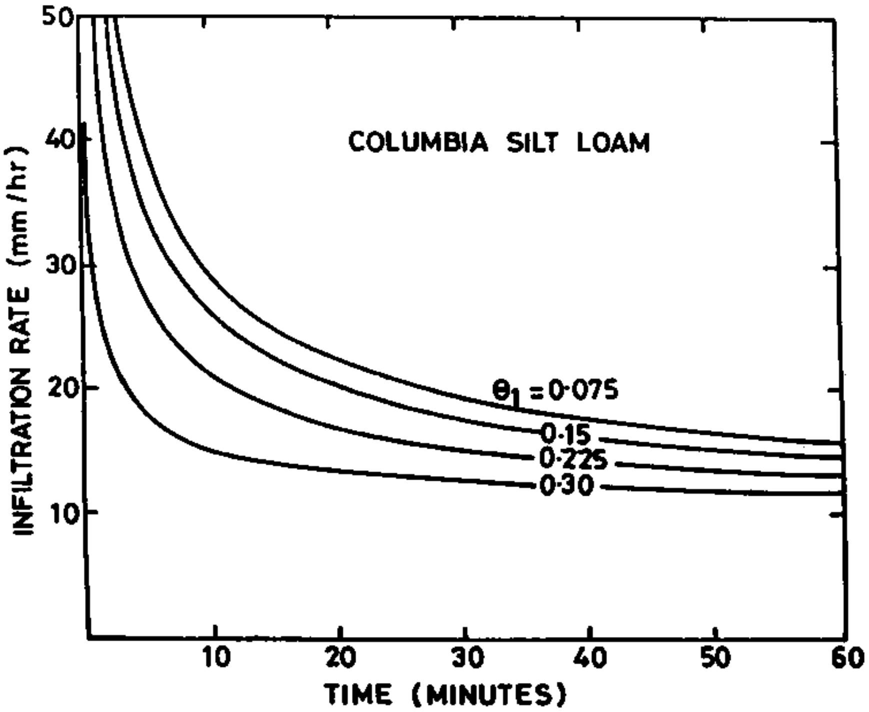


FIG. 2·3 INFILTRATION RATE FOR DIFFERENT SILTY LOAMY SOIL FOR DIFFERENT INITIAL SOIL MOISTURE CONTENT (Adopted from Hann 'Small Catchment Hydrology')

(iii) Rainfall rates

Infiltration depends on rate of water application as, well as soil conditions. If the rainfall rate R is less than K_s for a deep homogeneous soil, infiltration may confine indefinitely at a rate equal to the rainfall rate without ponding at the surface. The water content of the soil in this case does not reach saturation at any point but approaches a limiting value which depends on rainfall intensity. For soils with restricting layers, infiltration at $R < K_s$ will not always continue indefinitely without surface ponding. When the wetting front reaches the restricting layers water contents above the layer will increase and surface ponding may result even though the rainfall rate is less than Ks of the surface layer. Whether or not surface ponding and runoff, occurs under such conditions, infiltration depends on the soil properties of the restricting layer, its initial water content and lower boundary condition as well as the rate of drainage in the lateral direction. Detailed investigations of rainfall infiltration have been conducted by Rubin and Steinhardt(1963,1954') Rubin et al(1964) and Rubin(1966).

(iv) Surface tealing and crusting

The soil matrix or skeleton though generally is considered as rigid but actually the hydraulic properties cat the soil surface may change dramatically during application of water, such changes on the surface cover influences the rate of infiltration. Edward and Larson (1969) used the theory of soil-water movement to investigates the influence of surface of seal development on infiltration of water into a tilled soil.

(v) Layered soil

When water flow down through the layered soil, distribution of water content becomes discontinuous because of the difference in the soil water characteristics of the two soils. For a coarse soil layer over a fine soil, infiltration proceeds exactly as for a coarse soil aloe until the wetting front arrived at the boundary between the two layers. Then the, progress of wetting front slows down a positive pressure head develops in the top layer and the infiltration rate approaches that predicted for fine soil aloe. Whisler and Klute(1966) worked on infiltration through different layered soil.

(vi) Movement and entrapment of soil air

Generally constant air pressure is assumed under which infiltration takes place. This assumption is usually justified by the fact that viscosity of air is small relative to that of water and air can escape through large pores that remain partially open during infiltration. While these assumptions may hold in some instances, there are numerous cases where air is trapped by infiltrating water causing an air pressure build-up in advance of the wetting front and a reduction of the infiltration rate. Entrapment of a certain amount of air within individual soil pores usually occurs during infiltration whether or not there is an air pressure build up in advance of the wetting front. Pores containing entrapped air are unavailable for the transport of water and result in a hydraulic conductivity K_s rather than Ko. The difference in K_s and K_o depends on the number and size of pores blocked by entrapped air, Wilson and Luthin (1963) suggested that entrapment occurs primarily in larger pores. Slack(1978) resented a method for evaluating K_s for different amounts of air trapped in large pores.

2.2.6 Evapotranspiration

Evaporation and transpiration commonly called evapotranspiration (ET) is the conversion of water to vapour and the transport of that vapour away from the watershed surface into the atmosphere. The ET varies both in space and time and mainly depends on available water and solar radiation. Water is available at plant surfaces, streams and ponds or snowpacks. The bulk of evaporation and transpiration takes place during the time between runoff events, which is usually long. Hence, the abstractions are most important during this time interval. Estimation of ET require to consider three sets of variable in a vertical water budget within a system as (i) determination of potential ET (ii) plant-water-related characteristics and (iii) soil-water-related characteristics.

ET varies from place to place in a watershed and also varies throughout the day. Spatially average daily ET values may be used for hydrologic models. The evapotranspiration phenomenon was observed by the scientists since early recorded history (Biswas 1970). In 346 BC, Asistotle first wrote treatise on metrology and evaporation. Fitzgerald (1886) identifies many of the important quantities and variables related to pan and lake evaporation. In the mid 20th centuries Thronthwaite and Halzman (!942) describe method of calculating evaporation values. Penman (1948) in his model describe a method to calculate ET by combining the vertical energy budget with horizontal wind effect. Herald and Dreibelbis (1958,67) have done lysimeter studies and identifies plant characteristics effect. Gates and Hanks (1967) have done extensive work on effect of plant on ET. Evapotranspiration from vegetated surface is the result of several process like radiation exchange, vapour transport and biological growth, operating within the system involving atmosphere, plant and soil.

(a) Principles

Evaporation takes place from soil surface and water bodies while, Evapotranspiration takes place from vegetated surfaces. The process requires solar energy as input, water availability and a transport process from the surface into the atmosphere. Researchers like Tanner (1957), Goodell(1966), Penman et al(1967), Gray (1970) and Campbell (1977) have provided good descriptions of these primary variables which determine evapotranspiration rates.

Soil surface and water availability to the evaporating plant often limits ET . The rate of ET is limited to the diffusion rate of soil water to the soil surface and to the plant roots and through the plant system. Transport of water vapour upward from the evaporating surface for most vegetated situations does not often significantly limit the ET process. The horizontal advection of sensible heat from areas of excess energy to areas of limited energy is another important energy source for E.T. This is often called the clothes line or oasis effect.

Evapotranspiration varies spatially as a result of variations in climate, crops, or soils. Elevation, orographic effects and cropping patterns can cause large changes in E.T. Spatial averaging of E.T. values for a basin or sub-basins are generally done. The daily E.T. data indicate the annual distribution and daily variation of E.T. values. The considerable daily variation within each month demonstrates the dynamic behaviour of E.T. values.

Estimation of ET follows a vertical water budget within a system. It requires to consider three sets of variables (i) determination of potential E T (ii) plant-water-related characteristics and (iii) soilwater related characteristics.

(b) Potential E.T.

The potential E.T. (or PET) is usually defined as an atmospheric determined quantity, which assumes that the E.T. flux will not exceed the available energy from both radiant and convection sources. Techniques for estimating potential E.T. are based on one or more atmospheric variables like solar or net radiation and air temperature, and humidity or some measurement related to these variables, like pan evaporation. Measurement or prediction of some variables such as vapour or heat flux is difficult, only radiation is measured routinely.

(c) Pan Evaporation

Evaporation that takes place from shallow pan is called pan-evaporation. This is one of the oldest and most common method of estimating potential E.T. Methods for calculating pan evaporation from meteorological data are given by Penman(1948), Kohler et., al. (1955), Christianson (1966, 1968) and Kohler and Permele (1967)

(d) Energy Budget

In this method, calculation of potential E T is done by energy budget method. Energy limits evaporation where moisture is readily available and the necessary vapour transport occurs.

(e) Temperature Based Methods

Some correlation exists between the climatic variables causing potential E T and air temperature. Air temperature data are readily available. This is one of the most readily available climatic variables. There are several methods for predicting potential E T based on average air temperatures.

The Blaney-Criddle(1966) method is an extensively used method for irrigation design particularly in western US. Experience has shown the results of energy budgets are usually more reliable than temperature based method.

The other methods are (a) aerodynamic profile method as described by (i) Dyer(1961) for mass transfer eddy flux method or (ii) that of Parmele and Jocoby(1975) for the Bowen ratio measurements and (b) Combination method. Penman(1948,1956)

(f) Sensitivity Analysis

To assess the accuracy of prediction of potential evapotranspiration(PET), it, is necessary to evaluate the relative effect of several variables that cause PET. Sensitivity analysis help to determine the required accuracy of instrumentation for measurements and calculations needed for estimating. PET. Evaporation for each period is the result of. a unique set of variable effects, so no single answer is possible. But average guidelines have been developed by McCuen(1974 Saxton (1975), Colemanand Decoursey(1976).

Among the energy related variables, the net radiation flux variable R is very important. Aerodynamic variables are usually less important except when there are very dry winds.

(g) Spatial Variation

Climatologic variables which determine PET tend to vary slowly with distance given that major land form features are reasonable similar. For some applications, when data are transferred from off-site, the effects of aspect and 'slope may be important. Foyster(1973) described a grid technique to determine regional PET and the method of computing actual ET in the Stanford watershed model contains an empirical adjustment for spatial variation over large watersheds.

(h) Comparison of methods

The selection of a method for potential ET estimates depends on (i) data availability(ii) accuracy required(iii) time available to develop accurate estimates from available data sources.. Studies comparing the results of several methods were reported by McGuinness and Bordne(1972), Bordne and McGuinness(1973) and Parmele and McGuinnes (1974). Doorenbos and Pruitt(1975) and Burman(1976) showed similar comparisons for a variety of stations.

(i) Plant Transpiration

Plants control a large number of the processes that determine E.T. rates, such as(i) use of radiant energy (ii) stomatal control of leaf transpiration(iii) root interaction with available soil water etc. Federer(1975) showed the recent trend in research of ET from physically controlled process to a physiologically controlled process.

The effects of plants on ET can be divided into the main categories of(a) Canopy (b) phonology (c) root distribution, and (d) water stress. There are many interactions among these categories. Many of the basic interactions of crops with the atmosphere and soil are provided by Monteith(1976@, Kramer(1969) and Slatyer (1967).

The dynamic development, maturation and decay of crop canopies significantly influence plant transpiration effects. The canopy of any particular day largely determines the amount of intercepted solar radiation or absorbed advection thus hydrologic models must provide a representation of this dynamic plant behaviour.

The phenological of plants often modifies plants ability to transpire. As crop matures its need for water and ability to transpire diminishes. The crop effects on ET have often been represented by crop coefficients, either as average seasonal values or as seasonal distributions. Most often the coefficients account for the combined effects of crop canopy, oenological development and soil evaporation. Crop roots are also important in the process of connecting soil water with atmospheric energy and the resulting transpiration. However, root distribution and their effectiveness are difficult to study and quantify. Transpiration process reduces at some level of deficiency of' soil water and eventually ceases if water availability is severely limited.

j) Soil Water Evaporation

The process of evaporation from soil is similar to transpiration from a plant. Evaporation from soil takes place at three stages:

i) In the first stage, the drying rate is limited by and equals the evaporative demand.
ii) In the second stage, water availability becomes limiting and
iii) In the third stage, it becomes limited to a more, constant rate. Gardener and Hillel (1962), Idso et al (1974) did some studies on this.

2.2.7 Soil Moisture

Soil moisture is the term applied to the water held in the soil by molecular attraction. The forces acting to retain water in the soil are adhesive and cohesive forces. These forces act against the force of gravity and against evaporation and transpiration. Thus, the amount of moisture in the soil at any given time is determined the strength and duration of the forces operating on the moisture, and the amount of moisture initially present.

2.2.8 Streamflow

Most hydrological analysis involve runoff from a drainage area, and hence its measurement is of vital importance. Streamflow data are collected primarily for hydrologic studies.

If precipitation and runoff can be accurately measured, it is then possible to estimate the total loss on a drainage basin. This information can help predict runoff from similar drainage basin that have no gages. Streamflow measurements are used to develop physical or statistical relation between other variable and runoff volume or peak discharge. These relations form the basis for many calculation to predict stremflow characteristics of ungaged basin.

2.2.9 Base flow

Base flow is the flow to the channel of a watershed that comes from ground water or springe contribution and may be considered as the normal day to the day flow. The base flow component is composed of the water that percolates downward until it reaches the ground water reservoir and that flows to surface streams as ground water discharge. The ground water hydrograph during actual storm period may or may not shown an increase. The release period of ground water accreted due to a storm depend on the size of the basin, for small basin it may be one deny and for large basin this may vary from a month to a year.

2.2.10 Erosion and Sediment Yield

Estimates of watershed sediment yield are required for solution of a number of problem. Design of dams and reservoirs; transport of pollutants; design of soil conservation practices; design of stable channel; design of debris basin; depletion of reservoirs, lakes and wetland; determination of the effect of basin management; off-site damage evaluation; and the cost evaluation of the water-resources project are some of the example problems.

* * *

3.0 Watershed Models

A watershed model is nothing but is a set of some mathmatical equations which describe the physical process of that natural unit or in other words a watershed model incorporates various mathematical equation to describe transport process and account for water balance through time. A good watershed model have the structure do not change from region to region but only the watershed parameters are different and have to be recalibrates for each region separately. With the variation of various watershed parameters in space and time, the complex rainfall pattern and hetrogenious watershed can be simulated with such model. Every natural watershed unit comprises of different type of soil cover, vegetation, land use, topography, drainage pattern, density and slope etc. On account of this hetrogenity of watershed the various hydrological process involved are not uniform in space and time, e.g. interception losses depends upon the type of vegetation cover and its density and on rainfall amount, its intensity and duration. Interception losses are high at the begning of rainfall but reduces gradually to a constant value equal to potential evaporation rate till rainfall continue. Similarly infiltration rate varies in space and time and also depends upon initial soil moisture condition. To simulate these complex hydrological process, different watershed models have been developed, having different approaches, different method of approximation of each hydrological process. **In the present report a comparative study of various watershed model are carried out describing the model structure, various mathematical equation about each hydrological process, including data requirement, input and output.**

Classification of Models

The various watershed models can be classified into one of the following broad catagry (De Varies and Hromadka,1993);

- single event rainfall/runoff and routine models
- continuous simulation models
- flood hydraulics models
- water quality models

The above mentioned types of models can further be classified as Linear and Non-linear models, Event and Continuous models, Lumped and Distributed system models, and Deterministic and Stochastic models.

A deterministic watershed model usually includes the following elements:

- Input parameters representing physical characteristic of the watershed.
- Input of the precipitation and other metrological data.
- Calculation of water flows, both surface and subsurface.
- Calculation of water storage, both surface and

subsurface.
- Calculation of water losses.
- Watershed outflows and other outputs, if desired.

A deterministic watershed models consists of a series of a submodels each representing a particular hydrologic process and usually a structured accordingly. Each submodel representing basically flow of water and usually includes a storage. The submodel outflow is either an outflow to the next sub-model or a watershed itself. Most flows in a model are into or out of a storage. The flow is related to the amount of water in storage as well as other factors. Model building is a process of choosing appropriate submodels linking them together to form a watershed model, and making the resulting watershed model. Selection of appropriate model depends on the purpose of the overall model. The question to be considered in this connection are (i) Is the model intended for a particular type of watershed in terms of size, topography or land use and(ii) Is it intended for use on any type of watershed. Watershed models can also be characterised as event or continuous models. The accuracy of the model output may depend on the reliability of the input condition. Continuous watershed models keep a continuous account of the basin moisture condition and determines the initial conditions applicable to runoff event. Most continuous watershed models utilises three runoff process, direct runoff, inter flow and ground water flow, while an event model may omit one or both the sub surface components, and also evaporatranspiration. In terms of scope, there are complete models or partial models. It is useful also to characterise watershed models as fitted parameters models or measured parameter models. A fitted parameters model is one which has one or more parameters that can be evaluated only by fitting computed hydrogaphs to the observed hydrographs. A measured parameters model on the other hand is one for which all the parameters can be determined satisfactory from known watershed characteristics, either by measurement or by estimation. A measured parameters model can be applied to a totally ungauged watershed and, therefore, is highly desired. The development of such a model, that is also continuous, acceptably accurate and generally applicable is, however, a very difficult task.

Watershed models can be classified as general purpose models or spacial purpose models. A general model is one that is acceptable to watershed of various types and size. A spacial purpose watershed model is one that is applicable to a particular type of watershed in terms of topography, geology, and land use. Watershed models or submodels are also classified as distributed models or lumped models. A distributed model is one in which areal variation of watershed characteristics e.g. soil and land use can be utilise directly in applying the soil model. In a lumped model this can be done and therefore, representative or mean values of land slope, channel slope, length, soil characteristics etc. are usually used.

As such numbers of watershed models are available, a model user is encourage to select one of these and modify if necessary rather than develop one from scratch. Most model have sufficiently modular that component relationships can be changed to meet the specific needs of the user. some model requires calibration using previously used data; others don't requires calibration although most could benefit from some parameters optimisation. Some example of these models are discussed in this chapter.

3.1

LISEM MODEL

The Limburg Soil Erosion Model (LISEM) is a physically based hydrological and soil erosion model developed by the Department of Physical Geography at Utrecht University and the Soil Physics Division of the Winard Staring Centre in Wageningen, The Netherlands and can be used for planning and conservation purposes. The LISEM model is one of the first examples of a physically based model that is completely incorporated in a raster Geographical Information System, i.e. there are no conversion routines necessary, the model is expressed completely in terms of the GIS command structure. LISEM is written in a prototype GIS modelling language developed at Utrecht University. The language comprises all PC Raster GIS commands as statements with exactly the same syntax as the PC Raster command form of the statements. When compiled, an efficient run time mechanism eliminates redundant data transfer. A flowchart of LISEM model is shown in figure 1:

Components of Model

The various process incorporated in the model are rainfall, interception, surface storage, infiltration, overland flow and channel flow. These are described below :

(a) Rainfall

Data from multiple rain gauges can be entered in an input data file of the time series type. A map is used as input to define which rain gauge must be used for each pixel. For every time increment during the simulation of a storm, the model generates a map with the spatial distribution of the rain fall intensity using a single statement that uses the rain gauge identification map and the time series file.

(b) Interception

Interception by crops and/or natural vegetation is simulated by calculating a maximum storage capacity, using Von Hoyningen- Huene (1981)equation as :

$$SMAX = 0.935 + 0.498 * LAI - 0.00575 * LAI^2$$

where SMAX is the maximum storage capacity (mm) and LAI is the leaf area index. Cumulative interception during rainfall is simulated using an equation developed by Aston (1979), which is modified from Merriam (1960):

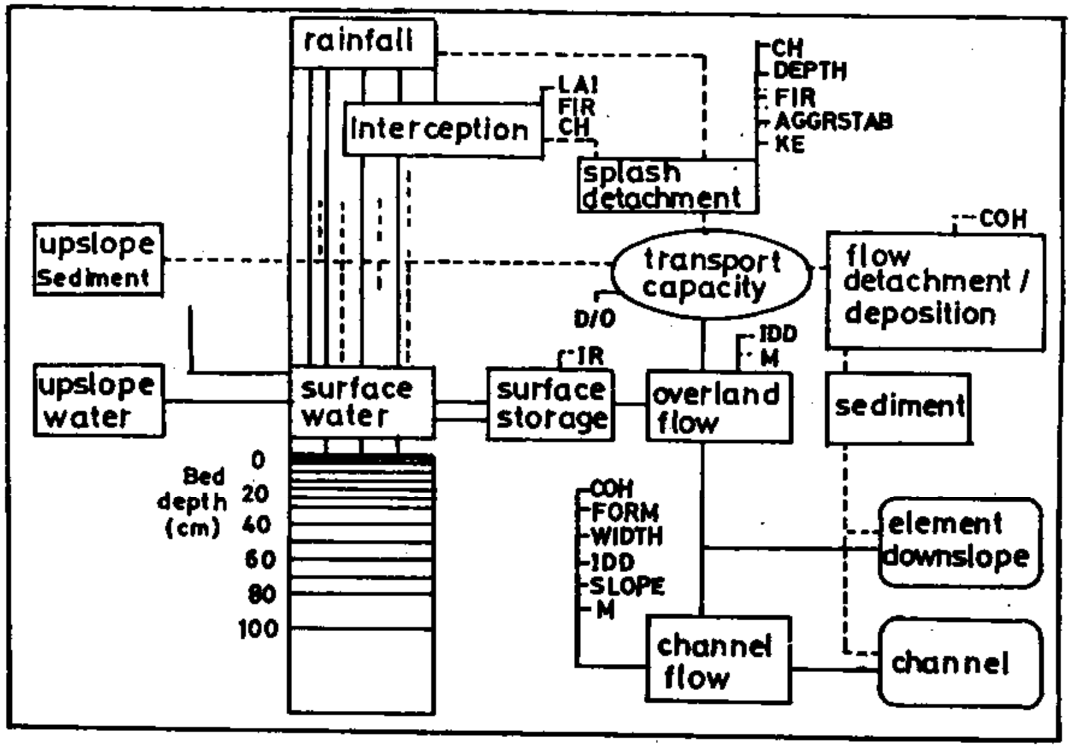


FIG.3.1 FLOW CHART OF LISEM MODEL

$$CINT = SMAX * [1-e^{-(1-p)*PCUM/SMAX}]$$

where CINT is the cumulative interception (mm), PCUM is the cumulative rainfall (mm) and p is the correction factor, equals (I - 0 046 x LAI).

