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A STATUS REPORT ON FOREST HYDROLOGY

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ROORKEE-247 667 (UP) INDIA
1991-92

PREPACE

The hydrological cycle is greatly influenced by forest eco-systems. Forest hydrology study is therefore getting importance especially in view of the global awareness for conserving the forests. The water balance is a central tool in any hydrological or meteorological study involving forest vegetation. Today there is a general consesus that the traditional formulae do not work well on forested lands. The need to develop comprehensive models has therefore been felt to estimate and predict the various components of water balance in a forested land. Forest management practices involving cutting, thinning etc. effect the stream flows, and hence the water resources potential down stream. Evaluating the impact of such land use changes is one important area in forest hydrology. Soil erosion problem arising out of forest clearing also need to be tackled.

The studies in India on hydrologic influences of forests have been on a modest scale and largely limited to experimental plots. The repeat brings out a status of important research work done so far in India and abroad on hydrological aspects of forested watersheds including some case studies.

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Satish Chandra
DIRECTOR

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ABSTRACT

Forests are an integral part of ecosystem. Now a days, the existence of forests is generally recognised and understood as an important factor in the economy of the water resources of the watershed. The water balance is a central tool in any hydrological, climatological or meteorological study involving forest vegetation. The report brings out status of important research work done so far in India and abroad on the hydrological aspects of forested catchments. There are nearly 16 hydrological research stations working in India on some aspects of forested hydrology. Mainly two research organisations viz., Central soil and water conservation research and training institute (CSWCRTI), Dehradun with its centers and Forest research Institute (FRI), and College Dehradun have done some appreciable studies on Hydrology of small forested catchments. The organisations like DVC, CWPRS, CWC, and Central unit of soil and water conservation, MOA, New Delhi etc. have also been carrying out studies on some aspects of forest hydrology.

Today there is a general consensus that the traditional formulae do not work well for forested lands. The need to develop comprehensive models has therefore been felt to estimate and predict the various components of water balance in forested catchments. Such predictions go a long way in planning an efficient forest management and water resources projects. Sophisticated third generation computers and remotely sensed data from satellites provide the required tools in understanding the various aspects of forest hydrology. The most significant advance towards understanding was achieved by the formulation of Rutter model. The other popular models include SWM-IV, SHE, Leavesley, Gash analytical and other regression models. Representative basin studies and experimental basin studies in forested catchments would help a great deal in understanding and identifying specific problems in forest hydrology.

1.0 INTRODUCTION

The influence of forests on their environment forms a part of a complex relationship between environment and forest vegetation. Investigators have found for the last several decades the influence of forests on hydrological parameters and water availability. In the recent times, the existence of forests is generally recognised and understood as an important factor in the economy of water resources of the watershed.

Watershed is a natural physiographic or hydrologic unit where land, water and vegetation interact in a perceptible manner. Watershed has a number of distinct types of land use, its extent and management are important characteristics in determining the functioning of a watershed. Watersheds may have pure or mixed land use e.g. agriculture, forests, grasslands, wasteland or a combinations of these. The hydrological functioning of a vegetated watersheds in turn is influenced by the type of vegetation its extent and management. Forests may however occupy smaller or greater fractions of watersheds. The vegetative management especially on upland watersheds is one important method to increase water yields. The hydrologic functioning of a vegetated watershed (or forested watershed) is influenced by the type of vegetation its, composition, density, extent and management practices. The forested watershed are largely confined to upper catchments of various water resources projects. The vegetation manipulation involving clearing, cutting, thinning, conversion to grass, change of tree species etc. in the catchment is one way of altering the water budget of the watershed. The vegetative management may vary from simple thinning to clearfelling or its conversion to some other land uses such as forest cover to be replaced by grass etc. The concepts of vegetative management for increased yields are discussed in detail in the later part of the report.

The existence of forest is generally recognised and understood as an important factor in the economy of the water resources of the watershed, closely associated with this function is that of protecting the soil from erosion. These functions of forest growth both in terms of water supply and soil conservation are of great importance to the national economy. The rapid pace of development of industry and increasing productivity of agriculture lead to ever larger amounts of water being required for industrial processes and irrigating crops. The irregular and intermittent nature of precipitation, which occasionally gives rise to floods can cause great damage to valuable land and result in the runoff and loss of much potentially useful water. This water may to some extent be saved and stored by the construction of dams and creation of reservoirs so that accumulated runoff or thawing snow can be used to generate electric power, irrigation development and industry. On the other hand the forests also has the effect of storing water although not in a way as dams. However, much more need to be done to know about the quantities of water involved and when and under what conditions this water is drawn upon by forest itself.