(c) Infiltration and soil water transport

Infiltration and soil water transport in soils are simulated by the solution of the Richard equation:

$$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial z}K(h)[\frac{\partial h}{\partial z}+1]$$

where X is the hydraulic conductivity ms is the pressure ; 0 is the volumetric water content (m3 m-3); z is the gravitational potential or height above a reference level (m) and t is the time (s). Using the soil water capacity equation

$$C(h)=d\theta(h)/dh$$

the unsaturated flow equation is derived as:

$$C(h)[\frac{\partial h}{\partial t}]=\frac{\partial}{\partial z}K(h)[\frac{\partial h}{\partial z}+1]$$

where C equals the soil water capacity. The Mualem-Van Genuchten equations (Mualem, 1976; Van Genuchten, 1980) are used to predict the soil-water retention curves and the unsaturated hydraulic conductivity. Storage in micro-depressions is simulated by a set of equations developed by Onstad (1984) and Linden et al. (1988). Surface storage in depressions is simulated by (Onstad, 1984) as:

$$RETMAX=0.112*RR+0.031*RR^2-0.012*RR*S$$

where RETMAX is the maximum depressional storage (cm); RR is the random roughness (cm) and S is the slope gradient (%). The rainfall excess (rainfall + overland flow - interception - infiltration) required to fill all depressions is calculated Using the equation (Onstal at el. 1984):

$$RETRAIN = 0.329 * RR + 0.073 * RR^2 - 0.018 * RR * S$$

with RETRAIN equal to the rainfall excess needed to fill depressions (cm). Moore and Larson (1979) identified three possible stages during a rainfall event: (a) micro-relief storage building up, no surface runoff; (b) additional micro-relief storage, accompanied by runoff and (e) runoff only with the micro-relief storage at maximum. To determine the transition from stage (a) to stage (b), the data from

Onstad (1984) were analysed. From this analysis the following equation was developed, which simulates the starting point of runoff:

$$DETSTART = RETRAIN * [0.0527 * RR-0.0049 * S]$$

where DETSTART is the rainfall excess needed to start runoff (cm). Thus, during stage (a), all excess rainfall becomes depression storage. Then, from point 'DETSTART' to point 'RETRAIN' both overland flow and further depressional storage occur, based on a linear filling of the depressions until RETRAIN. After RETRAIN, all excess rainfall becomes runoff. Thus, using these relationships the actual storage in depressions (RET) can be calculated. In addition, using the same input data, the maximum surface covered with water can be calculated (Onstad, 1984) as:

$$FWAMAX = 0.152 * RR-0.008 * RR^{2}-O.008 * RR * S$$

The actual fraction of the surface covered with water is calculated using a relationship based on the work Of Moore , Larson (1979) and Onstad (1984) as:

$$FWA = FWAMAX\ [\ \frac{RET}{RETMAX}\ ]^{0.6}$$

where FWA is the actual fraction of the surface covered with water. Based on the findings or Linden et al. (1988) some depressions are (temporarily) isolated and do not contribute to the overland flow. From their data it was determined that if the storage (RET) was less than 75% of the RETMAX, 20% of the depressions are isolated. If RET is between 75 and 100% of RETMAX then the following equation was derived:

$$FWAISO=0.20*FWA*[1-\frac{\frac{RET}{RETMAX}-0.75}{.25}]$$

where FWAISO is the fraction of the isolated depressions.

(d) Overland flow channel flow

For the distributed overland and channel flow routing, a four-point finite-diflference solution of the kinematic wave is used together with Manning's equation.

(e) Splash detachment

Splash detachment is simulated as a function of soil aggregate stability, rainfall kinetic energy and the depth of surface water layer. This submodel is calibrated by field experiments. The kinetic energy can arise from both direct throughfall and drainage from leaves. The following equation is used for the same as:

$$DETR=[\frac{2.82}{AGGRSTAB}*KE*e^{-1.48*DEPTH}+2.96]*(P-1)*(\frac{dx}{dt})^{2}$$

where DETR is the splash detachment (g/s); AGGRSTAB is the soil aggregate stability (median number of drops); KE is the rainfall kinetic energy (Jm^{-2}); DEPTH is the depth of the surface water layer (mm); P is the rainfall (mm); I is the interception (mm); dx is the size of an element (m); and dr is the time increment(s).

(f) Transport capacity

The transport capacity of overland flow is modelled as a function of unit stream power (Covers, 1990):

$$TC=*l[S*V-0.4]^{Dl}$$

where TC equals the volumetric transport capacity (cm3cm~3); S is the slope gradient (mm~1); V is the mean Row velocity (cm/s).

(g) Rill and inter-rill erosion:

Flow detachment and deposition are simulated using equations from the EUROSEM model (Morgan, 1994). Whenever the transporting capacity, calculated using above Equation , is less than the available sediment from splash, from unslope areas and from previous time steps, deposition occurs at the following rate:

$$DEP = W * V * [TC-C]$$

where DEP is the deposition rate (kg m^{-3}); are is the width of the flow (m); v, is the settling velocity of the particles (m s^{-1}); TC is the transport capacity (kg m^{-3}; and C is the sediment concentration in the flow (kg m^{-3}).

If the transporting capacity of the flow exceeds the sediment concentration in the flow, detachment by the flow takes place and is calculated using the following equation (Morgan, 1994):

$$DF=ywv[TC-C]$$

with DF equal to the flow detachment rate (kg m^{-3}) and y an efficiency coefficient. The efficiency coefficient in Equation above is determined by (Morgan et al.1992):

$$y = \frac{U_{gmin}}{U_{gerit}} = \frac{1}{0.89+0.56COH}$$

where ugmin is the minimum valtlc required for critical grain shear velocity (cm s^{-1}); Ugerit is thc critical grain shear velocity for rill initiation (cm s^{-1}); and COH is the cohesion of the soil at saturation (kPa). In the LISEM model, the user can enter both the cohesion of the bare soil (COH.MAP) as well as the additional cohesion caused by vegetation or crops (COHADD.MAP). These two cohesion values are added and used in equation above.

(h) Roads, wheel tracks and channels

Water and sediment flow in channels are simulated separately for the given, Manning's roughness coefficients, channel bed, the width, the channel gradient, channel form and width and the channel bed cohesion.

(i) Crusts and surface stones

Infiltration through crusted soils can be simulated using separate conductivity tables for crusts. In a map, the percentage of crusted soil within a pixel is entered. The Richard equation is solved for both 'normal' and crusted soils. After the infiltration equations, the water is summed and the other processes are simulated. The fraction of stone cover within a pixel can also be given in a separate map. The current version of the model simulates no splash or flow detachment on the stone-covered part. Infiltration effects are not (yet) taken into account.

INPUT AND OUTPUT FILE

3.1.1 Rainfall file and rain gauge file

Data from one, or multiple rain gauges, is entered in a time series file. In a map the rain gauge identification number is given for each pixel. Thus, the model allows for spatial and temporal variability of rainfall.

3.1.2 Tables for the soil Water model

A modified version of the SWATRE soil water model, which simulates the vertical movement of water in the soil (Belmans et al., 1983) has been incorporated in the LISEM model. Within the catchment, soil profiles are defined. The vertical soil water movement is simulated by sub-dividing a soil profile in a user-defined number of layers.

3.1.3 Maps of relevant topographical, soil and land-use variables

To run LISEM, the following maps are needed in the PCRaster format:

(i) A group of maps that describe the catchment morphology: an 'area.map', in which the main catchment is defined; an 'id.map', which defines the spatial rainfall pattern; a map with the locations of the main outlet and subcatchment outlets; a map with the 'local drain direction', which refers to aspect; a map with slope gradient; a map with the Manning's n for overland flow; a map with the slope gradient of the main channels; a map with the Manning's n for channel flow; two maps that describe the channel morphology; a map with the location and width of roads; a map with the location and width of wheel tracks from tractors.

(ii) A group of maps needed for the soil water sub-models: a map with the soil profile types, referring to the conductivity tables (option); a similar map, but for profiles under wheel tracks (option); a similar map, but for profiles under crusts (option); maps with the initial soil matric suction for each soil layer (option); maps with the Holtan infiltration variables (option); maps with the Green-Ampt infiltration variables (option).

iii) A group of maps with soil and land-use variables: a map of the leaf area index; a map with the soil coverage by vegetation; a map with the crop height; a map with the random roughness of the soil surface; a map with the aggregate stability of the soil; a map with the soil cohesion for bare soil surfaces; a map with the additional cohesion caused by vegetation; a map with the soil cohesion of channels. Command file, When the model is run, the user is prompted for the selection of the catchment, the rainfall event, a few tuning parameters and the desired output. Alternatively, the user can specify this information in a command file. This interface empowers the user to:

1) Select the catchment by specifying tile director of the topographical, soil and land-use map data-base.
2) Select the soil water model parameters by specifying the directory of the soil water tables. Separating the map database and the soil water tables permits optional sharing of the soil water tables between different catchments.
3) Specify the director where the results are written to.
4) Select the rainfall event by specifying the rainfall file.
5) Select the starting and ending time of the simulation.
6) Select the overall simulation time step, and the minimum time step for the soil water submodel.
7) Select a precision factor of the soil water sub-model.
8) Select a number of parameters and coefficients used in the detachment and transport formulae, such as settling velocity of the soil particle and a splash delivery ratio. If necessary, a few of these parameters could be used for calibrating the sediment part of the model.
9) Select names of the output files: e.g. hydrograph files, runoff maps at several times, soil erosion map and the result file with totals.

3.1.4 APPLICATION, ANALYSIS AND RESULT

LISEM model is effectively used for planning and evaluating various strategies for controlling pollution from intensively cropped areas. With the LISEM model several possible scenarios, of which a few control measures are seriously considered to be implemented can be evaluated and the best possible location for these measures can be determine. Maps of soil erosion and sedimentation of the scenarios can be compared by subtraction. These simulations indicated where the possible control measures would have the greatest positive and negative consequences.

a) *Sensitivity Analysis*

A. P. J. De Roo et al. (1996) performed sensitivity analysis by increasing and decreasing each individual input variable and parameters by 20% and examine the output. The analysis showed that the hydraulic conductivity is the most sensitive variable in the model with respect to the discharge. Slope gradients and random roughness are also important variable. Manning's n, random roughness, and the coefficient 'gl' in the transport capacity equation heavily influence the soil loss output. Thus hydraulic conductivity and Manning's roughness coefficient, n, are the most important variables with respect to the sediment output of LISEM.

b) Calibration and Validation

To calibrate and validate the LISEM model , measurement of discharge and sediment load at three outlet gauging station and six subcatchment sites, and measurements of the soil pressure head at 12 location, along four slop profile at nine depths down to the 150 cm, were available. The data and the simulation result show that there is clear difference between summer and the winter events. This difference response has been describe by Van Dijk and Kwaad (1996) and earlier by Kwaad(1991). On average winter storms are simulated best when the model has been calibrated on initial pressure head in the upper soil layers of 70 cm of the soil saturated. It is observed that about 40% of the simulated hydrograph have significantly different peak discharge or other deviation from the observed discharges. Based on the sensitive analysis and field observation the main reason for these difference seems to be spatial and temporal variability of the soil hydraulic conductivity, which is extremely high in the tilled soil of the research catchment. Another reason for the difference between measured and simulated result is our lack of understanding of the theory of the hydrological and erosion process. It is clear from the dat that the summer and the winter responses to rainfall are quite difference. But even within the main reason there are significantly different responses to rainfall due to tillage operations and biological activity, such as worms. The soil water transport has been tested by Ritsema et al.(1996) and concluded that the use of the one dimensional water flow module is appropriate and sufficient for simulating pressure head changes during the erosive rainfall events. Lateral flow through the hillslopes during these events is limited

c) Result of LISEM model:

- A summary file giving total rainfall, total discharge, total soil loss, peak discharge
- A time series file which can be used to plot hydrograph
- and sedigraph.
- PC raster maps of the soil erosion and deposition.
- PC-Raster maps of the overland flow.

3.1.5 Advantages of LISEM model

- Improve process description for infiltration and detachment.
- Integrate model with GIS to prevent lumping of topography.
- Allow input from remotely sensed data.

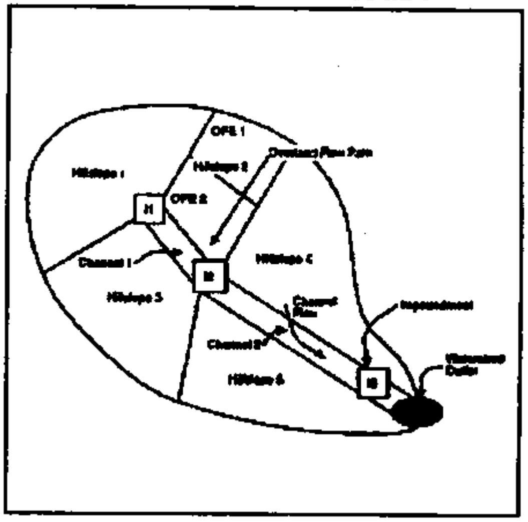
3.1.6 Conclusion:

The hydrological and soil erosion process during single rainfall event can be simulated using LISEM model. It is also possible to calculate the effect of land use changes and to explore soil conservation scenarios. It is available tool for planning cost effective measures to mitigate the effect of runoff and erosion.

3.2

WEPP Model

The WEPP model was developed by United States Department of Agriculture(USDA) under WATER EROSION PREDICTION PROJECT, called 'WEPP'. The objective of the Water Erosion Prediction Project was to develop new generation prediction technology for use by the USDA-Natural Resources Conservation Service, USDA-Forest Service, USDA Bureau of Land Management, and others involved in soil and water conservation and environmental Planning and assessment. This improved erosion prediction technology is based on modern hydrologic and erosion science, is process-oriented and is computer-implemented. This document is a detailed description of the WEPP erosion model as developed for application to small watersheds and hillslope profiles within those watersheds.



The **USDA Water Erosion Prediction Project erosion** model represents a new generation technology for estimating soil erosion on and sediment delivery from hillslope profiles and small watersheds The erosion processes of detachment and transport by raindrop impact on interrill areas, detachment, transport, and deposition by overland flow in rill channels, detachment, transport, and deposition by concentrated flow in channels, and deposition in impoundments are simulated by the WEPP erosion model. The continuous simulation model also includes components which mimic climate, surface and subsurface hydrology, winter processes, irrigation, plant growth and residue decomposition. The WEPP computer program calculates spatial and temporal distributions of soil loss, as well as sediment delivery and sediment particle characteristics. This includes WEPP erosion prediction system are user interface programs, input file building programs, a climate database, a soil database, a crop parameter database, and a tillage implement database. These additional programs and databases make the WEPP model a very powerful tool for users involved in natural resource conservation and environmental assessment.

The **WEPP** erosion model is a continuous simulation computer programme which predicts soil loss and sediment deposition from lowerland flow on hill slopes, soil loss and sedimentation deposition from concentrated flow in small channels, and sedimentation deposition in impoundments. In addition to the erosion components, it also includes a climate component which uses a stochastic generator to provide daily weather information, a hydrology component which is based on a modified Green-Ampt infiltration equation and solution of the kinematic wave equations, a daily water balance component, a plant growth and reduce decomposition component, and an irrigation component. The **WEPP** model computes spatial and temporal distributions of soil loss and deposition, and provide explicit estimates of when and where in a watershed or on a hillslope that erosion is occurring so that conservation measures can be selected to most effectively control soil loss and sediment yield.

The **USDA-Water Erosion Prediction Project (WEPP)** model represents a new erosion prediction technology based on fundamentals of stochastic weather generation, infiltration theory, hydrology, soil physics, plant science, hydraulics, and erosion mechanics. The hillslope or landscape profile application of the model provides major advantages over existing erosion prediction technology. The most notable advantages include capabilities for estimating spatial and temporal distributions of soil loss (net soil loss for an entire hillslope or for each point on a slope profile can be estimated on a daily , monthly, or average annual basis), and since the model is process-based it can be extrapolated to a broad range of conditions that may not be practical or economical to field test. In watershed applications, sediment yield from entire fields can be estimated.

Processes considered in hillslope profile model applications include rill and interrill erosion, sediment transport and deposition, infiltration, soil consolidation, residue and canopy effects on soil detachment and infiltration,. surface sealing, rill hydraulics, surface runoff, plant growth, residue decomposition, percolation, evaporation, transpiration, snow melt, frozen soil effects on infiltration and erodibility, climate, tillage effects on soil properties, effects of soil random roughness, and contour effects including potential overtopping of contour ridges. The model accommodates the spatial and temporal ariability in topography. surface roughness, soil properties, crops, and land use conditions on hillslopes.

In watershed applications, the model allows linkage of hillslope profiles to channels and impoundments. Water and sediment from one or more hillslopes can be routed through a small field scale watershed. Almost an of the parameter updating for hillslopes is duplicated for channels. The model simulates channel detachment, sediment transport and deposition. Impoundments such as farm ponds, terraces, culverts, filter fences and check dams can be simulated to remove sediment from the flow. For drainage studies, the WEPP model is not that sophisticated as other drainage models such as DRAINMOD and SWATREN (**Dierickx et al., 1986**) in calculating the drainage flux and drained volume-water table depth relationship, close agreement between simulated and measured runoff in a validation trial on a watershed in Oregon indicates that the WEPP model is able to simulate the effect of sub-surface drainage on storm runoff.

In the following sections an overview of the WEPP erosion model is presented. This briefly describes the model inputs, the model components, and the outputs.

3.2.1 MODEL INPUTS

Expected users of the new generation of erosion prediction models include all current users of the Universal Soil Loss Equation **(Wischmeier and Smith, 1978)**. Anticipated applications include conservation planning, project planning, and inventory and assessment. WEPP model overland flow profile simulations are applicable to hillslopes without concentrated flow channels, while watershed simulations are applicable to field situations with multiple profiles, channels (such as ephemeral gullies, grassed waterways, terraces), and impoundments **(Foster and Lane, 1987)**. The length of the representative profile to which the WEPP hillslope model components can be applied depends upon the topography and land use controlling stream channel density. Hillslope profile applications compute interrill and fill erosion and deposition along selected landscape profiles, while watershed applications also estimate channel erosion and deposition, and deposition in impoundments. The procedures do not consider classical gully erosion. Also, model application is limited to areas where the hydrology is dominated by Hortonian overland flow (i.e., rainfall rates exceed infiltration capacity and subsurface flow is negligible). The new erosion prediction technology is designed to be operational on personal computers and operate quickly so that several management schemes can be evaluated in a relatively short period of time. **Foster and Lane (1987)** describe in detail the model user requirements outlined above and the land uses to which the erosion prediction technology is applicable.

The WEPP computer model requires four input data files: climate, soil, slope and management files. Climate input files include daily maximum and minimum temperatures, solar radiation and rainfall(amount and distribution parameters). Soil input files include such soil parameters as soil albedo, initial water content, soil texture, percent rocks and soil cation exchange capacity (CEC). The slope file includes the land physical featurs such as slope length, slope steepness and aspect. The management file provides plant and management information for different land uses(crop, range or forest). For each land use, information about specific management practices are needed. For instance, for crop land, information about type of tillage, planting harvesting, irrigation and date of each management practice is needed. The model simulates the effect of various management practices while simulating hydrological and erosion processes on the site.

The WEPP model includes a Crop Parameter Intelligent Data Base System (CPIDS) **(Deer-Ascough et al., 1993)**, developed to assist users in deveoping WEPP plant growth parameters for crop not already parameterised. For cropland plant growth simulation, the following inputs are needed:

- number of Overland flow elements
- number of different crops
- cropping systems(annual perennial or fallow)
- crop types in the simulation
- number of tillage sequence in the simulation
- number of tillage operations within the sequence
- Julian day of tillage, tillage depth, and tillage type initial conditions at the start of simulation, including canopy cover, interril residue cover, rill residue cover, and prior crop type crop information including planting date, row width, and harvesting date.
- Base harvest index which is used for partitioning live biomass into that removed as a harvest crop material (grain, silage etc.) and that converted to dead crop residue.
- plant management information for annual crop including date of application of a contact herbicide to convert living biomass to dead residue.
- plant management information for perennial crops that are cut, including the number of cuttings, cutting dates, and cutting height
- plant management information for perennial crops that are gaged, including the date that grazing begins, the date that grazing ends, the number of annual units, Average body weight, filed size, and the digestibility of the forage.

For range land plant growth model, the options available in WEPP model are no plant growth, plant growth grazing by live stock, burning and habicide application. The model does not currently support mechanical practices on the range land.

3.2.2 Basic Concepts

The WEPP erosion model computes soil loss along a slope and sediment yield at the end of a hillslope. Interrill and rill erosion processes are considered. Interrill erosion is described as a process of soil detachment by raindrop impact, transport by shallow sheet flow, and sediment delivery to rill channels. Sediment delivery rate to rill flow areas is assumed to be proportional to the product of rainfall intensity and interrill runoff rate. Rill erosion is described as a function of the flow s ability to detach sediment, sediment transport capacity, and the existing sediment load in the flow.

The appropriate scales for application are tens of meters for hillslope profiles, and up to hundreds of meters for small watersheds. For scales greater than 100 meters, a watershed representation is necessary to prevent erosion predictions from becoming excessively large.

Overland flow processes are conceptualised as a mixture of broad sheet flow occurring in interrill areas and concentrated flow in rill areas. Broad sheet flow on an idealized surface is assumed for overland flow routing and hydrograph development. Overland flow routing procedures include both an analytical solution to the kinematic wave equations and regression equations derived from the kinematic approximation for a range of slope steepness and lengths, friction factors (surface roughness coefficients), soil textural classes, and rainfall distributions Because the solution to the kinematic wave equations is restricted to an upper boundary condition of zero depth, the routing process for strip cropping (cascading planes) uses the concept of the equivalent plane. Once the peak runoff rate and the duration of runoff have been determined from the overland flow routing, or by solving the regression equations to approximate the peak runoff and duration, steady-state conditions are assumed at the peak runoff rate for erosion calculations. Runoff duration is calculated so as to maintain conservation of mass for total runoff volume.

The erosion equations are normalized to the discharge of water and flow shear stress at the end of a uniform slope and are then used to calculate sediment detachment, transport. and deposition at all points 1 along the hillslope profile. Net detachment in a rill segment is considered to occur when hydraulic shear stress of flow exceeds the critical shear stress of the soil and when sediment load in the rill is less than sediment transport capacity. Net deposition in a rill segment occurs whenever the existing sediment load in the flow exceeds the sediment transport capacity.

In watershed applications, detachment of soil in a channel is predicted to occur if the channel flow shear stress exceeds a critical value and the sediment load in the flow is below the sediment transport capacity. Deposition is predicted to occur if channel sediment load is above the flow sediment transport capacity. Flow shear stress in channels is computed using regression equations that approximate the spatially-varied flow equations. Channel erosion to a Non erodible layer and subsequent channel widening can also be simulated. Deposition within and sediment discharge from impoundments is modeled using conservation of mass and overflow rate concepts.

3.2.3 Model Components

The WEPP model includes components for weather generation, frozen soils, snow accumulation and melt, irrigation, infiltration, overland flow hydraulics, water balance, plant growth, residue decomposition, soil disturbance by tillage, consolidation, and erosion and deposition. These components are briefly discussed. The model includes options for single storm, continuous simulation, single crop, crop rotation, irrigation, contour farming, and strip cropping.

3.2.4 WEATHER GENERATION

The weather generation methods used in the **WEPP** model are based on the generators used in the **EPIC (Williams et.al.,1984)**, and **SWRRB (Williams et al.,1985)** models. The weather generation methods used are modified form to include the additional requirements for rainfall intensity distributions. The WEPP generator is also known as **CLIGEN**.

The climate component **(Nicks, 1985)** generates mean daily precipitation, daily maximum and minimum temperature, mean daily solar radiation, and mean daily wind direction and speed. The number and distribution of precipitation events are generated using a two-state Markov chain model. Given the initial condition that the previous day was wet or dry, the model determines stocastically if precipitation occurs on the current day. A random number (0-1) is generated and compared with the appropriate wet dry probability. If the random number is less than or equal to the wet-dry probability, precipitation occurs on that day. Random numbers greater than the wet-dry probability give no precipitation. When a precipitation event occurs, the amount of precipitation is determined from a skewed normal distribution function. The method used to estimate the duration of generated precipitation events is that used in the **SWRRB** model **(Arnold et al.,1990)**. The assumption is that the rainfall duration for individual events is generated from an exponential distribution using the monthly mean durations. The peak storm intensity is estimated by the method proposed by **Arnold and Williams (1989)**. Time from the beginning of the storm to the peak intensity is estimated by calculating the annual accumulated distribution of time to peaks from the National Weather Service 15 minutes recording stations data. The precipitation amounts are reported to the nearest 2.54 mm (0.1"). The time to peak of each storm is calculated from the beginning of the first precipitation interval to the mid point of the 15 minute interval containing the peak intensity. Daily precipitation is partitioned between rainfall and snowfall using daily air temperatures. The dependency of air temperature on a given day to the precipitation occupance condition, is that for dry days, temperatures tend to be higher than normal and for wet days following wet days, temperatures tend to be lower. Similar results are seen for wet following wet days (**Nicks and Harp, 1980**), (**Richardson, 1981**). Daily maximum and minimum temperatures and solar radiation are generated from abnormal distribution functions. The generation of daily solar radiation is performed in a similar manner as temperature using a normal distribution of daily values during a month. The wind speed and direction are required in the WEPP models for the calculation of snow accumulation, snow melting and evapotranspiration. The method used to generate windspeed and direction is based on the division of the historical wind data into 16 cardinal directions by percent of time the wind is blowing from that direction an accumulated distribution of percent of time that wind is blowing each of these directions is derived from the wind data in the same manner as the time to peak distribution was constructed. The use of Geographical Information System (GIS) is under investigation. After development, it would allow the user agencies more flexibly in the parameter selection than specific site values. It may also provide the a partial solution to the problems that have plagued the user of climatic data in remote areas.

A desegregation model has been included in the climate component to generate time-rainfall intensity (breakpoint) data from daily rainfall amounts. In this form, the data contains two columns with cumulative time from beginning of the storm in the first column and average rainfall intensity over the time interval between the successive time in the second column. The data result from numerical differentiation of the cumulative time vs. cumulative rainfall depth curve at the changes in slope or break points. That is, given a rainfall amount and rainfall duration, the desegregation model derives a rainfall intensity pattern with properties similar to those obtained from analysis of breakpoint data. The breakpoint rainfall data are required by the infiltration component to compute rainfall excess rates and thus runoff. The **WEPP** user requirements **(Foster and Lane, 1987)** suggested that the maximum information required to represent a design storm consist of the following: (a) storm amount, (b) average intensity, (c) ratio of peak intensity, and (d) time to peak intensity. The intensity patterns in the WEPP model is represented with the double exponential function. Possible future improvements in the desegregation procedure may involve the generation of multiple storm events on the same day. For this modification, it is essential to reproduce the probability distributions of runoff and sediment yield.

3.2.5 Winter Processes

The winter processes which the WEPP model simulates are snow accumulation, density, snow melt and soil frost and thaw in the soil, all on a hourly basis. The snow accumulation routine predicts whether the hourly falling precipitation is rain or snow, as well as changes in snow depth and density. The melt component estimates the amount given hour during the day. The frost component estimates the extent of frost development and thawing over the winter period as well as changes in soil water content and infiltration capacity of the soil during the winter period. In order to make more accurate predictions, the average daily values for temperature, solar radiation, and precipitation are used to generate hourly temperature, radiation and snow fall values. The radiation value is the same value of hourly radiation on a sloping surface that is calculated by the model (SUNMAP routine). The aspect of the hill slope relative to the sun's angle which impinges upon it is calculated in the ASPECT subroutine. Values for slop steepness, slope aspect, latitude in radians, equivalent latitude and the change in longitude with respect to equivalent slope and latitude are also calculated in the subroutine. The average slope of the overland flow element (OFE) is calculated and converted to a decimal fraction and then to radians . The method that calculates hourly radiation given the daily radiation is based on work by **Swift and Luxmoore(1973)** and **Jensen(1990)**. This calculation is performed in the SUNMAP subroutine. The soil frost subcomponent is based on fundamental heat flow theory. The frost thaw subcomponent assumes that heat flow in a frozen or unfrozen soil or soil-snow system is unidirectional. Snow and soil thermal conductivity and water flow components are considered as constants. The soil frost subcomponent outputs values for hourly frost depth, thaw depth and the cumulative number of freeze-thaw cycles. This subcomponent predicts frost and thaw development for various combinations of snow, residue and tilled, and/or untilled soil. Adjustments to infiltration and erodibility parameters are made based on the frost or thaw location in the soil profile, and the soil moisture content. The winter hydrology routine works on hourly basis, however, WEPP climate input file provides daily values for precipitation, maximum and minimum temperature, dew point temperature and incoming radiation. In this, hourly precipitation, temperature and radiation need to be calculated before simulating snow accumulation or melt and frozen soil.

The snow accumulation subcomponent estimates the depth of the snow on the ground on a daily or hourly basis. Snow fall increases the snow pack, while warming temperatures and rainfall consolidate (increase the density) of the snow pack. All the snowmelt calculations are performed in the MELT subroutine of WINTER main routine. The melt routine is called on hours of days when snow depth is greater than zero. Snow drifting calculations are not made in the current WEPP model version.

The snow melt subcomponent is based on a generalized snow melt equation developed by the **U.S. Army Corps of Engineers (1956, 1960)**, as modified by **Hendrick et al. (1971)**, to adapt it for use with readily available meteorological and environmental data. This equation was further modified by Savabi et al. to make it compatible with a grid-based model. The snow melt equation incorporates four major energy components of the snow melt process: air temperature, solar radiation, vapour transfer, and precipitation. The following assumptions are made for snow melt calculations.

a. any precipitation that occurs on a day when the maximum daily temperature is below 0°C is assumed to be snowfall;
b. no snow melt occurs if the maximum daily temperature is below -2.8°C;
c. the snowpack does not melt until the density of the snow is greater than 0.35 g-cm3;
d. the surface soil temperature. is 0°C during the melt period; and
e. the albedo of melting snow is approximately 0.5.

3.2.6 Irrigation

The irrigation component of the WEPP hillslope profile version accommodates stationary sprinkler systems (solid-set, side-roll, and hand-move) and furrow irrigation systems. Four irrigation scheduling options are available:

i. no irrigation,
ii. depletion-level scheduling,
iii. fixed-date scheduling, and
iv. a combination of the second and third options.

The first option is the default option for irrigation in WEPP. For the second option, the decision of whether irrigation is necessary is determined by calculating the available soil water depletion levels for the entire soil profile and for the current root depth and comparing to an allowable depletion level. This is conducted on a daily basis. For the fixed-date scheduling option, specific irrigation dates are read into the model from a user-created data file. The fourth option is included primarily to allow a pre-planting irrigation and leaching of salts from the root zone. Parameters for depletion-level and fixed-date scheduling are read from individual data files.

3.2.7 Infiltration

The infiltration component of the hillslope model is based on the Green and Ampt equation as modified by **Mein and Larson (1973)**, with the ponding time calculation for an unsteady rainfall **(Chu, 1978)**. The infiltration process is divided into two distinct stages: a stage in which the ground surface is ponded with water and a stage without surface ponding. During an unsteady rainfall, the infiltration process may change from one stage to another and shift back to the original stage. Under a ponded surface the infiltration process is independent of the effect of the time distribution of rainfall. At this point the infiltration rate reaches its maximum capacity and is referred to as the infiltration capacity. At this stage rainfall excess is computed as the difference between rainfall ate and infiltration capacity. Depression storage is also accounted for. Without surface pending, all the rainfall infiltrates into the soil. The infiltration rate equals the rainfall intensity, which is less than the infiltration capacity, and rainfall excess is zero.

3.2.8 Overland Flow Hydraulics

Surface runoff is represented in two ways in WEPP hillslope model applications. First, broad sheet; flow is assumed for the overland flow routing and hvdrograph development. Overland flow routing procedures include both an analytical solution to the kinematic equation and an approximate method. The approximate method uses two sets of regression equations, one for peak runoff rate and one for runoff duration. These regression equations were derived from the kinematic approximation for a range of slope gradients and lengths, friction factors (surface roughness coefficients), soil textural classes, and rainfall distributions. Because the solution to the kinematic wave equations is restricted to an upper boundary condition of zero depth, the routing process for strip cropping (cascading planes) uses the concept of the equivalent plane. Once the peak runoff rate and the duration of runoff have been determined from the overland flow routing, or by solving the regression equations to approximate the peak runoff rate and duration, steady-state conditions are assumed at the peak runoff rate for rill erosion and transport calculations.

The proportion of the area in rills is represented by a rill density statistic (equivalent to a mean number of rills per unit area) and an estimated rill width. Representative rill cross sections are based on the channel calculations for equilibrium channel geometries similar to those used in the **CREAMS** model **(Knisel, 1980)** and width-discharge relationships derived from **Gilley et al. (1990)**. Depth of flow, velocity, and stress in the rills are calculated assuming rectangular channel cross sections. The erosion calculations are then made for a constant rate over a characteristic time to produce estimates of erosion for the entire runoff event.

3.2.9 LIMITATIONS OF WEPP ON OVERLAND FLOW REGIME

the WEPP considers only Hortonian flow or flow which occurs *when the rainfall rate exceeds the infiltration rate. It does not explicitly consider variable partial area response or return flow.*

- *As with most infiltration models, the implementation of GAML model in WEPP describe the movement of water within the soil profile at a point.*
- *changes in surface infiltration are lumped in the updated value of the effective saturated hydraulic conductivity parameter. All the infiltration parameters do not vary within on OFE nor within a single rainfall event.*
- *If there is hiatus within a single rainfall event, the soil moisture event is not redistributed so that the infiltration are when rainfall restarts is the same as when the rainfall ended.*
- *Depression storage is assumed to be satisfied before runoff begins.*
- *Rainfall excess is computed before it is routed on the flow surface. The result is that the routed rainfall excess volume (runoff)is equal to the rainfall excess volume before routing. In nature the routed volume is less because of infiltration during the recession period of the hydrograph. For partial equilibrium hydrographs, the routed volume is reduced to account for recession infiltration. However for all others cases it is not.*
- *Flow conditions are restricted to an initial condition of no flow for all cases and upper boundary condition of zero flow for a single OFE or the top most OFE of a cascade of OFFS.*
- *The approximate to compute peak discharge will show more error when the actual hydrograph has multiple peaks than when it has only a single peak.*
- *Infiltration on a multiple OFFS is computed using the OFE length weighted average GAML parameters or the OFFS under consideration.*

3.2.10 Water Balance

The water balance and percolation component of the hillslope model is based on the water balance component of **SWRRB** (Simulator for Water Resources in Rural Basins) (**Williams and Nicks, 1985**), with some modifications for improving estimation of percolation and soil evaporation parameters. The water balance component maintains a continuous balance of the soil moisture within the root zone on a daily basis. Redistribution of water within the soil profile is accounted for by the Ritchie evapotranspiration model (**Ritchie, 1972**) and by percolation from upper layers to lower layers based on a storage routing technique (**Williarns et al., 1984**). The water balance component uses information generated by the weather generation component (daily precipitation, temperature, and solar radiation), infiltration component (infiltrated water volume), and plant growth component (daily leaf area index, root depth, and residue cover).

The infiltration component of WEPP is linked with the evapotranspiration and percolation components to maintain a continuous water balance. Infiltrated water is added to the upper layer's soil water content and routed through the lower soil layers. Soil water in each layer is subjected to percolation and/or evapotranspiration. The upper layer soil water content is being used to establish initial moisture conditions for the infiltration component (Green Ampt model). Percolation below the root zone is considered lost from the WEPP water balance.

3.2.11 Plant Growth

The WEPP is continuous erosion model which requires a plant growth in order to simulate the growth of the plants and their impacts on the hydrologic and erosion processes. This predicts the development of cropland and rangeland plants. The root zone soil water redistribution is an important part of the WEPP model because 1) soil water content affects the subsequent rainfall/ runoff events, 2) root zone soil water content is used in the interaction between soil water and plant growth, and 3) soil water content is used in the decomposition. The purpose of this component is to simulate temporal changes in plant residue variables such as canopy cover, canopy height, root development, and bio-mass produced by the plants which is removed during a harvest operation or ends up as surface residue material, i.e. all those that influence the runoff and erosion processes. The cropland and rangeland plant growth are simulated in separate submodels of the WEPP model.

The cropland plant growth model is based on the **EPIC** model **(Williams et al.. 1984)** and predicts biomass accumulation as a function of heat units and photosynthetically active radiation. Potential growth is reduced by moisture and temperature stress. Crop growth variables computed in the cropland model include growing degree days, mass of vegetative dry matter, canopy cover and height, root growth. leaf area index, plant basal area, etc. The cropland plant growth model accommodates mono, double, rotation, and strip cropping practices. The crop yield predicted by the plant growth component is available as model output, and the biomass production and predicted crop yield through cautious adjustments for the plant specific input parameters may be incorporated.

The rangeland plant growth model estimates the initiation and growth of above and below- ground biomass for range plant communities by using a unimodal or a bimodal potential growth curve. Range plant variables computed in the rangeland model include plant height, litter cover, foliar canopy cover, ground surface cover, exposed bare soil, and leaf area index. Range management practices such as herbicide application, burning and grazing may be simulated.

3.2.12 Residue Decomposition

The residue decomposition component estimates decomposition of flat residue mass (residue mass in contact with the soil surface), standing material (residue mass standing above ground), submerged residue mass (residue mass that has been incorporated into the soil by a tillage operation), and dead root mass. Decomposition parameters must be specified in the management input file. The decomposition component partitions total residue mass at harvest into standing and flat components based upon harvesting and residue management techniques. The model also sets the initial stubble population at harvest equivalent to the plant population calculated in the plant growth component.

3.2.13 Soil Parameters

Soil parameters that influence the basic water erosion processes of hydrology as infiltration and surface runoff and erosion as soil detachment by raindrops and concentrated flow, and sediment transport are updated in the soil component, and include:

- critical shear stress
- random roughness,
- oriented roughness,
- bulk density,
- melting-front suction,
- hydraulic conductivity,
- interrill erodibility,
- rill erodibility.

Random roughness is most often associated with tillage of cropland soil, but any tillage or soil disturbing operation creates soil roughness. Random roughness decay following a tillage operation is predicted in the soil component from a relationship including a random roughness parameter and the cumulative rainfall since tillage. A random roughness parameter is assigned to a tillage implement based upon measured averages for an implement. Oriented roughness results when the soil is arranged in a regular way by a tillage implement. Depression storage of rainfall and hydraulic resistance to overland flow are positively correlated with soil roughness. Soil roughness changes temporarily due to tillage, rainfall weathering, and freezing and thawing. Bulk density reflects the total pore volume of the soil and is used to predict several infiltration parameters, including wetting front suction. Bulk density changes temporarily due to tillage, wetting and drying, and freezing and thawing. Adjustment to bulk density are needed to account for factors such as the volumes of entrapped air and course fragments in the soil. In WEPP hillslope applications, oriented roughness is the height of ridges left by tillage implements, which can vary by a factor of two or more depending upon implement type. Ridge decay following tillage is computed from a relationship including a ridge height parameter and the cumulative rainfall since tillage. A height value is assigned to a tillage implement based on measured averages for that implement.

Bulk density reflects the total pore volume of the soil and is used to update several infiltration related variables, including wetting front suction. Adjustments to bulk density are made due to tillage operations, soil water content, rainfall consolidation. and weathering consolidation. The approach to account for the influence of tillage operations on soil bulk density is a classification scheme where each implement is assigned a surface disturbance value ranging from 0 to 1, which is similar to the approach used in EPIC (Williams et al., 1984).

Effective hydraulic conductivity is a key parameter in the WEPP model tat controls the prediction of infiltration and runoff. The interrill erodibility parameter is a measure of the soil resistance to detachment by raindrop impact. Because the soil is disturbed for the cropland erodibility tests and not of rangeland tests (Laflen et al., 1987; Simanton et al., 1987), algorithms for adjusting the interrill erodibility parameter are different for cropland and undisturbed rangeland soils. Adjustment to the internll erodibility parameter on croplands are made to account for root biomass, freezing and thawing, canopy cover, residue cover, and sealing and crusting. Adjustments to the interrill erodibility parameter on rangeland are made to account for freezing and thawing.

The rill erodibility parameter is a measure of the soil resistance to detachment by concentrated roll flow and is often defined as the increase in soil detachment per unit increase in shear stress of the flow critical shear stress is a threshold parameter defined as the value above which a rapid increase in soil detachment per unit increase in shear stress occurs. As for the interrili erodibility parameter, different Feladonships are used for adjustment of the rill erodibility parameter and critical shear stress on rap land and rangcland soils. These adjusting equations include the effects of incorporated residue and roots, sealing and crusting, and freezing and thawing.

3.2.14 Hillslope Erosion and Deposition

Soil erosion is represented in two ways for WEPP overland flow profile applications: I) soil detachment by raindrop impact and transport by sheet flow on interrill areas (interrill delivery rate), and 2) soil particle detachment, transport and deposition by concentrated flow in rill areas (rill at erosion). Calculations within the erosion routines are made on a per unit rill width basis and Subsequently converted to a per unit field width basis. Interrill delivery rate is modeled as proportional to the product of rainfall intensity and interrill runoff rate. The mathematical function describing interrill delivery rate also includes parameters to account for the effects of soil roughness, slope steepness, and adjusted soil erodibility on interrill detachment and transport. Detachment due to rainfall occurring during periods when infiltration capacity is greater than rainfall intensity is not considered to contribute to interrill detachment. Rill erosion is modeled as a function of the flow's capacity to detach soil, transport capacity, and the existing sediment load in the flora Net soil detachment in rills occurs when hydraulic shear stress exceeds critical shear stress and when sediment load is less than sediment transport capacity. Net reposition occurs when sediment load is greater than sediment transport capacity. Sediment transport capacity and sediment load are calculated on a unit rill width basis. Sediment load is converted to a unit width basis at the end of the calculations. Sediment transport capacity is calculated as a function of (distance downslope) using a simplification of a modified **Yalin (1963)** equation. Conditions at the end of a uniform slope through the endpoints of the given profile are used to normalize the erosion equations. Distance downslope is normalized to the total slope length. The slope at a point is normalized to the uniform slope. Shear stress is normalized to shear stress at the of the Wiform slope. Sediment load is normalised to transport capacity at the end of the uniform slope.

The erosion and deposition component has four dimensionless parameters: one for interrill sediment delivery to rills, two for rill detachment, and one for rill deposition. The normalized sediment I continuity equation is solved analytically when net deposition occurs but it is numerically integrated when detachment occurs.