Afforestation is supposed to be the most effective method of protecting the soil. Extensive afforestation is carried out where the soil has been divested by erosion and allied destructive phenomena. Large scale afforestation is particularly effective in dry and warm localities where forest also enhances the environment and sets up a pleasant microclimate. Protective afforestation takes different forms according to the conditions under which it is carried out. For example the land which is in need of protection may have suffered devastation by sheet flow and wind erosion, or it may consist of rubble filled landslide areas, steep slopes of low stability, waste areas that were filled a long ago, or agricultural land of declining fertility. A forest which is managed primarily from the point of view of water supply requirements may also have a valuable protective function.

Much of the forested area in the world is yet to be surveyed but reliable estimates indicate that about 3 x 10^{10} ha area has about 20% or more tree crown cover, roughly one third of the worlds land surface and about the same average percentage as that for United States alone. The total forest land in United States as reported in Mc Graw Hill Encyclopedia of environmental science is about 296 Mha.

Latin America and tropical regions of Africa and South West Asia have most of the hardwood forests, while the soft wood forests are concentrated in north America and the Soviet Union. Latin America has about 43% of the world's hardwood growing stock and this is nearly half again as much as the hardwood area of Africa, Latin America and Africa account for 72% of the worlds hardwood, with South-East Asia adding 15%. North America has only 5% of the total hardwood.

In the important softwood category, however the Soviet Union and North America rank first and second respectively and both together account for 83% of world's softwood. Soviet Union has about 2.5 times as much softwood as North America. The forest coverage of some countries as percentage to land area is as given under:

S.No.	Country	% to land area
1.	World Average	30
2.	Australia	4
3.	U.K.	6
4.	Mexico	24
5.	India	23
6.	USA	31
7.	USSR	39
8.	Canada	45
9.	Burma	62
10.	Japan	72

Source: Hydrological Influences of Forests, NIH, Roorkee.

In India forests are largely confined to upper catchments of various water resources projects and catchments of flood prone area. Forests occupy 22.7% land area of the country as against 33% envisaged by the National Forest policy (1952). The forests are classified into 16 major forest types spread over 74 Mha of country's land area mostly restricted to mountainous, undulating and rugged terrain. The distribution of area under different land uses in the catchments of 31 river valley projects (RVP's) spread over an area of 78.6 Mha indicates on an average agricultural lands account for 62% forest for 20% and other lands (grass lands, wastelands, etc.) for 18% of the total area (Das et.al., 1981). It indicates that nearly 22% of the country's forests area is under the upper catchments of these projects which form the prestigious multipurpose water resources projects of the country. The poorly managed and degraded forests with tremendous biotic interference in the upper catchments are counter productive for proper hydrological functioning.

Integrated management of forest vegetation on upper watersheds may be one way to alter the water budget of a catchment which has substantial area under forest. The scientific management of vegetation on upper catchments is often of special interest to hydrologists and water resources planners to:

a. increase the yield of usable water for down stream consumers i.e. municipal water supply catchments in the hill districts.

b. reduce runoff volumes and peak discharges.

c. improve soil moisture storage for sustained base flow and

d. check soil erosion and sedimentation and maintain water quality of the streams.

While there has been a limited study in India in the area of forest hydrology, the state of art in developed countries has considerably advanced in leaps and bounds. Mathematical models have been developed to estimate evapotranspiration, interception, infiltration losses in forested catchments. Continuous monitoring of soil water pressure, rainfall runoff modelling have been carried out for remote forests to study hydrologic characteristics. Remote sensing data is also being applied to hydrological modelling in the recent times.

The report is intended to provide a basic insight into the subject of forest hydrology.

2.0 HYDROLOGY OF FORESTS - AN OVERVIEW

2.1 DEFINITION AND CONCEPTS

Hydrology is concerned with the processes governing the depletion and replenishment of the water resources of land areas of earth. Forest influences are defined as all effects resulting from the presence of forest upon the climate, soil water, runoff, streamflow, floods, erosion and soil productivity. Kittredge (1948, cited from Lee, 1980) suggested that the important phases of forest influences concerned with water, such as precipitation, soil water, stream flow, floods etc., may be grouped under 'Forest Hydrology'. Forest Hydrology can thus be defined as the science of water related phenomena that are influenced by forest cover. Forest watershed management (as applied to forest hydrology) is also used extensively to denote operational activities based on knowledge of forest hydrology.

Thus forests and their environment from a complex relationship with that of forest vegetation. It has direct or indirect influence on various hydrological parameters such as rainfall, interception, evapotranspiration, ground water, soil loss, water yield etc.