3.2.15 Watershed Channel Hydrology and Erosion Processes

The WEPP watershed model is a process-based, continuous simulation model built as an extension of the WEPP hillslope model. The model was developed to predict erosion effects from agricultural management practices and to accommodate spatial and temporal variability in topography, soil properties, and land use conditions within small agricultural watersheds. Hillslope **OFE** hydrologic and erosion output (e.g., runoff volume, peak runoff rate, and sediment concentration) is stored in a hillslope of watershed pass file and then read in and used by the channel component. The watershed model is capable of 1) identifying zones of sediment deposition and detachment within constructed channels (e.g. grassed, waterways or terraces) or concentrated flow (ephemeral) gullies; 2) accounting for the effects of backwater on sediment detachment, transport, and deposition within charnels; and 3) representing spatial and temporal variability in erosion and deposition processes as a result of agricultural management practices. It is intended for use on small agricultural watersheds (up to 260 ha) in which the sediment yield at the outlet is significantly influenced by hillslope and channel processes.

She channel component can be divided into the hydrology and erosion components. The channel hydrology component computes infiltration, evapotranspiration, soil water percolation, canopy rainfall interception, and surface depressional storage in the same manner as the hillslope hydrology component. Rainfall excess is calculated using a Green-Ampt Mein-Larson (**GAML**) (**Mein and Larson, 1973**) infiltration equation. Two methods are provided for calculating the peak runoff rate at the channel (subwatershed) or watershed outlet: 1) a modified version of the Rational equation similar to that used in the **EPIC** model (**Williarns, 1995**); or 2) the equation used in the Chemicals, Runoff, and Erosion from Agricultural Management Systems (**CREAMS**) model (**Knisel, 1980**). Channel water balance calculations are performed after the channel runoff volume has been computed. The channel water balance and percolation routines are identical to those used in the hillslope component. Input from the climate, infiltration, and crop growth routines are used to estimate soil water content in the root zone, soil evaporation, plant transpiration, interception, and percolation loss below the root zone.

The watershed model erosion component assumes that watershed sediment yield is a result of detachment, transport, and deposition of sediment on overland (rill and interrill) flow areas and channel flow areas. that is, erosion from both hillslope areas and concentrated flow channels must be simulated by the watershed version. Flow depth and hydraulic shear stress along the channel are computed by regression equations based on a numerical solution of the steady-state spatially-varied flow equation. Outlet conditions for the channel are assumed to be controlled by a downstream uniform flow, critical depth, or a structure having a known rating curve (e.g., an experimental flume). Subcritical flow is assumed unless the user specifies that slope of the energy grade line (friction slope) equals the channel (bed) slope. Channel computations are made assuming triangular, or naturally eroding cautions, however, the actual channel must be approximated by a triangular channel to compute the friction slope. The triangular channel section may have cover, but the naturally eroding channel section is assumed to be bare with no cover.

The movement of suspended sediment on rill, interrill, and channel flow areas is based on a steady-state erosion model developed by **Foster and Meyer (1972)** that solves the sediment continuity equation. Detachment, transport, and deposition are calculated by a steady-state solution to the sediment continuity equation. Relationships for the detachment capacity of channel erosion are computed using expressions developed from an experimental and analytical rill erosion studx by **Lane and Foster (1980)**. The flow detachment rate is proportional to the difference between: **1)** the flow shear stress exerted on the bed material and the critical shear stress; and **2)** the transport capacity of the flow and the sediment load. Net detachment occurs when flow shear stress exceeds the critical shear stress of the soil or channel bed material and when sediment load is less than transport capacity. Net deposition occurs when sediment load is greater than transport capacity. A nonerodible boundary is assume to exist at some depth below the bottom of the channel. When a channel erodes to the nonerodible boundary, the channel widens and erosion rate decreases with time until the flow is too shallow to cause detachment.

3.2.16 Watershed Impoundment Component

Impoundments can significantly reduce sediment yield by trapping as much as of incoming sediment. dependent upon particle size. impoundment size, and inflow and outflow rates. Typical impoundments include terraces, farm ponds, and check dams. The watershed model impoundment component calculates outflow hydrographs and sediment concentration for various types of outflow structures suitable for both laroe (e.g., farm ponds) or small (e.g., terraces) impoundments including culverts, filter fences, straw bales, drop and emergency spillways, and perforated risers. Hydrologic inputs to the impoundment component include precipitation event generated runoff volume and flow rate. Sedimentologic inputs include the sediment concentration, particle size diameter for five particle size classes (clay, silt, sand, small aggregates, and large aggregates), and the fraction of each particle size in the incoming sediment.

The impoundment component contains both hydraulic and sedimentation simulation sections. The hydraulic simulation section numerically integrates an expression of continuity using an adaptive time step which increases when the inflow and outflow rates are relatively constant. A predicted outflow hydrograph including the time, stage, and outflow at each time step is then generated The sedimentation simulation section determines the amount of sediment deposited and the outflow sediment concentration for each time step. Deposition of sediment in the impoundment is calculated assuming complete mixing and later adjusted to account for stratification, nonhomogeneous concentrations, and the impoundment shape. Conservation mass balance and overflow rate concepts are used to predict sediment outflow concentration. Impoundment component outputs include: 1) peak outflow rate and volume leaving the impoundment; 2) peak sediment concentration and the total sediment yield leaving the impoundment for the five particle size classes; and 3) the median particle size diameter of the sediment leaving the impoundment for the five particle size classes.

3.2.17 Residue Decomposition And Management

This helps to simulate plant residue decomposition and management options for cropland and rangeland ecosystems. Plant and residue options are available as tillage, burning or removing residue. To simulate the decomposition process, the "decomposition day" concept as presented by **Stroo et al.,(1989)** for winter wheat residue decomposition is used as a basis for residue biomass loss calculations. The model simulates residue decay under constant environmental conditions using C and N dynamics based on **Knapp et al.,(1983)**. WEPP uses single equation as used in the RESMAN model **(Scott and Barrett, 1995).**

3.2.18 Program Design and Development

The WEPP erosion model and interface programs have been developed and tested on IBM/compatible personal computers running under MS-DOS 5.0+ operating system environments.

The computer program has been developed in a modular fashion, integrating in a top-down design all the specialised modules (program units) which perform the basic computations. This modular s structure has been designed to facilitate substitution of different components and/or subroutines as improved technology is developed. No restrictions have been imposed on the input data length, the only limitation being due to the storage capacity of the hardware support. The source code is written in INSI FORTRAN 77 for efficiency and portability, especially among personal computers. Work continues on code analysis and reprogramming to a standard coding convention to improve WEPP model maintainability and performance.

3.3

TOPMODEL (topography based hydrological MODEL)

The hydrological processes within the catchments are dynamically and hetrogeneosly distributed and are very complex in nature such that each process of catchment hydrology behave in its own separate mathematical function. Each hydrologist may have an individual 'perceptual model' of hydrological process. The complexity of such a complex perceptual model mitigates against the formal conceptualisation of hydrology process into the functional, mathematical structures in a model such as **TOPMODEL** (a **TOP**ograpyh based hydrological **MODEL**). It is a simple physical hydrological model that aim to represent the effect of catchment hetrogenity and, particularly, topography on the dynamics of hydrological response. It is a topography based watershed hydrology model that has been used to study a range of topics, including spatial scale effect on hydrological process, topographic effect on hydrological process topographic effect on water quality, topographic effect on stream flow, climatic change effect on hydrological process, geomorphological evolution of basin , and the identification of hydrological flow path etc.

It can be justify as a, product of two objectives. One is the development of a pragmatic and practical forecasting and continuous simulation model. The other is the development of a theoretical framework within which perceived hydrological process issues of 'scale and realism' and model procedures may be researched. It is premised upon following basic assumptions:

1) that the dynamics of the saturated zone can be approximated by successive steady state representations;
2) that the hydraulic gradient of the saturated zone can be approximated by the local surface topographic slope tan(b)
3) that the distribution of downslope transmissivity with depth is an exponential function of storage deficit or depth to the water table as:

$$T=T_0e^{-s/m}$$

where To is the lateral transmissivity when the soil is just saturated. S is the local storage deficit(m) and m is model parameter(m).

In terms of water table depth this can be written as

$$T=T_0e^{-fz}$$

where Z is local water table depth (M) and f is a scaling parameter (M). Under the assumption (2) of an effective water table gradient and saturated flow parallel to the local surface table , then at any point, i on a hill-slope, the downslope saturated sub surface flow rate per unit contour length (m /n) may be described by the equation:

$$q_i=T_0\tan be^{-fz}$$

under the assumption (1) that, at any time step, quasi-steady-state flow exists throughout the soil, then assuming a spatially homogeneous recharge rate r (m/h) entering the watertable, the sub-surface downslope flow per unit contour length q_i may also be given by :

$$q_i=ra$$

a is the area of hillslope per unit contour length(m)

By combing above two we can relate local water table depth (Z), topographic index, parameter f, the local saturated transmissivity and the effective recharge rate r as:

$$Z_i=-(i/f)\ln(ra/T_0\tan b)$$

for calculating the expression for the catchment lumped, or mean, water table depth (Z) the above equation can be integrate over the entire area of the catchment (A) that contributes to the water table. Thus the above equation yields the following expression

$$f(z^{-}-z_i)=[\ln(a/tanb)-\lambda]-[lnT_0-lnT_e]$$

where lambda is a topographic constant for the catchment.

The above equation may also be written in terms of storage deficit as:

$$(S^{-}-S_i)/m=[\ln(a/tanb)-\lambda]-[lnT_0-lnT_e]$$

The above Equation implies that every point having the same soil/topographic index value a/T tan behaves functionally in an identical manner. The a/T tan variable is therefore an index of hydrological similarity.

3.3.1 INPUT AND OUTPUT

(a) Evapotranspiration

TOPMODEL, follow generally-adopted practice in calculating actual evapotranspiration (ETa) as a function of potential evapotranspiration (Ep) and root zone moisture storage. The Ea is given by

Ea = Ep(1-Srz/Srmax)

where the variable Srz and Srmax are, respectively root zone storage deficit.

(b) Recharge

For unsaturated zone fluxes the total recharge Qv to the water table in any time step is given by

$$Q_v = \quad q_{v_i} A_i$$

where q is the flux of water entering the water table locally at any time and Ai is the fractional area associated with topographic index class i as a fraction of total catchment area. Similarly the output from the saturated zone is given by the base flow term, Qb by the summation of sub-surface flows along each of m stream channel reaches of length l, thus

$$Q_b = \quad L_j (T_0 tanb) e^{-fz_j}$$

In terms of average catchment water table z, we have

$$Q_b = Q_0 e^{-fz}$$

where $Q_0 = Ae^{-\lambda}$

(c) Channel Routing

In TOPMODEL structure the overland flow is routed by the use of a distant-related delay. The time taken to reach the basin outlet from any point is assumed to be given by

$$= \quad X_i / vtanb_i$$

where Xi is the length and tan the slope of the ith segment of a flow path comprising N segment. The velocity parameter v (m/h) is assumed constant.

3.3.2 Topographic Index

For a given Digital Terrain Maps (DTM) generally Digital Terrain Analysis (DTA) techniques are used which are based on raster elevation data with the aim of investigating their utility in deriving the topographic information required by TOPMODEL.

The topographic index & soil topographic index are the indices of hydrological similarity at a point within the catchment. The response to any individual catchment as predicted by the TOPMODEL is then depend upon the similarity in the distribution of the indices & in the input sequences to which the catchment is subjected including both the time and space variability of rainfall rates & evapotranspiration losses. Furthermore in Non-dimensional version of TOPMODEL different catchment can be compared in terms of various scaling coefficients.

3.3.3 Model Calibration

In spite of many parameters to be calibrated there is only three or four critical parameters that most directly control the model response are set to be calibrated. These are the saturated zone parameter f (or m in the original storage deficit formulation , the saturated transmissivity values To, and the rote zone parameters SMAX and channel routing velocity V . In TOPMODEL Generalised Likelihood Uncertainty Estimation (GLUE) methodology is used whereby the calibration of a hydrological model generates a set of uncertainty bounds defining the range of expected model responses.This is a Bayesian method based on Monte-Earlo simulation in which the prediction of each model/parameter set realisation are given a likelihood weighting according to how well that model has fit the observed data used for concision. New observation can be used to update the likelihood weights associated with each model/parameter set.

3.3.4 Application & Result

i) Humid catchment

TOPMODEL provides good simulation of stream discharges, & broadly believable simulation of variable contributing area (Quinn & Beran) calibration of the to transmissivity which control the drainage rate from set zonal often yields high value.

ii) Drier catchments

A model that purports to predict fast catchment responses on the basis of the dynamics of saturated contributed areas may not seem to be a likely contender to simulate the responses of catchments that are often dry, such as in mediterranean or savannah climates. However, Durand et al. (1992) have shown that TOPMODEL can successfully simulate discharges in such catchments at Mont-Lozere in the Cevennes, southern France. Sempere Torres (1990) and Wendling (1992) have also used a TOPMODEL based runoff production function to simulate the response of the Gardon D'Anduze and Real Collobrier catchments in southern France respectively. They show that the runoff production function can be successfully used for flood forecasting purposes after calibration to a small number of storms and proved to be more robust in validation than other functions studied.

However, experience in modelling the Booro-Borotou catchment in the Cote d'lvoire (Quinn, 1991), and catchments in the mountains of Catalufia, Spain, suggests that TOPMODEL will only provide satisfactory simulations once the catchment has wetted up. In many low·precipitation catchments, of course, the soil may never reach a "wetted" state, and the response may be controlled by the connectivity of any saturated downslope flows. Such catchments also lend to receive precipitation in short, high intensity storms. Such rainfalls may lead, at least locally, to the production of infiltration excess overland flow which is not usually included in TOPMODEL (but see Beven, 1986a,b). The underlying assumptions of the TOPMODEL concepts must always be borne in mind relative to the pertinent perceptual model for a particular catchment.

iii) Flood frequency predictions

Beven (1986a,b) linked a version of TOPMODEL to a random rainstorm and inter storm period model to make flood frequency predictions for a number of climates. The simulations made use of soil topographic index distributions based on hypothetical distributions of hydraulic conductivity, which were also used with the variation of the Green-Ampt infiltration model of Beven (1984) to make predictions of distributed infiltration excess runoff. The model allowed runoff production to be analysed in terms of volumes of infiltration excess, saturation excess and subsurface stormflow, together with the frequency distributions of infiltration excess and saturation excess contribution areas. These were, however, hypothetical simulations. Beven (1987b) applied a similar model to the Wye catchment at Plynlimon in mid-Wales with storm based simulations and a random initial condition model based on field observations. The model was able to reproduce the observed peak over threshold frequency characteristics of the catchment for the 14 year record available after calibration of a single parameter. Uncertainty in the frequency predictions was evaluated using multiple simulations of 14 year period (Fig.18.9). Sivapalan et al. (1990) produced a scaled flood frequency model based on the TOPMODEL concepts and showed that catchment runoff production could be compared on the basis of eight similarity variables. Their flood frequency curves were derived from storm by storm simulations and showed a transition between saturation excess overland flow dominated flood peaks.

iv) Geochemical predictions

One attraction of TOPMODEL is the possibility of making predictions of the split between surface and subsurface runoff production and the way in which this varies in different parts of a catchment. In fact, by assuming some knowledge about the depths and chemical characteristics of different soil horizons, it is possible to use the predictions of depth to the water table in different locations at different times to examine the mix of soil waters entering the stream channel. This possibility has been explored by Robson et al. (1992) in an application of TOPMODEL to the Hafren catchment. Plynlimon, mid-Wales. They showed that the model results compared well with a two soil component mixing interpretation of chemical signals in the stream, provided that the flow generated on the saturated contributing areas was assumed to have a well mixed composition (either a mix of organic soil and deep waters or the chemistry of mean rainfall). The possibilities of inferring chemical behaviour from such distributed predictions still requires more exploration and internal validation.

The fact that there may be some relationship between the topographic characteristics of a catchment and its chemical characteristics, with the inference that this is due to the effects of topography on flow pathways, has also been explored by Wolock et al. (1989, 1990). In studies of catchments in the north-eastern United States and Wales they showed that the mean of the In(a/tan) distribution is strongly related to catchment acidification. TOPMODEL predictions of areas susceptible to surface saturation have also been used in Wales to decide areas for liming (Waters et al., 1991)

3.4

SHE MODEL

3.4.1

BRIEF DESCRIPTION OF SHE

The SHE is a deterministic, distributed and physically based modelling system. It has been jointly developed by the Danish Hydraulic Institute (Denmark). the Institute of Hydrology (UK) and SOGREAH (France). The partial differential equations describing the processes of overland and channel flow, saturated and unsaturated zone are solved by finite difference methods. In addition different methods are used for description of interception evapotranspiration and snowmelt. The unsaturated zone computations are made in one-dimensional columns Abbott et al (1996a, 1996b).

In the SHE model the basin is divided in a number of equal sized grid squares. The size of the individual squares depends upon the size of the basin, the data availability, the purpose of the study and the computational facilities available.

In the SHE model, a separate sub-model component is solved for each hydrological process with a master component controlling the running of each of these as well as data exchange among them. The linkage of one-dimensional unsaturated Zone and two-dimensional saturated zone is achieved through a coupling component. Similarly, the exchange of water between river and aquifer is achieved with the help of an exchange component. The SHE, by virtue of being a modular system, allows the user to make a choice among the components which he wants to invoke. In case it is decided to skip execution of a particular component, a corresponding dummy component is called which sets and transfers boundary conditions. This permits greater application- flexibilities since the same code can be used for modelling a single unsaturated zone column as well as a large basins with manifestations of all component processes, A brief description of various components is summarised as :

EVAPOTRANSPIRATION (ET) COMPONENT

This is a one-dimensional interception and evapotranspiration component. The interception model calculates net rainfall reaching the ground through canopy, water stored on the canopy and evapotranspiration from the canopy. No distinction is made between throughfall and stemflow nor the interception of snow and fog is accounted for. The approach based on Leaf-Area is used to calculate

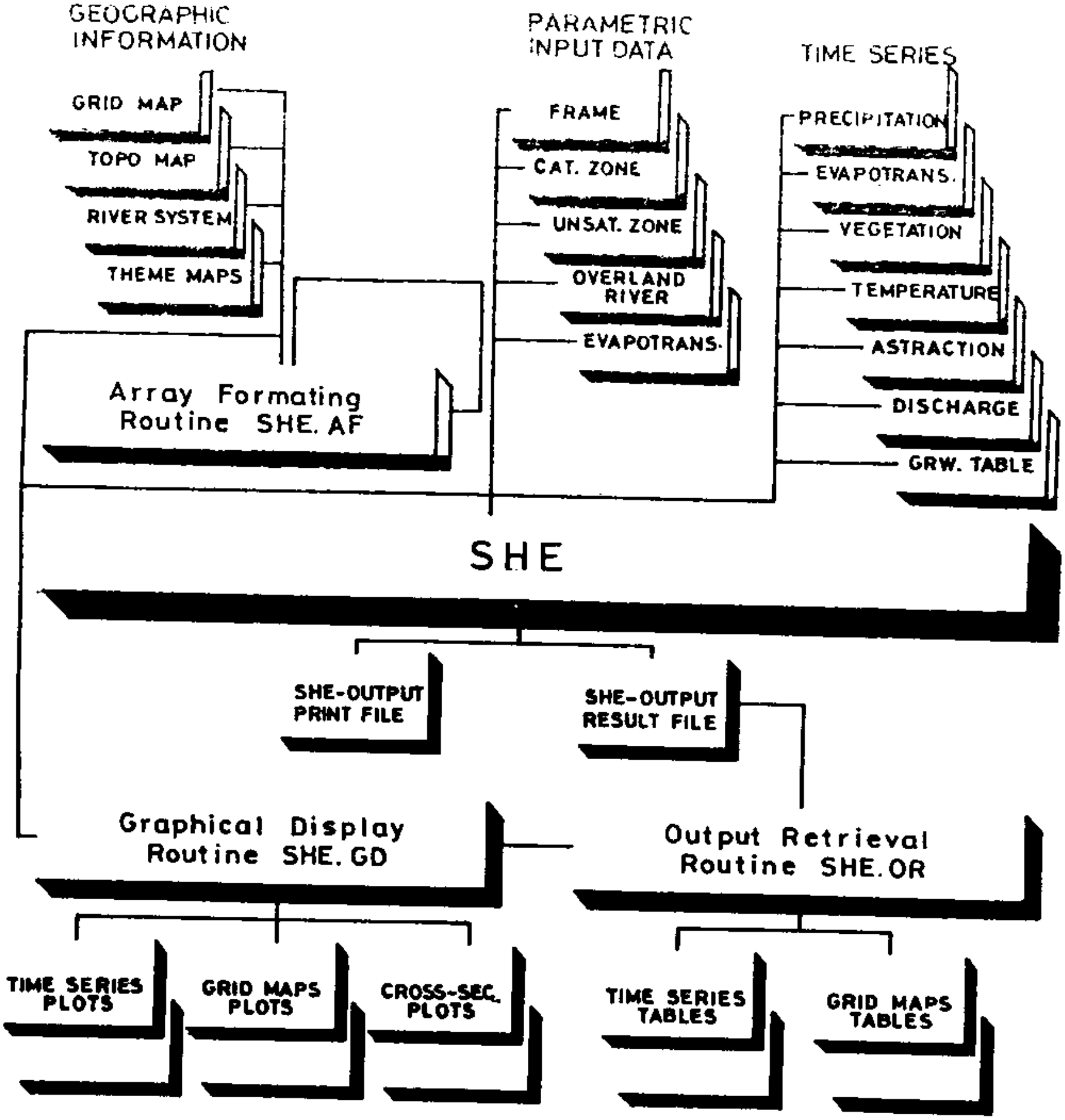


FIG. 3·4 FLOW CHART OF THE SHE MODEL

interception
C=CINT *LAI
where C = water stored on canopy,
CINT = Interception coefficient,
LAI = Leaf Area Index

The input rainfall in excess of C+Evaporation will only reach to the ground. The evapatranspiration module of SHE calculates evaporation of intercepted moisture from the canopy surface, uptake of water by plant roots and its transpiration. Four calculation options are available. The choice of a particular option depends on data availability and the understanding of the evapotranspiration process in a particular application.

SNOWMELT (SM) COMPONENT

This component models the snow pack thickness as affected by precipitation and melting and also the rate of deliveries of meltwater from the snow pack to the soil surface. The model is structured so that the total heat flux to the snow pack is calculated either by Degree-Day or by Energy Budget method, the amount of melting by this flux is calculated and finally the meltwater is routed through the snow pack.

3) OVERLAND AND CHANNEL (OC) FLOW COMPONENT

The generation of overland flow takes place in three conditions a) when precipitation input is greater than infiltration capacity of soil in which case it is termed as Hortonian Flow, b) when top soil layer is saturated in which case even a low intensity rainfall is able to generate flow termed as saturation excess flow, and c) when subsurface flow is forced up to the ground surface where it flows as overland flow and in which case any rainfall will generate overland flow (Dunne's overland flow mechanism). The surface runoff is routed in the down gradient towards the river system, during the journey, whose route is determined by the topography and surface resistance. The quantity of water undergoes changes because of evaporation infiltration and additional rainfall. The water reaching river system is routed in the downstream direction.

In SHE the overland flow is modelled using a two - dimensional model and the river flow is modelled using a one - dimensional model. In the models it is assumed that the rivers run parallel to grid boundaries. The routing of surface runoff as well as streamflow is done using the St. Venant Equations. In the simplied form, these continuity and momentum equations can be written as :

$$\delta A/\delta t+\delta Q/\delta x = 0$$

$$\delta Q/\delta t+\delta(U^2A)/\delta x+gA((\delta h/\delta x)-So)+gASf = 0$$

where

A = A(x,t) is wetted cross section area,
U = U(x,t) is flow velocity,
S_o = Bed slope,
S_f = Friction slope,
Q = Discharge

Provision has been made in the model which enables a user to specify the catchment roughness on a distributed basis. The model also accounts for the surface detention storage. The finite difference form of Richard Eqnis solved using an implicit scheme. An efficient numerical scheme which takes advantage of the special matrix structure is used to obtain the solution. A module to simulate the behaviour of a lake inside a catchment has also been developed,

4) UNSATURATED ZONE (COMPONENT)

This is a one - dimensional model component which is used for computation soil moisture changes in the unsaturated zone. The upper part of this zone loses water due to soil evaporation and extraction by plant roots. In the lower part of unsaturated zone, moisture changes take place due to fluctuations in water table. The UZ columns are modeled by one-dimensional Richards' equation,

$$C\,\delta\psi/\delta t = \delta(K\delta\psi/\delta z)/\delta z + (\delta K/\delta z) - S$$

Where;

C del(Psi)/del(t) is the slope of soil water retention curve, Theta is the volumetric soil moisture contents, Psi is the pressure head, k is the unsaturated hydraulic conductivity and S is the root extraction sink term.

which is non-linear and its solution requires knowledge of physical properties of soil. Two important parameters of soil physical property are hydraulic conductivity K(e) and moisture content W(e). The hydraulic conductivity KE decreases sharply as the moisture content decreases from saturation. This happens because as saturation decreases more pores get filled with air, less area becomes available for flow and also the flow path becomes more tortuous. In SHE, the relationship between K(e) and e is described using Averianov's (1950) formula according to which

$$K_r = \{(e-e_r)/(e_s-e_r)\}^n$$

where,

e = actual moisture content.

e_s = saturated moisture content.

e_r = residual moisture content.

n = Averianov's exponent. varying with soil type.

In the SHE model, a fully implicit formulation has been adopted to solve the Richards equation. The space derivative are represented by their finite difference analogs at time level n+1, The values of C(e) and K(e) are referred to at time **level** n+1/2, These are evaluated in an iterative procedure.

5) UNSATURATED ZONE (SZ) COMPONENT

As the name suggests, this component is used to simulate the response of saturated subsurface zone of ground water. The present version is capable of handling three dimensional multi-layered aquifer systems. In the SZ component, provision of horizontal drainage has also been made, This drainage acts as a bypass and water can quickly pass to the river. The elevation of the drainage and its time constant are specified by the user.

6) IRRIGATION (IR) COMPONENT

A new module, named Irrigation component has been time recently added to the SHE to model the process of irrigation. This is a two dimensional model to simulate the irrigation practice in an area.

7) WATER BALANCE PROGRAMME

SHE water balance programme has been developed to prepare component wise water balance summary of the catchment for a specified span of time or in instantaneous mode, The output from this programme can be inspected to determine the response mechanism of the basin, to find the contribution of each individual component, to find where water in going and from where water is coming to river, etc,

8) PROGRAMMING ASPECTS

In the SHE programme, separate set of routines are available for modelling of different components of the hydrologic cycle. The main programme named **FRAME**, is responsible for calling initialization routine, reading the input data and determining the time step size. It also calls different subroutines in proper order and ensures data exchange among them. in case it is decided to omit a particular component a dummy is called instead. The advantage of this modeled programming is that whenever a new version of **a(iy** component is developed it can replace its older version without affecting any other component. Each component reads its input data from, separate files,

The SHE requires rather large computational requirements both in terms of size CPU memory and disk storage) and execution.time. Just to give an idea, for a machine having speed of the order of several maps. the time required for simulation of a basin of size 1000 square km will be of the order of one hour of CPU time for data of one year. Of course. this time is dependent on a number of factors. e.g. number of grids, river links, calculation columns and volume of precipitation input etc. However, with the current trend in developments in the computer industry. it will be possible to run SHE on micro computers within a few years.

9) DATA REQUIREMENTS

A large number of parameters describing the physical characteristics of the catchment on a spatially distributed basis is required in addition to the hydrological, and meteorological time series for successful running of the SHE model. The purpose of model application will govern the accuracy of input data.

The data required for a typical SHE Model application may be obtained from field measurements and from such measurements supplemented by the available scientific literature. For example, the soil hydraulic properties which are required for a SHE application may not be available in Indian context and field and/or laboratory measurements will have to be carried out in such cases to determine the required parameters. The data and parameters required for a typical SHE application can be divided in two categories fixed data and time series data.

The fixed or time unvarying data for each grid square (or channel link) for the SHE model consists of a) Ground surface elevation, b) impermeable bed elevation, c) distribution codes for rainfall and meteorological stations, d) distribution codes for soil and vegetation types, e) soil hydraulic properties, f) river channel geometry and conveyance properties, g) surface roughness characteristics, h) surface detention storage,

The time series data consists of the a) precipitation data series. b) potential evaporation series, c) temperature data series, d) variation of root zone depth and leaf area index with time, and e) initial phreatic surface level

10) DATA PREPARATION

Since the model requires a huge amount of spatially distributed data, it is a very time consuming and tedious process to prepare the input files of SHE in the particular format required. Moreover, the data are often available on maps of different scale. It is. therefore convenient to provide the data on the scales available and then automatically set up the spatially distributed data an the scale which has been selected for the numerical computation. In order to facilitate the data preparation, a preprocessor. SHE Array Formatting Routine (SHE.AF), may be used.

11) THE SHE ARRAY FORMATTER (SHE.AF)

The SHE.AF reads a series of data files containing various arrays of spatially distributed data, prepares a setup for SHE model on the desired grid scale, and writes the data to the appropriate files in the required format. It also requires a set of existing SHE input files which are read and updated again with appropriate new data arrays, The entire data preparation can be finalized within short time for grid systems comprising several thousands squares using SHE.AF. With each component, one data file is attached. The naming of the files is usually given in a way which identifies the specific catchment followed by three letters indicating the component

*.FRD - Fame data file,
*.SZD - Saturated zone data file,
*.UZD - Unsaturated zone data files
*.DCD - Overland and channel flow data file,

*.ETD - Evapotranspiration data file,
*.SMD - Snowmelt data file,
*.PRD5 - Precipitation data file,

12) RUNNING SHE PROGRAMME

After preparation of the required SHE data files the SHE simulation can be started. The user is prompted to give the catchment name, Using this catchment name, appropriate data files are opened, These data files are then read in and the input data is obtained. Two output files are created in SHE run. The SHE output print file contains various results, warnings and error messages. It is recommended that in the initial phase of a SHE application, the initial conditions may be written on the print file for checking up of data. The results of a SHE run are stored in a result file which is a binary file. The results may be retrieved from this file by applying the output retrieval routine SHE.OR.

13) PRESENTATION OF INPUT AND OUTPUT DATA

The SHE Graphical Display Routine SHE.GD can be applied either for display of SHE results which are retrieved by applying the SHE.OR, or for display of in data to the SHE, A number of options are available

A host of other peripheral programmes have been developed as a part of the SHE package to do a variety of chores.

3.5

USLE MODEL

The Universal Soil loss equation is the most widely used empirical overland flow or sheet rill erosion equation(Wischmeier and Smith, 1978). The history of efforts goes back to mathematically predict soil erosion by water started only a half century ago(USDA, 1991). Initially the equation was developed as a tool for soil conservationists to use in developing farm management plans to control erosion and maintain soil productivity. Initial works were carried out by Cook to identify the major variables that affect soil erosion by water. He listed three major factors: the susceptibility of soil erosion, potential erosivity of rainfall and runoff, and the soil protection afforded by plant cover. Later Zingg(1940) gave the first equation for calculating field soil loss, which describes the effects of slope steepness and slope length on erosion. Smith(1941) added another factor of cropping pattern. Browning and his associates(1947) added soil erodibility and management factors to the above equation and prepared more extensive tables of relative factor values for different soils, rotations, and slope lengths. This approach emphasised the evaluation of slope length limits for different cropping systems on specific soils and slope steepness with and without contouring, terracing, or strip cropping. Smith and Whitt(1947) presented a method for estimating soil losses from fields of claypan soils. Soil loss ratios at different slopes were given for contour farming, strip-cropping, and terracing. Further Smith and Whitt(1948) presented a rational erosion-estimating equation, which broadened the application.

The work carried out by United States Department of Agriculture(USDA) brought about Musgrave equation, accounting the rainfall factor, flow characteristics of surface runoff as affected by slope steepness the slope length, soil characteristics, and vegetal cover effects (Musgrave, 1947). Further works during sixties established that the maximum permissable loss for any soil as 5 tons/acre/year and set lower limits for many soil groups. Subsequent studies combined crop rotation and management factors into one factor (Wischmeier et al., 1958).

Actual measurement of soil loss is not feasible for each of the level of these factors occur under field conditions. Erosion and sedimentation by water involve processes of detachment, transport and deposition of soil particles (Foster, 1982). The major forces are from rain drop impact and water flowing over the land surface. Erosion may be noticed on exposed soil surfaces even though raindrops are eroding large quantities of sediment, where as it can be dramatic where concentrated flow creates extensive rill and gully systems. Factors affecting erosion can be expressed in an equation of the form (Renard and Foster, 1983)

$$E = f\ (C\ ,S\ ,T\ ,SS\ ,M\ )$$

where, E = Erosion, f = function of (), C = Climate, S = Soil properties,

T = Topography, SS = Soil surface conditions, and M = Human activities. More recently, it has been used to estimate the sediment yield for design of small reservoirs. With the increasing awareness in water quality aspects, it has been increasingly used to estimate sediment yield and erosion's contribution to mon-point source pollution. The equation is simple. It is based on a large data set of over 10,000 plot-years of data from natural runoff plots and the equivalent of 1,000 plot-years of data from field plots under rainfall simulators. The term 'Universal' in the USLE distinguished this prediction model from the regionally based models that preceded it. USLE does not address the sediment yield. The USLE compute the average annual erosion expected on field slopes. The USLE is given by

$$A = R * K * L * S * C * P$$

where, A = the computed spatial average and temporal soil loss per unit area, expressed in units selected for K and period selected for R. In practice, these are usually selected so that A is expressed in t/acre/year, but other units can be selected (i.e. mt/ha/year), i.e it is soil loss averaged over the slope length, λ(mass per unit time period of R); R = is the number of rainfall erosion index units, plus a factor for runoff from snowmelt where such runoff is significant, is a base variable which combines erositivity of rainfall and runoff (EI unit per unit time which is usually average annual in the units of 100 (ft-tons/acre)* (in/h), the common value of EI range from 50 to 550 in the east part of US); K = is the soil loss rate per erosion index unit for a specified soil as measured on a unit plot, which is defined as a 72.6 feet (22.1 m) length of uniform 9% slope in continuous clean tilled 39fallow, the soil erodibility factor (soil. loss, mass from unit plot* on a specified soil per unit area per EI unit, in tons/acre, the value range from 0.05 to 0.60); L = the slope length factor, is the ratio of soil loss from the field slope length to that from a 72.6 feet length under identical conditions (dimensionless; $L=\lambda/\lambda_u)^n$, where λ= slope length, λ_u = length of unit plot (22.1m) and n = slope length exponent (usually 0.5); S= the slope steepness factor, is the ratio of the soil loss from the field slope gradient to that from a 9% slope under otherwise identical conditions [$s = (65.4 S^2 + 4.56s + 0.065)$ where $s = \sin \theta$ and θ = slope angle]; C = the cover and the management factor, is the ratio of the soil from an area with specified cover and management to that from an identical area infilled continuous fallow (dimensionless ratio of soil loss with a given management practice to that from the unit plot), OR it is the ratio of the soil from an area with specified cover and management to that from an identical area infilled continuous fallow; and P = supporting practices factor (dimensionless, the ratio of soil loss with support practice like contouring, strip cropping, or terracing to that with straight-row farming up and down the slope where contouring or other supporting practices is used to that from the unit plot) In this only R and K have units. All other factors are dimensionless and express that factor's effect on erosion when all other factors are identical.

The USLE lumps interrill and rill erosion together by the help of a regression equation with nonhomogeneous units which requires special consideration, in case the unit is to be converted from English to metric. EI from map when multiplied with 1.072 gives R in N/h(Newton per hour) in SI metric unit. Similarly by , multiplying English K with 0.1317 gives metric K ($(kg/N)* h/m^2$). $RK = N.kg.h/h.N.m^2 = kg/m^2$, where 1 kg/m^2 =0.1 Mg/ha.

The erosion is a result of combination of numerous physical and management variables occurring at a particular site. There is difference between sediment yield and erosion. Sediment yield is the amount of eroded soil that is delivered to a point in the watershed remote from the origin of the detached soil particles. In a watershed the sediment yield includes the erosion from slopes, channels, and mass wasting, less the sediment that is deposited after it is eroded but before it reaches the point of interest. The equation is applicable wherever numerical values of its factors are accurately available and the conditions for which it can be reliably applied Wischmeier(1976). Further, Wischmeier and Smith (1965,1978) have updated the content and incorporated new material that has been available infirmly or from scattered research reports and professional journals. The aim being i) to represent the loss by a single number, ii) it could be represented from meteorological, soils, or erosion research data on locational basis., and iii) must be free from any geographically oriented base.

The USLE was developed from plots of uniform steepness, soil and cover. Generally no deposition other than local deposition in micro depression occurs on uniform slopes, especially those greater than 3%, the slope of the flattest USLE plot. Therefore the USLE is an erosion equation, that does not estimate deposition. However nonuniformities that do not cause deposition including slope shape, soil, and cover management can be analysed (Foster and Wischmeier, 1974). Since A in the USLE is the average loss for the slope length λ, the sediment load q, at any location x downslope is therefore:

$$q_s = R\,K\,x^{(N+1)}\,S\,C\,P/\lambda^N{}_U$$

In case deposition occurs, transport relationship is required in addition to USLE. Total sediment transport capacity of overland flow for a storm may be estimated from (Neibling and Foster, 1977).

$$T_C = 138\,V\,q_p\,s^{1.55}\,C_T$$

where $_{TC}$ = total transport capacity for a storm, mass per unit width (g/m), V = total discharge per unit width (m^3/m), q_p= peak discharge per unit width ($m^3/s.m$), s = sine of the slope angle, and C = a factor reflecting the direct influence of soil cover on the flow's hydraulic forces. When transport capacity decreases below the sediment load, the coarser and denser particles are deposited within a shorter distance. Fine particles like clays, travel a considerable distance before setting out.

3.5.1 IMPROVEMENTS

An improvement in the erositivity factor was suggested by (Foster et al. 1977) as $R_m = 0.5 R_{st} + 0.35 V_u \sigma_{pu}^{1/3}$, where R_m = a modified erositivity factor to replace R when USLE is used to estimate soil loss from a single storm soil loss, R_{st} = EI_{30} (N/h) for the storm (E, being the total energy and I_{30} is the storm's maximum 30 min intensity), V_u = runoff volume (mm) , and σ_{pu} = peak rate (mm/h) of runoff from a unit plot of the same soil assuming that the given storm had occurred on the test plot. The C and P factors are selected based on conditions at the time of the storm, accounting for the effect of cover-management and supporting practices on runoff as compared with runoff from unit plots. The slope length exponent n for the slope length factor $L = (\lambda/\lambda_u)^n$ varies from storm to storm (Foster et al., 1977b). It is greater when rill erosion is greater e.g., a storm occurring on a bare, wet soil produces greater runoff and thus more rill erosion. Conversely, n is smaller for a rain on a dry soil where runoff is smaller. Data are inadequate to estimate how much n changes. A conservative change would be to increase n by 0.1 when rill erosion is considerably more than normal and decrease n by 0.1 when rill erosion is considerably less than normal. A similar variation may also exist in the slope steepness effect (Foster and Meyer, 1972a)

3.5.2 **Merits** (Wischmeier, 1972):

i) It provides more complete separation of factors effects so that results of a change in the level of one or several factors could be more accurately predicted.

ii) An erosion index that provided a more accurate, localised estimate of erosive potential of rainfall and associated runoff;

iii) a quantitative soil erodibility factor that was evaluated directly from research data without reference to any common benchmark;

iv) an equation and monograph capable of computing the erodibility factor for numerous soils from soil survey data

v) a method of including effects of interactions between cropping and management parameters; and

vi) a method of incorporating the effects of local rainfall patterns through the year and specific cropping conditions in the cover and management factor.

3.5.3 Demerits

The USLE is intended to estimate average soil loss over an extended period, e.g. average annual soil loss. Errors are large in the estimated soil loss from a single storm from substituting storm EI for R in the soil loss equation, primarily because the great variation in runoff which can occur from rainfall to rainfall for a given rainfall amount is not considered.

3.5.4 Limitations

There three major limitations of USLE, which restrict its application in many modelling analyses. They are:

i) It is not intended for estimating soil loss from single storm events.

ii) It is an erosion equation, and consequently it does not estimate deposition (Wischneier, 1976).

iii) It does not estimate gully or channel erosion.

3.5.4 MODIFIED UNIVERSAL SOIL LOSS EQUATION (MUSLE)

The modified form of USLE is called Modified Soil Loss Equation(MUSLE). Knowledge from such research was used in developing physically based models such as erosion/sedimentation components of CREAMS(Knisel, 1980) Foster et al., 1981) and process oriented Water Erosion Prediction

Project (WEPP) models (Foster and Lane 1987, Lane and Nearing 1989), which were developed by ARS, SCS and other agencies and are treated to be the most superior than USLE/RUSLE lumped model.

The modified Universal Soil Loss Equation (MUSLE) is used to for the estimation of the sediment yield. Sometimes, the sediment yield is estimated as gross erosion with the USLE and then multiplying by a delivery ratio (ASCE, 1975). For small watersheds, especially fields, this method is often inadequate and can lead to totally false conclusions. MUSLE is the improvement over USLE erosion model designed to predict the longtime average annual losses(A) carried by runoff from specific field slopes in specified cropping and management systems as well as from range. Widespread use has substantiated its usefulness and validity for the purpose. They include new a new and revised isoerodent maps, a time varying approach to reflect freeze thaw conditions and consolidation caused by moisture extraction of the growing crop for the soil erodibility factor (K); a subfactor approach for evaluating the cover and management factor (C) for cropped land, rangeland , and distributed areas; a new equation to reflect slope length(L) and steepness(S) (new terms also reflect the ratio of rill to interrill erosion); and new conservation practice value (P) for both crop land and rangeland practices(USDA Agriculture Handbook No 537). It is also applicable for nonagricultural conditions such as construction sites. Concept of multiplying with the delivery ratio in USLE should be used as first approximation only. To make it more clear, let us take a terraced field in conventionally tilled corn that produces a given runoff for a given storm. Now, for a typical delivery ratio for terrace is 0.2, means that 80% of the sediment produced on the inter terrace interval is trapped in the terrace channel. Assuming that no-till corn is planted next year, the runoff may not decrease significantly. As a result, the sediment transport capacity in the terrace channel is not greatly reduced although crop residue in the channel may slightly reduce it. With the incoming sediment load being greatly reduced, no corresponding reduction in transport capacity, deposition may not occur in the terrace channel. The fraction deposited in the terrace channel depends on the amount of sediment entering the flow relative to the transport capacity of the flow. As a result, the delivery ratio is not constant as it is assumed.

With appropriate selection of its factor values, MUSLE will compute the average soil loss for a multicrop system, for a particular crop year in a rotation, or for a particular crop stage period with in a crop year. It computes the soil loss for a given site as the product of six major factors (some of which also include numerous subfactors) whose most likely values at a particular location can be expressed numerically. Erosion variable reflected by these factors vary considerably from storm to storm about their means. But the effects of the random fluctuations such as those associated with annual or storm variability in rainfall runoff erosivity(R) and the seasonal variability of the cover management factor (C) tend to average out over extended periods. Because of the short term fluctuations in the levels of influential variables, however present soil loss equations are substantially less accurate for prediction of specific events than those for prediction of long term·averages.