2.2 TREE MORPHOLOGY

The Crown: The shape and size of the Crown, i.e., the branch system with the foliage it bears, vary greatly with species and growth conditions. Palms, tree ferns and cycads have a single bunch of large leaves at the top of a un-divided stem, and their shape is the same whether growing isolated or among other vegetation. Bamboos likewise have an unbranched stem of characteristic form uninfluenced by the surrounding vegetation. Dicotylendnous trees and conifers developed a branch system carrying the foliage, and through specific characters are still evident, the crown form is much influenced by environment. Isolated trees generally carry branches over most of the length of the stem, and the individual branches are much larger than on the same trees growing in more or less closed canopy. The typical outline is an elongated cone becoming broader and move rounded with increasing size or age, the final shape ranging from almost cylindrical through more or less oblong and spherical forms to broad flat topped or umbrella shapes. Fig-01 shows the range of forms.

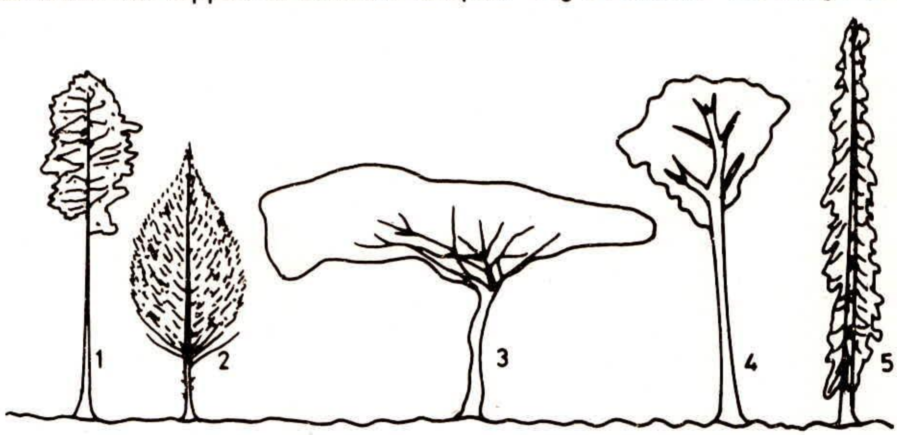

Fig.-1 Typical Bole and Crown Forms
1. Mature deodar 2. Immature deodar in a rather open crop
3. Acacia planifrons 4. Dipterocarpus 5. Abies pindrow
(outlines traced from photograpns)

The Foliage: The most important variations in tree foliage is its deciduous or evergreen habit. It is obviously related to climatic conditions whether associated with low temperature or dryness and yet where evergreen and deciduous are mixed the latter may be leafless at different times just as in a mixed wood the species differ in their individual sequence of leaf fall and coming into new leaf, although all experience same climate. The leafless portion in deciduous species varies considerably over its geographical range, being longer where the dry season is longer and it also varies from year to year in the same way.

Teak is virtually evergreen where rain fall is abundant and well distributed, whereas in the dry parts of its range it may be leafless for nearly half the year. The old leaves of evergreen may only persist slightly longer than those of some deciduous trees but long enough for the new foliage to be fairly well developed before there is an appreciable fall of the old, this appears mostly in trees of moist tropical forest. In general, however, the life of evergreen leaves is considerably longer, commonly 2 or 3 years, and even upto 7 years or more for conifers at high elevations.

The other important characteristics of foliage includes the leaf size, texture, drip and twig shedding.

2.3 FOREST TYPES IN RELATION TO PHYSIOGRAPHY AND CLIMATE

In an applied Science such as forestry it is the general experience that most of the techniques devised for directing or controlling the development of a forest are only applicable within a limited range of of conditions and forest "type". A classification is therefore required both to facilitate application of advances in knowledge and minimize waste from wrong application. For purposes of such classification, a forest type may be defined as a vegetation unit which possesses broad characteristics is physiognomy and structure sufficiently pronounced to permit to its differentiation from other such units.

Physiography is patently important in the occurance and distribution of forest types. The immediate effect is its influence on climate, and if climate differences are dominant then those (in temperature, rainfall radiation and light) between a steep southern slope and a gentle northern slope both at the same altitude, will be expected to determine the presence of the different forest types associated with those different climatic regimes. In such cases the vegetation becomes an indicator of climate.

The chief climatic factors affecting forest types includes temperature, rainfall and moisture.