In many watershed, especially those larger than fields, some deposition usually occurs; the overall sediment yield response is influenced by a variety of deposition features rather than by a single major feature. When deposition does occur, sediment yield is highly correlated with runoff characteristics, since flow controls sediment transport capacity which is closely related to sediment load when deposition occurs. Williums(1975a) modified the USLE to estimate sediment yield for individual runoff events from a given watershed by replacing the USLE 'R' factor with $R_w = 9.05\ (V.Q_p)^{0.56}$, where V is the volume of runoff (m^3) and Q_p = peak discharge rate (m^3/s). The USLE with this R factor is referred to as the modified USLE or MUSLE. Sediment yield is now given in mega grams for the total watershed area rather than kg/m^2. Channel and gully erosion or deposition in impoundments are accounted for separately and added to or subtracted from the equations estimate (Williums, 1978).

The MUSLE assumes that deposition occurs in the watershed, it only gives an estimate of total sediment yield and not an estimate of the yield of the individual particle classes. Deposition segregates particles. The more easily deposited particles settle out early after they leave their source area while the smaller and lighter ones travel further through the watershed before depositing. An exponential decay function can be used to route sediment through the watershed to estimate this segregation (Williums, 1975b; Williums, 1978). The equation is a function of travel time and particle size.

3.5.5 MODEL INPUTS

i) The EROSION INDEX OR 'R' factor

This is rainfall and runoff factor of the Universal Soil Loss Equation (USLE) was derived empirically by (Wischneier, 1959; Wischmeier and Smith, 1958). This indicates that keeping rainfall constant, storm soil losses from cultivated fields are directly proportional to a rainstorm parameter, the total storm energy (E) times the maximum 30 min intensity (I_{30}). Rill and sediment deposits are usually a function of peak storms. The rainfall factor used to estimate average annual soil loss must include the cumulative effects of many moderate sized storms as well as the effects of occasional severe ones. It must consider the raindrop effect and must also reflect the amount and rate of runoff likely to be associated with the rain. The erosion index, R, may be evaluated directly from maps. This index does not include the erosive forces of runoff from snowmelt, rain or frozen soil, or irrigation. The values of this index on local basis is taken from the map of equal rain erosivity(Isoerodent maps). Exact values at a point may be had by linear interpolation. The value of $R=27.38P^{2.17}$, where P is 2-yr frequency, 6hr rainfall amount (Wischmeier, 1974) was found to give

ii) EI PARAMETER

The EI is energy times intensity and not simply the energy for a given storm is the product of total storm energy (E) and maximum 30 min intensity (I_{30}), Or , a statistical interaction that reflects how total energy and peak intensity are combined for the respective storms. Technically it indicates how particle detachment is combined with the transport capacity. The value of E is in (1/100*ft-tonf/acre), and I_{30} is in inches per hour(in*/hr). It is observed that the rainfall intensity is not a good indicator of the erosive potential. The energy of the storm indicates that the volume of rainfall and runoff for a long and slow rain may have the same E value as the shorter rain at much higher intensity. Raindrop erosion increases with intensity, The I_{30} indicates the prolonged peak rates of the detachment and runoff.

The EI and soil loss are assumed to follow linear relationship. The sum of the storm EI values for a given period is a measure of the erosive potential of the rainfall within that period. The average annual total of the storm EI values in a particular locality is the rainfall erosion index(R) for that locality. Rain showers less than 0.50" are not considered from the erosion index computations, unless the intensity is 1"/hr, and hence it is considered as the threshold value.

Since raindrop size increases with rain intensity (Wischmeier and Smith 1958) and terminal velocities of free fall water drops increase with increase drop size (Gunn and Kinzer, 1949) and the energy of a given mass in motion is proportional to velocity-squared, the rainfall energy is directly related to rain intensity. Based on Laws and Parsons(1943), the value of the kinetic energy 'e' in ft-tonf/acre/inch is given by

$$e = 916+331 \log_{10} i \quad i \leq 3 \ inch/hour$$

which corresponds to

$$e_m = 0.119 + 0.0873 \log_{10}(i_m) \quad i_m \leq 76 \ mm/hr$$

$$e = 1074 \quad i > 3''/hr$$

Or, this corresponds to

$e_m = 0.283 \quad i_m > 76 \ mm/hr$, where e_m is in 10^6Joule/ha/rain(mm)

where 'i' is the intensity in inch/hour. A limit of 3"/hr is imposed on i because median drop size does not continue to increase when intensities exceed 3"/hr (Carter et al., 1974). Finally the equation for calculating the kinetic energy emerges to

$$e = e_m [1- a\, e^{-bi}]$$

where e_m is the maximum unit energy as intensity approaches infinity, and a&b are the coefficients. whereas the US customary is to use the following equation

$$e = 1099[1- 0.72\, e^{(-1.27i)}]$$

where i is in inch/hour and e is in ft-tonf/acre/rain(inch).

3.6

EPIC MODEL

The **Erosion Productivity Impact Calculator (EPIC)** is one amongst a site or field scale models, which simulates biophysical processes on SUs within definable management systems to determine the effect of alternative practices. The model is particularly adept at addressing issues dealing with erosion sediment delivery to edge of field, terracing, impacts of ground cover/ deforestation, nutrient issues, soil acidity/aluminium toxicity, organic matter management and decomposition, plant available water/soil water holding capacities, plant bio-mass/ yield, plant variety and planting dates, and other management options.

Stewardship unit(SU): Taking a lowest common basic unit for describing a complex of intersecting themes found in an area of geographic space an Stewardship unit(SU) is described. This SU is an area of land(or water which responds in a predictably similar way. It is comprised of sufficiently homogeneous combinations of attributes such that the values of the attributes can be assumed to be the same value or kind. A SU is based upon an integrated analysis of hydrology, soils, vegetation, land use, management, economic opportunities, and other relevant parameters associated with dynamic modelling and database environment. If a technological invention operates at a scale of forest site or a farmer's field than SU's would be needed which would distinguish opportunities at the site level. If the impact of a national policy is to be assessed, then the associated SUs would reflect a resolution suited to the task. The distinction is critical when modelling for watershed management because of two fundamental concepts. 1) Models require discrete numbers as inputs into equations. 2) Appropriate decisions and resulting treatment differ among SUs.

The EPIC model **(Williams et al., 1984)** was originally developed to assess the effects of the soil erosion productivity of the natural resource base. It was developed and first used for national planning in the United States as part of the 1985 Resource Conservation Assessment (a national assessment conducted in the USA every 10 years as part of the development of a Conservation Plan).

It is a continuously daily time step model designed to provide simulation output summaries on a daily, monthly, annual and/or multi-year basis. It will run for long sequences of year following for development of frequency distribution output statistics for many simulated attributes. It is frequently used for 50-100 year simulations or longer. The drainage area considered by EPIC is generally a field-sized area, up to 100 ha. The major components and processes simulated by model are hydrology, erosion-sediment, nutrient, nutrient cycling, plant growth, aluminium toxicity/lime, soil temperature, tillage, economics, and plant environment control. In more recent years the model has evolved to also address issues of

1. water quality with the addition on pesticide fate, better nitrification and submodels;
2. climate change assessment capabilities with addition of CO_2 sensitivity and vapour pressure deficit equations, and
3. improved wind erosion submodel,
4. improved estimation curves for peak runoff rates,
5. newly developed sediment yield equations, and
6. better manure and organic carbon management and decomposition capabilities.

Current activities and plans will address salt issues in soil and water, improved inter-cropping routines, and improved near real time(within season) management evaluation.

3.6.1

Model Component

A brief description on some of the major sub-models for a better understanding of the watershed management issues which can be addressed using this simulation tool is provided hereunder.

(a) Surface Runoff

Runoff volume is determined by using a modification of the soil Conservation Service(SCS) Curve number technique(**US Department of Agriculture, Soil Conservation Service 1972**). The technique is attractive because it used generally available daily rainfall data in the calculation making technique generally applicable to many location and conditions. The model addresses rainfall intensity by either of two following methods:

- the input of rainfall intensity if available at location
- a stochastic generation of intensity from daily and/or monthly rainfall intensity records.

(b) Percolation

The percolation submodel of EPIC operates from a total water storage technique. Once the surface runoff is calculated, the remaining water infiltrates into the soil. The water flows from soil layer to deeper soil layers according to saturated conductivity coefficients and fills the soil profile to the total water holding capacity of the soil profile(providing sufficient rainfall and infiltration occurs). The soil will then drain into deep percolation or lateral flows until the soil reaches its stable field capacity (drained upper limit) of each layer of the soil.

(c) Lateral Sub-surface Flow/ Deep Percolation

Lateral subsurface flows and deep percolation are calculated simultaneously since they are inter-dependent. Lateral flows are the lateral travel time and land surface slope in calculating the lateral movement. Lateral movement is defined as water movement in one of the soil horizons identified in the soil profile description. Any water which leaves the bottom of the identified profile is deep percolation by the definition of the model accounting system. Water defined as deep percolation can be returned to the system in watershed accounting models like SWAT as base flow. However, in EPIC water leaving the profile (generally root zone) is lost for use by the plants in the field or SU. The presence of the dense soil layers(manmade or natural)will force more water into lateral flow and can prevent the filling of the deeper areas of the root zone. Removal or opening of these barriers may increase the plant available water stored in the profile.

(d) Evapo-Transpiration

The EPIC model allows four options for estimating potential evapotranspiration. **Hargrieves and Sumani(1985)**, **Priestey and Taylor(1972)**, **Penman(1948)**, and **Penman Monteith (Monteith, 1965)**. The equation chosen will depend on the preference of the user and on the amount and kind of the weather data available. The Penman and Penman- Monteith require solar radiation, air temperature, wind speed and relative humidity while the Hragrieves equation only requires maximum and minimum daily temperatures. The casual transpiration is calculated as soil evaporation and plant transpiration separately as developed by **Ritchie(1972)**.

(e) Snowmelt

Snow and snow pack are melted as a function of snow pack temperature calculated from equations using surface temperature and soil temperature below snow pack. Melting snow is treated same as rainfall in estimating the runoff volume an percolation with the exception the snow melt does not have rainfall energy only runoff energy.

(f) Weather

The weather attributes required by the model includes maximum and minimum air temperature, precipitation(rain and snow), and solar radiation. As indicated above wind speed and the relative humidity are required for Penman and Penman Monteith Equations. The model will operate with either actual historical weather data or generated data provided by a stochastic weather generator submodel included as part of the EPIC code. Several options permit the user to simulate daily values for one or all of these parameters depending on the availability of data and the intended use of the simulation runs.

The weather generator **(Richardson, 1982)** **(Nicks, 1974)** will create a sequence of daily values for use by the other subprogrames. The simulated weather values will have the same statistical properties as the historical weather file. The technique allows one to take 15020 years of historical data, obtain the statistical properties from that location, and simulate 100 or more years of daily weather. The longer simulations will be more likely to contain occurrences of the extreme events like very large runoff/erosion events and provide more useable frequency distributions for risk analysis.

(g) Soil Erosion by Water

The EPIC model simulates soil erosion caused from rainfall, runoff, irrigation (sprinkler and flood) and snowmelt. The erosion submodel estimates soil losses from six alternative equations designed to predict erosion using various methodologies. They differ in the way the erosive energy is calculated. The most well known USLE (Universal Soil Loss Equation) **(Wishmeier and Smith, 1978)**, considers rainfall energy only for use only the runoff energy, and one uses a combination of both types of energy. The Four all versions MUSLE (Modified Universal Soil Loss Equation), **(Williums, 1975)**, using the runoff energy only have advantages in watershed modelling because they increase the prediction accuracy, eliminate the need for a delivery ratio to estimate sediment yield, and enables the equation to give single storm estimates of sediment yield. Output from the model will report all estimates if required, however one of the six equations must be chosen the control equation for water related erosion. This is critical to the simulation because the model removes the eroded soil from the profile after the amount is calculated. This means the soil carried off in the runoff and the nutrients attached to the sediments and dissolved in water are not available for present or future plant growth. The soils become thinner and the water holding capacity of the profile changes.

The wind erosion sub-programme in EPIC has recently been designed. Under this design the potential wind erosion is estimated for a smooth bare surface by soil type and wind speed and direction. This potential erosion is then adjusted by conditions for that day for changing soil properties (e.g. soil moisture), surface roughness, cover, and distance across the field in the wind direction.

(h) Nutrients

i) Nitrogen

The model is sensitive to many related processes. Some of these include losses from leaching, surface runoff, lateral subsurface flows, organic nitrogen transport by sediment, denitrification, volatilisation. Nitrogen is made available to the plants through, inorganic fertiliser, animal manure, crop residues, nitrogen fixation, rainfall, and irrigation water. Nitrogen is removed between available and non-available pools through mineralisation and immobilisation(micro-organisms).

ii) Phosphorous

Phosphorous processes include soluble P losses in surface runoff, P transport by sediment, mineralisation, immobilisation, and P conversions of the mineral P cycle which is affected by such things as soil type, pH, aluminium saturation, liming, and fertiliser history(rates and type).

ii) Liming

A liming sub-model is available which will change the pH and other characteristics of the soil and availability of nutrients and soil water.

iii) Pesticides

Pesticides have become very important in the issues of the water quality. Recently the chemical sub-models from CREAMS Model (Leonard et.al. 1987) have been added to the EPIC Model. These include the processes simulating pesticide transport by runoff, percolation, soil evaporation and sediment attachments. This has improved the use of EPIC Model for addressing water quality issues in small watersheds.

iv) Plant Growth

The plant growth sub-model in EPIC is one of the primary reasons EPIC is so versatile and adoptable to so many conditions. A single model is used for simulating all plants (crops trees, shrubs, grasses) whether cool season/warm season, temperate tropic, annual/perennial, legume/non-nitrogen fixing, irrigated dryland, single crop/rotation/inter-crops, multiple harvest/single harvest, seeds/whole plants, or above ground/below ground harvest.

The versatility is possible because the generic plant model controls plant growth and processes through a table of plant coefficients and general equations. Plant growth and maturity is controlled through the accumulation of heat units from planting to maturity/ and or harvest be it one season as in crops or years as in trees. Plants are divided into aboveground and below ground biomass/harvest and non-harvest biomass. The system allows harvest of more than one product from a plant (e.g. grain and straw). The model calculates potential growth from previous days biomass and leaf area and from the available solar radiation for a day. The model then reduces the potential to actual through the use of the principle of the most limiting constraint. All constraints are plotted to find one which is most limiting for that day. Present constraints included in the model are available water, available light, nutrients, temperature (both cold and hot), and aeration of root zone. Other constraints can be added without affecting the basic existing model code.

This is another reason model like EPIC and SWAT which use the principle of limiting resource have become widely accepted. They are easily modifiable to add new capabilities in the form of new constraints. Once the limiting resource for the day is identifies, the plant biomass and leaf area are increased to the extent possible under the constraint and process starts the next daily cycle. Other plant growth characteristics determine the plant partitioning between harvested products and non-harvest biomass, above and below ground biomass nutrient requirements, and other critical plant attributes as they vary by age of plant. At harvest the economic yield is estimated from the accumulation of this daily accounting system.

f) Management Practices/ Plant Environment Control

There are only six resources currently considered as limiting for biomass growth, there are a mired of processes determining what is available to the plant for each resource. Many things control plant available water and plant available nutrients. There are uncontrolled attributes such as weather, soils and topography. One of the most frequent uses of simulation models and the primary reason to look in the present discussion to the attributes which can be controlled and to study the impact alternative combinations of these controlled resources would impart on the SUs and the watershed. The type of plant grown, the growing period, the condition of the soil at planting, the residue on and in the soil, and the surface texture are all important. Timing as to when nutrients, pest control, irrigation water, lime, cultivation, weed control, and harvest all effect the economic variability, productivity, Sustainability and health of the watershed. All of these controllable attributes can be simulated with EPIC. The model allows for the daily input of activities which are controlled by management decisions.

g) Evaluation of Management alternatives

One simulates the impact of alternative combinations of these decisions by executing multiple runoff the model of the comparing the differences among the output attributes of interest. Examples of these attributes include runoff, erosion, yield, biomass, plant water use, nutrient requirements, nutrient losses, organic content of soil, water permeability, and many others. As one explores the potential options and possible combinations of the resource uses, one will start to understand the value of using simulation models to design systems and screen possible combinations of resource to be considered as viable practices worthy of additional testing on specific SUs while rejecting same combination of practices on other SUs.

3.4.2

OTHER MEMBERS OF THE EPIC FAMILY

APEX is multifold version of EPIC; it simulates biophysical processes on several fields simultaneously. APEX keeps track of both surface and lateral flows for runoff and runoff for adjustment fields. It is particularly adapted to address water quality and sediment trapping issues associated with buffer zones. It also can simulates water harvesting and nutrient movement issues.

ALMANAC is a version of EPIC specifically designed to simulate multi-species competition issues. This includes intercropping, weed competition and tree crop combination of agro-forestry systems. In this model the plants grow simultaneously and all compare for the same set of available resources (light water nutrients) available on any given day. What each plant receives depends on the plant height, canopy cover above the plant, depth of roots and rooting density are compared to the other plants in the system.

All these models EPIC, APEX and ALMANAC can be used in the small plots or the SUs to feed into the watershed models like SWAT allowing aggregation and nesting of watersheds into larger watershed areas.

3.7

SWAT MODEL

The Soil and Water Assessment Tool (SWAT, Arnald et al., 1993) is designed to model biophysical processes at virtually any drainage area level. SWAT divides river basin into smaller drainage areas according to natural flows and watershed boundaries, and simultaneously simulates multiple processes on several hundred drainage areas. Like EPIC those processes include hydrology, weather sedimentation, soil temperature, crop growth, nutrients, pesticides, ground water, lateral flow and agricultural management. SWAT functions on daily time step and can simulate in excess of hundred total years. This model is designed to predict stream flow using soil, land use, elevation and weather information. It was constructed to be sensitive to changing land use and environmental practices. The appropriate drainage area for applying simulation models depends on the questions to be answered. Environmental projections concerning proposed solutions at the basin level require different model input and output than local problem solving by micro-watershed inhabitants. In both cases the environmental effects of proposed policy alternatives to the status quo can be assessed. The key is to pose modelling hypothesis and scenarios that address drainage area environmental problems as identified by local people. SWAT modelling is designed to simulate the nested lay out of the smaller drainage area with in larger basins, and thus support environmental analysis at virtually any level of basin activity. The SWAT model was developed by the US Department of Agriculture- Agriculture Research service and modified for use in the Hydrological Unit Model of the United States (HUMUS) support project. This project developed under the leadership of the TEXAS A & M University(TAMU), is addressing the entire river system network of the United States by Watershed boundaries. The system is built around a GIS framework.

The SWAT model operates as a continuous time model on a daily time step as does EPIC. The objective of this model is to predict the impact of management on water, sediment and agricultural chemicals on small and large ungauged basins.

3.7.1

SUB-BASIN COMPONENTS IN SWAT

The Components of SWAT can be placed into eight major divisions i.e hydrology, weather, sedimentation , soil temperature, crop growth, nutrients , pesticides and agricultural management. The model has many submodel which are in common with EPIC minor modifications of the EPIC submodels. Among these submodels are the surface runoff hydrology, percolation, lateral subsurface flow, evapotranspiration, snowmelt, weather simulation capabilities, sediment yield, crop growth model, nitrogen uses and exchanges phosphorous balances, pesticide degradation, and irrigation scheduling. A few submodels are described which are unique to SWAT because of the need to provide accounting for the entire watershed rather than just a single field or forest area.

3.7.2

ROUTING

For routing runoff and chemicals through a watershed the model uses a command structure similar to the structure of HYMO (Williums and Hann, 1978) Commands are included for routing flows through streams and reservoirs, adding flows, and inputting measured data or print sources(withdrawals and returns). Using a routing command language, the model can simulate a basin subdivided into grid cells or sub-watersheds. Additional commands have been developed to allow measured and point source data to be input to the model and routed with simulated flows. Also, output data from other simulation models can be input to the SWAT. Using the transfer command, water can be transferred from and reach or reservoir to any other reach or reservoir within basin. The user can specify the fraction of flow to divert, the minimum flow remaining in the channel or reservoir, or a daily amount to divert. The user can also apply water directly to a subbasin for irrigation. Although the model operates on a daily time step and is efficient enough to run for many years, it is intended as a long term yield model and is not capable of detailed, single-event, flood routing.

5.7.3

GROUND WATER FLOW

Ground water flow contribution to the total streamflow is simulated by creating a shallow aquifer storage (Arnold et al. 1993). Percolate from bottom of the root zone is recharge to shallow aquifer. A recession constant, derived from daily streamflow records, is used to lag flow from the aquifer to the stream. Other components include evaporation, pumping withdrawals, and seepage to the deep aquifer.

5.7.4

TRANSMISSION LOSSES

Many semiarid watershed have alluvial channels that subtract large volume of streamflow. The abstraction or the transmission losses, reduce runoff volumes as the flood wave travels downstream. Channel losses are a function of channel width and length and flow duration. Both runoff volume and peak rate are adjusted when losses occur.

5.7.5

SMALL STORAGE AREA

Small structures can be accommodated within a sub-basin. These ponds are simulated as a function of capacity, daily inflows and outflows, seepage and evaporation. Required inputs are capacity and surface area. Surface area below capacity is estimated as a non-linear function of storage.