Temperature : Given adequate moisture, the effect of temperature shows itself in the luxuriance of the forest in height, density, variety of species and rate of growth, all fall of with falling temperature. The conifers react somewhat differently from broad leaved trees reaching their best in temperate climate, where they surpass the broad leaved associates. Ascending in the hills temperature falls with increasing altitudes and winter deciduous species become more prevalent, still higher the forest gradually falls off to scrub forms at timber limit where the evergreens predominate. Thus temperature zones provide a basis for forest type classification as tropical, subtropical, temperate and Alpine.

Rainfall and moisture : Total annual rainfall may be a important factor in determining the nature of the vegetation, but its seasonal distribution exerts a far reaching influence. The value of vegetation growth of a given fall of rain is appreciably influenced by the period over which it is spread, and this is borne out by experience so that all other conditions being equal, the nominal fall necessary for the development of a given type increases with increasing length of the dry period.

The other factors which influence the type of forest under microclimate include the light, humidity and wind. Variations in floristic composition in all the strata commonly reflect variations in microclimate.

2.4 FOREST MANAGEMENT AND SILVICULATURAL SYSTEMS

In addition to forest types and their characteristics, forest operations/management practices play an important role in modifying the hydrology of a forested catchment. These include the Silvicultural system (i.e. the system of forest regeneration), other forest operations varying from simple cultural operations to thinning of different grades to clear felling, burning, grazing and other biotic interferences which influence hydrological attributes of a catchment to a certain extent depending upon the severity of these operations.

Best management practices (BMP) for forestry activities are needed to minimise adverse impacts on soil and water resources while planning forestry activities.

Silvicultural systems - involve forest regeneration known as silvicultural system by which forest crops are tended, harvested and replaced by new crops of distinctive form, and have been briefly discussed with reference to its role in modifying the land phase of hydrologic cycle.

The clear felling and coppice systems affect the hydrologic cycle more adversely than the other systems. The clear felling system involving whole sale elimination of the existing cover (naturally or planted) as a drastic one associated with many of environmental ill effects. It affects the water quality and yield of a catchment as there is considerable time lag between the disappearance of the old cover and appearance of an effective new cover. The coppice system involving cutting of existing crops such that the coppiced shoots produce new shoots which grow into the next crop is less drastic than clearfelling system from hydrologic point of view, because restoration of cover is relatively quick in this system and it does not involve soil disturbance.

In the shelterwood system, where crop is replaced gradually in three successive stages called seeding, secondary and final felling and the regeneration takes place naturally is slow and less drastic than the clearfelling and coppice system in terms of the hydrologic effect. It helps in the conservation of the environmental quality. The selection system causes least disturbance and is close tonature and brings about much hydrological changes in the catchment as only some mature trees above a particular diameter limit not creating permanent gaps are felled. This system is generally suitable for areas where conservation of water supply, minimisation of silt load, moderation of peak discharge etc. are of prime importance. The improvement system in which dead, dying and diseased trees are disposed off and do not bring any drastic change to hydrological attributes of a catchment. The system of protection and non exploitation and protection and planting are for full protection to an area. These are close to nature and no hydrological attributes are disturbed.

2.5 FOREST CHARACTERISTICS AND INTERACTION BETWEEN FOREST COVER AND HYDROLOGY

The important components of a forest from hydrological point of view are canopy, leaf litter and humus with dense roots. The canopy of a forest can be divided into top storey, underwood and undergrowth. Top storey or canopy consists of dominant trees which form the uppermost canopy and includes predominant trees. Underwood refers to trees growing under top storey consisting of second and third tier of trees. Undergrowth is the fourth tier/ storey of forest canopy and consists of tall bushes and trees and ground cover. Evergreen forests, semi evergreen forests and moist deciduous forests have four tiers while dry deciduous have three tiers, thorn forests and natural grass lands have one or two tiers where as agricultural crops have one tier only. Therefore, forests with more tiers of canopy have greater influences on soil erosion and hydrology of catchment.

Interception, surface detention, obstruction of the surface runoff by leaf litter mulch, debris storage of water by humus and organic matter, dead root and burrows of organisms are the effects of forest cover on hydrology of the basin. Leaf litter and humus act as a cushion against the impact of raindrop and provide temporary poundage as rich organic content of the dense leaf litter helps in high infiltration of soil moisture storage. Water holding capacity of humus is several times its weight and the presence of organic matter improves the soil structure. The leaf litter and humus is high in temperature subtropical zone and in tropical zone. Hence good cover, high organic matter, ramified root system and protective cum productive vegetation as found in a forest catchment regulates the streamflow. Thus the important components of a forest which influence hydrology of a catchment are canopy (including top storey, underwood and undergrowth) density, leaf litter and humus with dense root.