5.7.6

CHANNEL ROUTING

Channel routing uses a variable storage coefficient method developed by Williums(1969). Channel inputs include the reach length, channel slope, bankfull width and depth, channel side slope, flood plane slope, and Manning's 'η' for channel and flood plane. Flow rate and average velocity are calculated using Manning's equation and travel time is computed by dividing channel length by velocity. Outflow from a channel is also adjusted for transmission losses, evaporation, diversions and return flow.

5.7.7

MODEL LINKS WITH GIS

Watershed modelling can be greatly enhanced by the use of GIS in connection with model operations. In recent years, there has been considerable effort devoted to utilising GIS to extract input (soil, land use and topography) for comprehensive simulation models and spatially display model outputs. An interface has been developed foe SWAT(Srinivas and Arnold, 1993) using the GRASS(Graphical Resources Analysis Support System) (US Army,1988) as the GIS support system. Using submodel developed to support watershed management the interfaces will automatically subdivide a basin (either grids or subwatersheds)and then extract model input data from map layers and associated relational data based for each subbasin, soils, land use, weather, management, and topographic data are collected from the GIS and written to appropriate model input files. In like manner, output interfaces allow the use to display outputs like maps, graphs, hygrographs and other relevant statistics, by selecting a subbasin from a GIS map. This technique greatly facilitates the exploration of alternative watershed management options.

3.8

SWMHMS MODEL

SMALL WATERSHED MONTHLY HYDROLOGIC MODELING SYSTEM (**SWMHMS**) is a continuous simulation conceptual MODELING program which attempt to account for all watershed precipitation through hydrologic processes such as surface runoff, infiltration, and evapotranspiration from a small nonurban watershed. The input needed to run model simulation include daily precipitation n , monthly data for evapotranspiration i.e. average temperature, crop consumptive coefficients, and present daylight hours, and six watershed parameters.

SWMHSM was originally developed in order to test a statistically procedure for the evaluation of hydrologic models. It was written with the purpose of providing a computational less complex computer MODELING program capable of accurately predicting monthly runoff while requiring a minimum of watershed data input. In terms of application, this modelling program should prove quite useful for establishing hydrologic management practices on small watersheds. Also, conceptually simple nature of SWMHMS allow it to be productively utilized as a tool for teaching hydrologic MODELING principles.

Figure 1 gives the flow chart of conceptualization of SWMHMS. All model components are calculated on a daily basis. Monthly values are then obtained through summation of the daily estimates. As shown in Figure 1, precipitation is partitioned

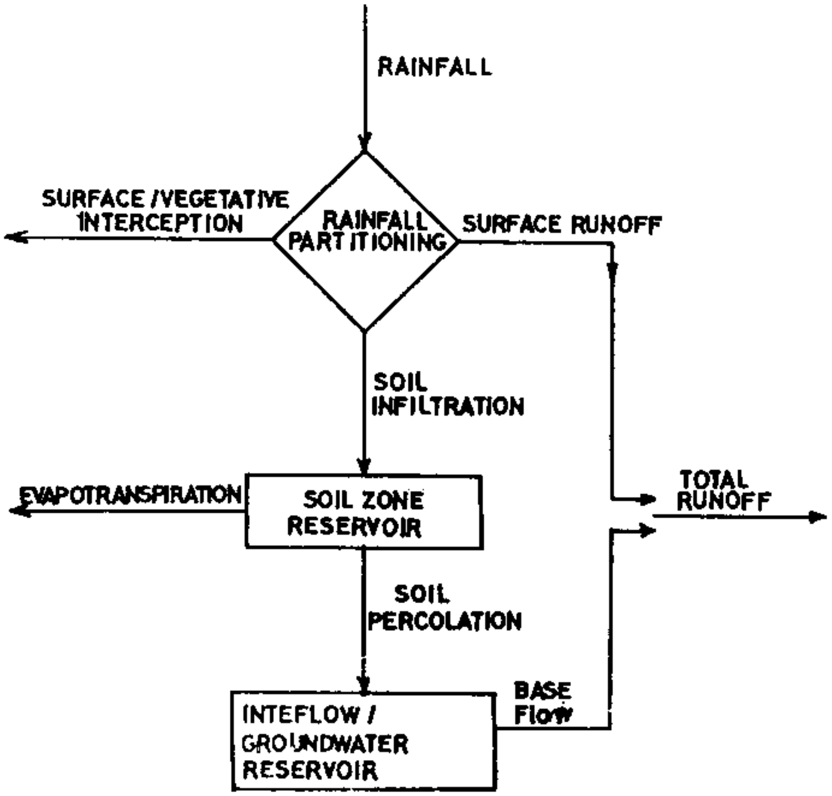


FIG.3·8FLOW CHART OF SWMHMS MODEL

into three components, which include soil infiltration, surface/vegetative interception, and surface runoff. Surface runoff is calculated using the Soil Conservation Service (SCS) curve number procedure (SCS,1972).The rainfall amount partitioned for infiltration is placed in the soil zone reservoir. Evapotranspiration losses from the soil zone are determined using an equation developed by Blaney and Criddle (1950). Excess soil water above field capacity is directed through percolation to the interflow/ground water reservoir. Baseflow from the interflow/ground water reservoir is then added to surface runoff to obtain the total runoff.

3.8.2 Data Input And Output

SWMHMS watershed parameters are listed in Table 1. These parameters and variables are used in computing the major hydrologic components of the MODELING program, which include surface runoff, surface/vegetative interception, soil infiltration, soil evapotranspiration, soil percolation, soil zone water balance, Baseflow, interflow/ground water reservoir storage, and total runoff. The following mathematical equation are used to predict the watershed components.

a) Surface Runoff

Methods developed by the Soil Conservation Service (SCS, 1972) were utilized to determine surface runoff. The three proceeding equations are

$$CNI = -16.91 + (1.348*CN) - (0.011379*CN^2) + (0.0001177*CN^3)$$

$$SMX=(1000/CNI)-10$$

$$S=SMX*((TWC-AW)/TWC)$$

used to calculate S, which is the maximum rainfall abstraction possible under given soil moisture conditions. The above as equation described by Smith and Williams (1980) are used for determining CNI, the SCS curve number for antecedent condition I, which represents dry soils. CN is the standard curve number found in tables and represents antecedent condition II or average soil moisture conditions. SMX is the maximum rainfall abstraction under dry conditions, and TWC is the total water capacity of the soil. TWC equals the sum of the available water capacity, AWC, and specific yield capacity, SYC. AW is the amount of water present in the soil zone at any particular time. The initial rainfall abstraction, IRA, is equal to 0.2 * S, and runoff will not occur when precipitation is less than this value. Daily surface runoff is calculated using the following equation when precipitation is greater than IRA:

TABLE 1:

SWMHMS Watershed Parameters

Parameter	Description
I	Monthly Number
J	Day Number
K	Year Number
AET	Actual daily soil evapotranspiration
AWP	Available water percentage in soil zone
BSFL	Daily base flow from interflow/ground water res.
CKi	Monthly crop consumptive coefficients
CNI	SCS curve number for ANC 1
CPi	% daytime hours of year for month I
DPETi,k	Daily PET from soil
F	Evapotranspiration coefficient
IGS	Water present in interflow/groundwater reservoir
INFIL	Daily soil infiltration
INTCP	Daily surface/vegetative interception
IRA	Initial rainfall abstraction
MAETi,k	Predicted monthly soil ET.
MBSFi,k	Predicted monthly base flow
MFLOWi,k	Observed monthly watershed runoff
MINFi,k	Predicted monthly soil infiltration
MONTEMPi,k	Mean monthly temprature
MPETi,k	Monthly PET from soil
MPRECi,k	Monthly precipation
MRUNi,k	Predicted monthly watershed runoff

OBJVALav	Absolute difference objective function value
OBJVALss	Sum of sq. difference objective function value
PARAMn	Value of one of the six watershed parameters
PERC	Daily soil percolation
S	Rainfall abstraction
SMX	Max. rainfall abstraction under dry soil condition
SRVALn	Relative sensivity value for one of watershed
TRUNOFF	Total daily watershed runoff
TWC	Total water capacity of soil zone
ZZi	Number of days in month
AWC	Available water capacity of soil zone (inches) (This equals the amount of water between filed capacity and the wilting point).
CN	SCS curve number (Values range between 0 and 100)
IRAC	Initial rainfall abstraction coefficient (Values range between 0 and 1.)
PERCCOEF	Percolation coefficient (Values range between 0 and 1.)
SC	Baseflow coefficient (Values range between 0 and 1).
SYC	pecific yield capacity of soil zone (inches) (This equals the amount of water between total saturation and field capacity).

b) *Surface/Vegetative Interception*

The interception losses are calculated as:

For RAINFALL > IRA

INTCP = (1-IRAC)*IRA

For RAINFALL < IRA,

INTCP = (1-IRAC)*RAINFALL

IRA represents the sum of total interception capacity. The

The IRAC coefficient partitions this initial rainfall between surface/vegetative interception and soil infiltration.

c) Soil Infiltration

Daily soil infiltration is determined as :

For RAINFALL > IRA

INFIL = (RAINFALL-RUNOFF) - INTCP

For RAINFALL <_ IRA

INFIL = IRAC * RAINFALL

d) Soil evapotranspiration

Monthly potentialevpotranspiration is is estimated using Blaney and Criddle equation (1950) as :

$$MPET_{i,k}=MONTEMP_{i,k}*CK_i*(CP_i/100)$$

where $MONTEMP_{I<K}$ is the average monthly temprature, CK_i is the monthly crop consumptive coeffients, and CP_i is the monthly percent daytime hours. I and K designates the month and year, respectively. Monthly crop consumptive are found by the procedure described by Blaney (1950).

The daily potential evaporation is calculated as:

$$DPET_{i,k}=(MPET_{i,k}/ZZ_i)$$

where ZZ_i is the number of days in a particular month

Actual daily soil evapotranspiration is calculated as:

$$AWP=(AW/AWC)*100 \vee AWP=100 if(AWP/AWC)>1$$

F = In(AWP+1)/In(101)

$$AET=F*(DPET_{i,k}-INTCP)$$

e) Soil percolation

When TWC >_ AW >_ AWC soil percolation occur and is estimated as :

PERC = PERCCOEF * (AW-AWC)

f) Soil Zone Water Balance

The daily soil zone water balance equation can be written as :

$$AW_j=Aw_{j-i}+INFIL-AET-PERC,$$

where AW_{j-i} is amount of available soil water from the previous day . J is simply the day number.

g) Baseflow

Daily Baseflow is calculated as :

BSFL = SC * IGS

where SC is a coefficients that regulates the release of water from interflow/ground water storage, IGS.

h) Interflow/Ground Water Recharge Storage

Storage of water in the reservoir is increased by percolation and decreased by Baseflow, the governing equation can written as

$$IGS_J=IGS_{J_I}+PERC-BSFL$$

where IGS_{J_I} is the amount of water present in the storage on the previous day.

i) Total Runoff

Sum of daily surface runoff and Baseflow is used to determine the daily value for total watershed runoff :

3.8.3 MODEL OPERATION

a) Simulation

To simulate monthly watershed runoff, the modelling program combines the various hydrologic components previously described. The three types of input required for a simulation run are daily precipitation, monthly data for evapotranspiration determination ($MONTEMP_{I,K}$, CK_I, CP_I) and watershed parameter value (AWC, CN, IRAC, PERCCOEF, SC, SYC). Besides monthly precipation ($MPREC_{I<K}$) summed from daily rainfall and estimated monthly runoff (MRUN) the output from an SWMHMS simulation includes predicted monthly values of soil evapotranspiration (MAET), surface/vegetative interception (MINT) soil infiltration (MINF) and Baseflow (MBSFL). If the data are available, observed monthly runoff (MFLOW) can be listed along with the estimated values for comparison purposes. Various statistics (mean, standard deviation, skewness, correlation coefficient, and linear regression constants) corresponding to the predicted or observed monthly hydrologic values are also provided as output.

b) Optimization

To calculate best watershed parameters SWMHMS uses a two-stage "brute force" optimization procedure for monthly runoff prediction. The first optimization stage gives a rough estimate of the best parameter set, and it begins with the computation of five evenly distributed values within each user defined parameter range. A model simulation is then conducted and an objective function value calculated for every possible permutation of the six watershed parameters. SWMHMS provides two objective function choices. One is the sum of squared differences between observed and predicted monthly runoff,

$$OBJVAL_{ss}=\sum\sum(MFLOW_{i,k}-MRUN_{i,k})^2$$

and the other is the sum of absolute differences between observed and predicted runoff,

$$OBJVAL_{av}=\sum\sum(MFLOW_{i,k}-MRUN_{i,k})$$

The best parameter set is then chosen on the basis of having the minimum objective function value.

The second optimization stage proceeds in a manner similar to the first and further refines the watershed parameters. Refinement is accomplished using a much narrower range to bracket the rough parameter estimates already determined in the first stage. This "brute force" optimization procedure, although being computational less efficient than other methods, has the advantage of not being affected by local minimums in the objective function. In the future, a method developed by Rosenbrock (1960) will be used for the second optimization stage. This should substantially reduce optimization times.

c) Sensitivity Analysis

A sensitivity analysis can determine which watershed parameters have the greatest impact on predicted monthly runoff. By finding which parameters are important, a sensitivity analysis can narrow the focus and therefore reduce the effort required for optimization. SWMHMS conducts two types of sensitivity analysis. First, a set of simulations are run where individual parameters are altered from their initial values by various percentage amounts (-50 percent, -25 percent, -10 percent, -5 percent, -2 percent, -1 percent, +1 percent, +2 percent, +5 percent, +10 percent, +25 percent, +50 percent_. For each simulation, only one parameter is changed while the others are maintained at their beginning values. Parameter sensitivity is then evaluated through calculation of the summed differences (squared or absolute value) between monthly runoff computed with the initial parameter set and monthly runoff computed with one of the parameters altered.

The second method used by SWMHMS for determining parameter significance involves the calculation of relative sensitivity coefficients for each parameter. The relative sensitivity coefficients are expressed as

$$SRVAL_N=(\sum\sum(\delta MRUN_{i,k})/\delta(PARAM_N)$$

where PARAM is one of the six watershed parameters, and (PARAM) represents a percent change in value. Because SRVAL is dimensionless, it can be used to rank parameter sensitivity.

3.8.4 APPLICATION AND RESULTS

SWMHMS was tested on six watersheds from different locations across the United States. This group was chosen on the basis of having both diversity and an adequate record length (7-13 years). All six are experimental agricultural watersheds in which site conditions and rainfall-runoff data were made available from the Agricultural Research Service (ARS) of the United States Department of Agricultural (USDA). Climatological data from the National Oceanic and Atmospheric Administration (NOAA) were used to obtain mean monthly temperatures and percent daylight hours.

Watershed description is provided below:

Watershed	Data	Area	Elevation	USDA	Vegetation	Annual

		Record Period	(acres)	Range (feet)	Soil Classi.	Cover	Rain. Runoff (inches)
11	Little River Watershed	1968-75	646	410-480	Loamy sand to sandy loam	47%forest,42%row crops 11% pasture	49
5	Watershed Y Riesel	1968-79	309	510-560	silty clay to clay	36% pasture,25% oats/clover 14% cotten, 13%sorghum, 8% corn, 4% misc.	34
1.4	Watershed 612, Alex	1962-74	563	1100-1180	silty loam to loam	96% pasture, 4% alfalfa	28
9	Watershed W-A4 Ashoskie	1965-72	1664	NA	fine sandy loam to silt loam	60% woodland, 39% row crops	45
15	Watershed 196, Ohio	1968-78	303	950-1150	sandy loam to silt loam	50% grassland, 27% woodland 19% crops, 4% misc.	37
8	Watershed Murphy Creek Idaho	1967-77	306	4600-5900	gravelly loam	100% sagebrush	21

Evaluations of SWMHMS was done in three phases. First, the parameters were determined through optimization, applying both objective function criteria. All optimized parameters were computed with information found in the first half of the watershed data record. Second, a sensitivity analysis was conducted to assess the importance of each parameter. Here, the input data records from the first phase along with the corresponding optimized parameter values were incorporated. Third, monthly runoff was predicted using the optimized parameters. These simulation runs utilized information from the last half of the watershed data record. Statistical comparisons of observed and predicted monthly runoff were then employed to gage the effectiveness of SWMHMS.

Of the six watershed parameters, most sensitive is the curve number, CN. Depending on the watershed, either AWC or IRAC is a distant second. The optimal curve number for the majority of the watershed was found to be closest to an SCS III type value. In terms of monthly runoff prediction, SWMHMS functional best where snowfall accumulation were low. The testing result indicate this modeling programme can be significantly useful for determining water management practices on small agricultural watersheds.

3.8.5 ADVANTAGE OF SWMHMS

- SWMHMS is less complex than any other computer model to calculate monthly runoff.
- t can be used as an educational tool for student learning the principle hydrologic modeling.

3.9 AGNPS MODEL

AGricultural **N**on-**P**oint **S**ource is an event based non point source pollution model for evaluating agricultural watersheds of mild topography. The model simulates runoff, sediments and nutrients from agricultural watersheds. The AGNPS model consists of four components, basically hydrology, erosion, sediments and chemical transport. The model simulates nitrogen (N) and Phosphorous(P) as major surface water pollutants. Model also consider point source of sediments from Gullies and input of water, sediment, nutrients, and chemical oxygen demand (COD) from animal feedlots, springs and other point source.

3.9.1 MODEL STRUCTURE

Several model are being used for prediction of runoff, sediment yield or nonpoint source pollution from field and small watersheds. These models ranges from simple empirical models with geographically lumped parameters to geographically distributed models with algorithms that define physical phenomena as much as possible. The AGNPS model was develop to analyse non point source pollution in agricultural watersheds. The model uses a distributed parameters approach to quantify a watershed by dividing the area into square grid data units (cells) within geographical area. Runoff characteristics and transport process of sediment and nutrients are simulated for each cell and routed to the outlet in stepwise manner so that flow at any point between cells may be examined. Thus, flow, erosion, and chemical movement at any point in the watershed may be examined. Upland sources contributing to a potential problem can be identify and location can be prioritized for remedial action to improve water quality most efficiently. Runoff is predicted using the soil conservation service (SCS) runoff curve number method. Sediment yield are predicted using a modified version of the universal Soil Loss Equation (USLE) (Wischemeier and Smith, 1978). Nutrient movement components have been adapted from the CREAM model (Frere et al., 1980). Chemical transport calculation are divided into soluble and sediment absorb phases. AGNPS can be used for watersheds upto 20,000 ha. in size with element size of 0.4 to 16 ha. Accuracy of result can be increased by reducing the cell size, but this increases the lime and labour required to run the model. Conversely, enlarging the cell size reduces time and labour, but saving must be balanced against the loss of accuracy resulting from treating larger areas as homogeneous units. The model is available for use on personal computers, but can also, with slight modification, be run of UNIX work stations.

The distributed parameter approach of this model preserves spatial characteristics and makes it appropriate to use a GIS system for storage of those spatial characteristics. Thus the characteristics, of raster GIS storage, retrieval, and manipulation can be used effectively with the AGNPS model. The AGNPS model can be linked with various GIS or terrain description methods.

3.9.2 MODEL COMPONENTS

Hydrology, erosion, sediment and chemical transport are the basic model components describe in details in the following section.

a) *Hydrology*

Runoff volume and peak flow are calculated in this part of the model. Runoff volume estimates are based on the SCS curve number method. The basic equation is as follows:

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)}$$

where Q is the runoff volume, P is the rainfall, and S is a retention parameters, all expressed in uniform dimension of length. The retention parameter is defined in terms of a curve number (CN), as follows:

$$S = \frac{1000}{CN} - 10$$

The curve number depends upon land use, soil type, and hydrologic soil condition. This method was chosen because of its simplicity and widespread use among the principle user agencies for which the model was developed.

Peak runoff rate for each cell is estimated using an empirical relation proposed by Smith and Williams (1980) as follows:

$$Q = 3.97\, A^{0.7}\, C\, S^{0.16} \left(\frac{RO}{25.4} \right)^{0.903A^{0.017}} \cdot LW^{-0.19}$$

where Q is the peak flow rate in m s , A is the drainage area in km, CS is the channel length in m/km, RO is the runoff volume in mm, and LW is the watershed length - width ration, L is the watershed length. Values of the coefficients were determined from measurements.

b) Erosion and Sediment Transport

In the model, modified soil loss equation is used to predict upland erosion for single storm as follows:

$$SL = (EI)\, K\, L\, S\, C\, P\, (SSF)$$

where SL is the soil loss, EI is the product of the storm total kinetic energy and maximum 30-minute, K is the soil erodibility factor, LS is the topographic factor, C is the cover and management factor, SSf is a factor to adjust for slope shape within the soil. Erosion equation factors are calculated using the procedure as found in Agricultural Hand Book. Soil loss is calculated for each of the watershed. Eroded soil and sediment yield are subdivided into five particle size classes-Clay, Silt, Small aggregate, large aggregate and sand.

After the runoff and upland erosion are calculated, the detached sediment is routed from cell to cell through the watershed to the outlet. The procedure used involved sediment transport and depositional relations described by foster at el. (1982) and Lane (1982). The basic routing equation is derived from the steady state continuity equation as follows:

$$Q_s(x) = Q_s(O) + Q_{sl}\left(\frac{X}{L_r}\right) - \int_0^x (x)\, w\, dx$$

Where $Q_s(x)$ is the sediment discharge at the down stream end of the channel reach; $Q_s(O)$ is the sediment discharge into the upstream end and of the channel reach; Q_{sl} is the lateral sediment inflow rate; x is the downstream distance; L_r is the reach length; w is the channel width; D(x) is the deposition rate and is calculated as follows:

$$D(x) = [\frac{V_{ss}}{q(x)}]\ [q_s(x)\ - g_s(x)]$$

where V_{ss} is the particle fall velocity; q(x) is the discharge per unit width; $q_s(x)$ is the sediment load per unit width; and $g'_s(x)$ is the effective transport capacity per unit width. Effected transport capacity is computed using a modification of the Bagnold stream power equation(I) as follows:

$$g_s = \eta g_s = \eta k\ \frac{\tau v^2}{V_{ss}}$$

where g is the transport capacity; η is a effective transport factor, τ is the sheer stress; v is the average channel flow velocity determined by the Manning's equation. Values for the effective transport capacity are described by the Young et al.(1986). Sediment load for each of the five particle size classes leaving a cell is calculated as follows:

$$Q_s(x) = [\frac{2q(x)}{2q(x)+\Delta x V_{ss}}][Q_s(o)+Q_{sl}(\frac{x}{L})-\frac{w\Delta x}{2}[\frac{V_{ss}}{q(o)}[q_s(o)-\acute{g}_s(O)]-\frac{V_{ss}}{q(x)}\acute{g}_s(x)]$$

The above equation is the basic routing equation that drives the sediment transport model.

C) *Chemical Transport Model*

The chemical transport part of the model estimates transport of N, P and COD throughout the watershed. Chemical transport calculations are divided into soluble and sediment adsorbed phases. Nutrient yield in the sediment absorbed phase is calculated using total sediment yield from cell as follows:

$$Nut_{sol} = (Nut_f) Q_s(x) E_R$$

where Nut_{sol} N or P transported by sediment; Nut_f is N or P content in the field soil ; and E_R is the enrichment ration calculated as follows:

$$E_R = 7.4\ Q_s(x)^{-0.2}\ T_f$$

where $Q_s(x)$ is the sediment yield and T_f is the correction factor for the soil texture.

Soluble nutrients estimates consider the effect of nutrient level in rainfall, fertilisation, and leaching. Soluble nutrients contained in the runoff are estimated as follows:

$$Nut_{sol} = C_{nut} Nut_{ext}\ Q$$

where Nut_{sol} is the concentration of soluble N or P in the runoff, C_{nut} is the main concentration of soluble N or P for movement into runoff, and Q is the total runoff.

COD in the model is assumed soluble. Estimates of COD in runoff are based on calculated runoff volumes and average concentration of COD in that volume. Background concentration of COD available in the literature are used as a basis for predicting COD concentration from each cell. Soluble COD is assumed to accumulate without any losses.

d) Point Source Input

The model treats nutrients and COD contributions from animal feedlots as point sources and routes them with contributions from diffused sources. Chemical contributions from feedlots are estimated using the feedlots pollution models developed by Young et al. (1982) as subroutine. The feedlot model estimates nutrient concentrations and mass at both the feedlots edge and at a receiving body of water.

Other point source inputs of water and nutrients, such as springs waste waters treatment plant discharge, etc are accounted for by inputting incoming flow rates and concentration of N, P and COD to the cells in which they occur.

Stream bank, steam bed, and gully erosion are accounted for using estimates values as point sources. Sediment from these sources are added to upland sediment and considered as the transport phase of the model.

Sediment and runoff routing through impoundments is accomplished using relationships described by Laflan and et al.(1978). These relations were developed. for impoundment terrace systems having pipe outlets. The fraction of each particle class passing through the impoundments is a function of the surface area, depth, diameter of the pipe outlet, and infiltration rate. Interms of the water quality, impoundment reduces peak discharges, sediment yield, and yield of the sediment attached chemicals.

3.9.3 MODEL INPUT

The table below lists the input for AGNPS model

DATA

Watershed Input

a. watershed identification
b. cell area in Acres
c. Total number of cells
d. Precipitation in Inches
e. Energy Intensity Values

Cell Parameters

f. Cell Number
g. Number of the Cell into which it trains
h. SCS Curve Number
i. Average land slots (%)
j. Slope safe factor (uniform, convex or concave)
k. Average field slope length (Feet)
l. Average channel slope (%)
m. Average channel side slope (%)
n. Manning's roughness coefficient for the channel
o. Soil errodibilty factor K from USLE
p. Cropping factor C from USLE
q. Practice factor P from USLE
r. Surface condition constant (factor based on land use)
s. Aspect (one of 8 possible directions indicating

the principal drainage direction from the cell)

t. Soil Texture (sand, silt, Clay, peat)

u. Fertilisation level (Zero, Low , Medium , High)

v. Incorporation factor (% fertiliser left in top 1 cm of soil)

w. Point source Indicator (indicates existence of a point source input within a cell)

x. gully source level (estimate of amount tons or gully erosion in a cell)

y. Chemical oxygen demand factor

z. Impounding factor(indicating presence of an impoundment terrace system within the cell)

aa. Channel Indicator (indicating existence of a defined channel within a cell)

3.9.4 MODEL OUTPUT

Hydrology output
- Runoff Volume (inches)
- Peak runoff rates (Cubic feet/second)
- Fraction of runoff generated within the cell

Sediment Output
- Sediment yield (tons)
- Sediment Concentration (ppm)
- sediment particle size distribution
- Upland erosion (tons/acres)
- Amount of deposition (%).
- Sediment generated within the cell (tons)
- Enrichment ratios by particle size
- Delivery ratios by particle size

Chemical Output
- Nitrogen
  - Sediment associated mass (pounds/acre)
  - Concentration of soluble materials (ppm)
  - Mass of soluble material (pounds/acre)

Chemical Oxygen Demand
- Concentration (ppm)
- Mass (pounds/acre)

AGNPS is written in FORTRAN 77 computer language and was originally developed on a Hewlett-Puckered 1000 computer system. The model requires 400k storage (3200 cells), 34k compiled code, and 1865 lines of source code (1090) programme code. The time require to analyse a watershed containing 3000 cells is less than five times the 600 cells per minutes.

The IBM_PC version is written in Microsoft FORTRAN with a user friendly shell in IBM basic. It operates similar to the large version but is limited in the number of cells that it can handled. This version has a full screen data entry editor, help screen, previewing of results on the microcomputer monitor and printing of result on paper. Computational efficiency is much lower with the PC version, about 6 to 8 cells per minutes, but the cost is also much lower.

3.9.5 AGNPS Model with GIS

From the literature riveiw it is found that the model can be effectively and efficiently linked with GRASS GIS to develop a decision support tool assists with management runoff and erosion from agricultural watershed. Panuska et al.(1991) used a terrain analysis method to interface with the AGNPS model. They develop two terrain-enhanced version of the AGNPS model and tested these enhancement using five storms from a small watershed near Treynor, Iowa. Feezor at el.(1989) used an ARC/INFO GIS system to develop AGNPS input files on an individual basis for the study of a watershed in western Illinoise. Olivieri et al.(1991) develop a method for automatic generation of most data required by the AGNPS model, using Landsat imagery, soils maps, and USGS topographic maps with an ERDAS (Erdas,1990) GIS system. Hession et al.(1989) linked the Virginia GIS (VIRGIS) with the AGNPS model. Srinivasan and Engel (1991) have develop a GIS linkage to the AGNPS model for both input and output.

The AGNPS-GIS interface was develop as a GRASS GIS tool with programme written in the C language(Srinivasan and Engel 1991). GRASS uses a raster format to represent stored data. A tool box rationale was used to provide a collection of GIS programme to assists with model data development and analysing in interpreting AGNPS and GRASS (Engel et al. 1993). The basic GIS layers required for input are watershed boundry, soils, elevation (contour map from which digital elevation may be derived), and field boundaries. From these basic GIS layers, all 22 input parameters for the AGNPS model are obtain either by using GRASS routines or by reclassifying one of the original GIS layers. From instance, the USLE K factor, percent sand, percent clay, and hydrologic soil group are obtain by reclassifying the soil map GIS layer. The SCS curve number is obtain using a GRASS tool with other GIS layers of information available (Srinivasan and Engel,1991). An AGNPS_GIS output/visualisation tool is also available that provides GIS layers for 19 different parameters. A summary of the result at the watershed outlet is also available as the text file hard copy. The GIS output layers are intended to be used in planning study to determine locations within a watershed that are critical in the contribution of the pollutants.

3.9.5 MODEL APPLICATION AND RESULT

The AGNPS model has been preliminary tested for runoff estimation with the data from 20 watersheds located in the central United States (Young et al. 1989). The regression of the estimated values on the observed values yielded the equation:

$$\text{Estimated} = \text{Observed} \times 0.984$$

which has a coefficient of determination, r^2, of 0.81.

Due to extremely low sediment concentrations from such small events, the data were insufficient to to adequately test either the sediment yield estimates or the sediment particle size relationship of AGNPS. However a comparison of measured versus estimated N and P concentration from 20 different sampling points in the seven watersheds indicated that, on the average, AGNPS provided realistic estimations of nutrient concentration in runoff water, at least from smaller runoff events. The lack of data from larger rainfall events lends an elements of uncertainty to the relationship shown.

a) *Sensitivity*

Young et al.(1989) reported on the sensitivity of the AGNPS model. Of the various parameters analysis antecedent moisture condition was the most sensitive parameter for these watersheds. Channel slope and channel side slope were not sensitive parameters. The USLE C factor, which reported to be very sensitive parameter, was obtain for each field using the computer version of the Revised USLE (Rinard and Weesies, 1990). This routine requires previous and present land use information to determine the C factor. Thus the C factor used initially in the calibration was based on the best available information.

b) *Calibration*

Mitchell (1993) calibrated the AGNPS model and the GIS tool kit on two watersheds of University of Illinoise Allerton farms near Monticello Illinoise for monitoring the rainfall, runoff, and sediment concentration during 1980 through 1983. The calibration run showed that 20x20 meters cell size provide best simulation s of peak runoff rate and sediment yield. USLE C factor were varied from upward or downwards required. A channel was included or excluded. Usually the inclusion of the channel increased the peak flow rate greater than required, but did not increase the sediment yield. Varying the channel length had little effect. The 0.3 meters slope length for a border xell slope of zero was the best setting for various attempts. Adjustment in C factor had little effect on the sediment yield. It appeared that the best division for antecedent condition for these watersheds was AMC

1 < 12 mm of five day antecedent rainfall <AMC 2 < 41 mm < AMC3.

c) Validation

The runoff events not used for calibration were used for validation. The 20x20 meters AGNPS cell size was used. USLE C factor were as obtain from the Revised USLE computer routine. A channel was not included. The AMC division determined during the calibration runs was used. The results of the paired comparison of the observed and simulated runoff, peak runoff rate, and sediment yield for the validation events shows that result are not significantly different at the 95 percent confidence level. However the standard deviation of the difference between pairs is greater than the mean of either the observed or simulated characteristics . Also, examination of the observed and simulated characteristics indicate a poor simulation of the real event.

3.9.7 Conclusion

- AGNPS model with GRASS-GIS linkage is acceptable (Srinivasan and Engel 1991).
- The study of Young at el.(1989) was for much smaller watershed and needed further testing.

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CONCLUSIONS

(a) The LISEM model is one of the first example of a physically based model that is completely incorporated in a raster Geographical System. This incorporation facilitates easy application in larger catchments, improves the user friendliness by avoiding conversion routines and allows remotely sensed data to be used. Special attention has been given to the influence of tractor wheeling, small roads and surface sealing. LISEM model provides improve process description for infiltration and detachment. The LISEM model can be used as an effective tool for planning cost effective measures to mitigate the effect of runoff and erosion.

(b) The WEPP model is developed with the objective soil and water conservation and environtal planning and assessment tool particularly for small watersheds and hillslope. It is a continuous model simulation computer programme which predicts spatial and temporal distribution of soil loss and deposion and it provides explicit estimates of when and where in a watershed or on a hillslope that erosion is occuring so that conservation measures can be selected most effectively to control soil loss and sediment yeild.

(c) TOPMODEL is not a hydrological modelling package. It is rather a set of conceptual tools that can be used to reproduce the hydrological beheviour of catchments in a distributed or semi-distributed way in particular the dynamics of surface or subsurface contributing areas. Model parameters are intented to be physically interpretable and their number is kept to a minimum to ensure that their values do not become merely the statistical artefacts of a calibration exercise. The simplicity of the model comes from the use of topographic index $a/\tan\beta$ where a is the area draining through a point from upslope and $\tan\beta$ is the local slope angle. Only a few studies are available on TOPMODEL as applied to Indian watersheds and so further more work is felt. The model can be interact effectively with GIS.

(d) The SHE is designed as a practical system for application in a wide ranges of hydrological resource conditions. Its physical and spatial distributed basis gives it advantage over complex regression and lumped models in simulating landuse change, impact, ungauged basins, ground water and soil moisture conditions, spatial variability in catchments input and output and water flows controlling the movements of pollutents and sediments. The model has been applied successfully to Indian watersheds such as Kolar basin within the data constraints.

(e) The USLE is the most widely used equation for predicting overland flow and sheet rill erosion and provides more complete sepration of factors effect so that results of a change in the level of one or several factors could be more accurately predicted. The erosion index accurately estimates the localised erosive potential of rainfall and runoff. The equation anf monograph capable of computing the erodibility factor for numerous soils. The equation estimates average soil loss over an extended periode and does not estimates soil loss from single event. Also the equation does not estimates gully or channel erosion. The USLE is an erosion equation and does not estimate deposition (wischneier, 1976).

(f) The EPIC is field scale model and simulates biophysical process on SUs within definable management systems to determine the effect of alternative practices. The model effectively simulates hydrology, erosion-sediment, nutrient, nutrient cycling, plant growth, aluminium toxicity/lime, soil temprature, tillage, economics, and plant environmental control.

(g) The SWAT model is designe for biophysical process. The model can be effectively link with GIS the output can be display in the form of maps, graphs, hydrographs, and other relevant statistics bu selecting a subbasin from a GIS map which explore the alternative watershed management option.

(h) SWMHMS model is less complex as compared to the other available watershed model and can be used as educational tool for students learning the principle hydrologic modeling. The model estimates surface runoff, surface/vegetation interception, soil infiltration, soil evapotranspiration, soil percolation, soil zone water balance, base flow, inter flow, reservoir storage and total runoff by using the set of watershed parameters and variables.

(i) The AGNPS model is a distributed grid model with model parameters for each grid. The model simulates a single storm event. The runoff is predicted using SCS runoff curve number method. sediment yield are predicted using USLE modified version. The model also simulates nutrient movement. The AGNPS model can be used for watershed upto 20000ha with element size of 0.4ha to 16ha. The studies available are only for smaller watersheds and need further testing (Young et. al. 1989).

REFERENCES

(1) Allred, B. and Haan, C.T., (1996). SWMHMS- Small Watershed Monthly Hydrologic System. Jr. Water Resources Bulletin, Vol. 32, No. 3.

(2) Arnold, E. & Srinivasan, R., (1993). A Continuous Time, Grid Cell Watershed Model. In Proceedings of Application of Advanced information Technologies for the Management of Natural Resources.-Anonymous

(3) Bennett, J. P., (1974). Concepts of Mathematical Modeling of Sediment yield. Water Resources Research, Vol. 10 (3) pp. 485-492.

(4) Bingner, R.L., Murfee, C.E. and Mutchler, C.K (1987). Comprison of sediment models on various watersheds in Mississippi. Paper No. 87-2008. ASAE. St. Joseph, Mich.

(5) Bruce, R. R., Harper L.A., Leonard R.A, Snyder W.M., and Thomas A.W., (1975). A model for runoff of pesticides from small upland watersheds. Journal Environmental Quality Vol 4(4) pp. 541-548.

(6) Comprative study of components of watershed models, review notes, report RN-13, 1985. National Institute of Hydrology, Roorkee.

(7) Das, D. C., (1994). Waters Harvesting System in Watershed Management and Their Cost Effectiveness- Indian case stidies, Indian Jr. Soil Conservation, Vol 22, No. 1-2, pp. 236-250.

(8) De Roo, A.P.J., (1996). The LISEM project: an introduction, Hydrological Process, 10, 1021-1025.

(9) De Roo, A.P.J.Wesseling and Ritsema C.J., (1996). "LISEM: A single - event physically based hydrological and soil erosion model for drainage basins. 1: Theory, Input and Output. Jr. Hydrological Process, Vol 10, 1107-1117.

(10) De Roo A.P.J., Offermans R.J.E., and Creamers N.H.D.T. ,(1996). "LISEM: A single - event physically based hydrological and soil erosion model for drainage basins. 1: Sensitivity Analysis, Validation and Application. Jr. Hydrological Process, Vol 10, 1119-1126.

(11) Fisher P., Abrahart J.R. and Herminger W., (1997). " The sensitivity of two distributed non-point source pollution model to the spatial arrangement of the landscape". Jr. Hydrological Process, Vol. 11, 241-252.

(12) Foster, G. R. and Meyer L.D., (1972). A closed-form soil erosion equation for upland areas. -Anonymous-

(13) Foster, G.R. and Lane L.J., (1987). User Requirements. USDA Water erosion prediction project(WEPP). NSERL Report No.1, Sept, 1, 1987. USDA-ARS National Soil Erosion Research Laboratory, West Lafayette, IN.43pp.

(14) Haan, C.T., Johnson, H.P. and Brakenslek, D.L., (1982). Hydrologic Modelling of small watersheds, ASAE Monograph.

(15) International Symposium on Water Erosion, Sedimentation and Resource Conservation (1990), CSWCRTI, Dehradun.

(16) Laflen, J.M, Thomas, A.W. and Welch, R.W. (1987). Cropland experiments for the WEPP project ASAE Paper No. 87-2544, American Society of Agricultural Engineers, St. Joseph, Ml.

(17) Lane, L.J., Nearing, M.A., Laflen, J.M., Foster, G.R., and Nicholas, M.H. (1992). Description of the US Department of agriculture Water erosion Prediction Project (WEPP) Model, in persons, A.J. and Abrahams A.D. (Eds), Overland flow: Hydraulics and erosion Mechanics, UCL press limited, London, pp. 377-391.

(18) Lane, L.J. and Foster, G.R. (1980). Ch.11, Concentrated flow relationships. In: Knisel, W.G. (Ed), CRAMS : A field scale model for chemicala, runoff and erosion from agricultural management system, USDA, conservation research report No. 26, pp 640.

(19) Lardson, C.w. (1981). Stochastoic simulation of daily precipatation, temprature, solar rediation, water Resources Research, 17 (1) : 182-190.

(20) Mitchell J.K., Engel B.A., Srinivasan R. and Wang S.S.Y. (1993). "Validation of AGNPS for small watersheds using an integrated AGNPS/GIS system". Jr. Water Resources Bulletin, Vol. 29, NO. 5. 833-842.

(21) Merriam, R.A. (1960). A note on the interception soil loss

equation. Jr. Geophys. Res., 65, 3850-3851.

(22) Pilgrim, D.H., Chapman, T.C. and D.G. Doran (1988). Problem of Hydrological Modelling in arid and semi-arid regions, Jr. Hydrological Sciences, No. 33(4), pp. 379-400.

(23) Quick. M., and Pipes, A. (1986). Watershed Modeling in Mountainous Catchments, Hydrology Jr. of Indian association of Hydrologists (IAH), Vol. V(1&2).

(24) Schultz, G.A. (1993). Hydrological Modeling based on Remote Sensing Information, Adv, space Res. Vol. 13, No.5.

(25) SHE project report, (Nov. 1987-Mar 91), Vol. VII, National Institute of Hydrology, Roorkee.

(26) Simanton, J.R., West, L.T., Weltz, M.A. and Wingate, G.D. (1987). Rangeland experiment for the WEPP ASAE Paper No. 87-2545, American Society of Agricultural Engineers, St. Joseph, MI.

(27) Singh, D.K. (1993). Hydrologic Modeling of Small Hilly Watersheds, Ph.d. Thesis, Agri. Engg. Division, IARI, New Delhi.

(28) Singh V.P. (1995). Computer Models of Watershed Hydrology" Chapter 18, TOPMODEL, 627-667.

(29) Smith, R.E., and woolhiser, D.A. (1990). KINEROS, USDA-SEA-AR, Engineering Research Centre, CSU Foothills Capus, Fort Collins, CO 80521.

(30) Smith, R.E. (1981). A kinematic model for surface mine sediment yield. Trans, ASAE, 24, 1508-1514.

(31) Thangaraj C. (1997). "Remote sensing and GIS Application in Hydrological Modelling and Water Resources Planning". Jr. Indian Water Works Association, 7-15.

(32) Tiwari, K.N.., et. al., (1991). Hydrologic Modeling for Runoff Determination-Remote Sensing Techniques, Water Resources Development, Vol.7, No. 3, pp.178-184.

(33) Williams, J.R. (1995). The EPIC model. In: V. P. Singh (Ed), Computer Models of Watershed Hydrology. Chapter25: pp909-1000. Water Resources Publications, Littleton, CO.

(34) Williams, J.P., Jones, C.A. and Spanel D.A. (1989). The EPIC Crop Growth Model. Trans. ASAE 32(2):497-511.

(35) Williams, J.R., Modified Universal Soil Loss equation (MUSLE), USDA-SEA-AR, Blackland Research Çentre, Box 748, Temple,. TX 76501.

(36) Woolhiser, D.A., Smith, R.E. and Goodrich, D.C. (1990). KINEROS : A kinematic runoff and erosion model : documentation and user manual. USDA-ARS. ARS-77.

(37) Wischmeier, W.H. and Smith, D.D., and Anderson, W.P (1989). "AGNPS : a non-point source pollution model for evluating agricultural watersheds". Jr. Soil and water Conservation. 168-172.

(38) Yang, R.A., Onstad, C.A., Bosch, D.D., and Anderson, W.P. (1989). "AGNPS : a non-point source pollution model for evaluating agricultural watersheds". Jr. Soil and Water Conservation, 168-172.

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