Water that is intercepted by tree crowns is important hydrologically because it causes non-uniform wetting of the forest soil, inhibits transpiration and reduces the draft on soil moisture, evaporates more rapidly than transpiration can occur in the same microclimate and adds significantly to vaporization loss. Hydrologists need estimates of these losses because interception loss may affect total water yield from forested catchments.

Canopy interception is that part of precipitation which does not reach the forest floor and quantitatively it is the difference between precipitation and the sum of throughfall and streamflow.

Throughfall is that portion of precipitation which reaches the forest floor directly or by dripping from leaves, twigs and branches. It is the difference between precipitation and the sum of canopy interception and streamflow. The duration of throughfall is greater than that of rain or snowfall and its intensity smaller.

stemflow is a minor element in the water budget of a forest and is usually less than 10% of rainfall and is often omitted in interception studies. But in any complete interception study, stem flow must be measured.

Litter interception is a function of the amount of litter on the forest floor, its moisture holding capacity and climate. A fraction of rainfall during the storms is retained by the litter layer (leaf litter), where it is not available to plants but is subject to evaporation.

The influence of forest characteristics, forest operations and protective forest belts on hydrological cycle can be visualized in three stages.

The first stage includes interception by foliage and subsequent evaporation from the canopy and litter on the forest floor. The second stage includes infiltration into the soil and subsequent percolation, soil moisture storage, ground water recharge and sub-surface and base flow.

The third stage includes surface runoff (i.e. the portion which can infiltrate and also flow again on surface). The interaction between various components of the hydrologic cycle and forest characteristics and management practices have been diagrammatically represented and discussed by Qureshi et.al. (1964), Anderson and Hoover (1976), Gupta (1978) and Mathur and Naithani (1982).

3.0 FORESTS OF INDIA

3.1 INDIA'S FORESTS WEALTH

According to the survey made by Forest Survey of India during the period 1985-87, the estimate of the forest cover in the country is as follows:

	Category	Area in Sq.kms.	% of the total Geographical area of the country
A.	**Forest**		
1.	Dense forest (crown density 40% and over)	3,78,470	11.51
2.	Open forest (crown density 10% to less than 40%)	2,57,409	7.83
3.	Mangrove forest	4,255	0.13
	Total forest	6,40,134	19.47
B.	**Shrub Area** (Three lands with less than 10% to less than 40%)	66,121	2.01
C.	**Uninterpreted area** (under clouds etc.)	3,893	0.12
D.	**Non Forest** (includes tea gardens)	25,77,649	78.40
	Grand Total	**32,87,797**	**100.00**

Source : F.R.I., Dehradun

According to the assessment in 1985-87 the actual forest cover was 64.01 million Ha against the previous assessment of 64.20 million (1981-83). Thus on the basis of gross figures there has been a reduction of 0.19 million ha. of forest cover during the last 4 years. The annual rate of loss of forest cover works out at 47,500 ha. The comparison however indicates that during the 4 years the extent of dense forest cover increased by 16,456 sq.km. The comparative situation is indicated in the following table:

Sl. No.	Category	Period 1981-83 Sq.km.	Period 1985-87 Sq.km.
1.	Dense forest (crown density 40% and over)	3,61,412	3,78,470
2.	Open forest (crown density 10% to less than 40%	2,76,583	2,57,409
3.	Man-grove forest	4,046	4,255
	Total	6,42,041	6,40,134

Source : F.R.I., Dehradun

3.2 LAND USE AND FOREST COVER

The land use and forest cover based on the report of the Irrigation Commission, 1972 is indicated in table 1. The classification is made river basin wise. The rivers of Chambal, Yamuna, Ramaganga, Tons, Karamanasa, Gomti, Ghagra, Son Gandak etc. form part of the main Ganga basin, which constitute almost 25% of the land area of the country. Within these catchments, there is a wide variation of percentage of forests.

The percentage of forests in some catchments like the Son and Barak is as high as 38-40%. In the catchments of the Narmada, Mahanadi and Godavari, the percentage of forests varies from 30-32%. This figure is 18-20% in the catchments of Panner, Tons, Karamnasa and others. While in Yamuna catchment this figure is 11%. About the lowest percentage of forests is in the catchment of Gomti river being 6% and only 2-3% in that of the Gandak and Luni. A close study of the land use, forest area and the conditions of erosion in different catchments is basic to the development planning for these areas.

3.3 PRINCIPAL FORESTS TYPES OF INDIA AND THEIR GEOGRAPHICAL DISTRIBUTION

The chief types of forest of India are briefly discussed below. A diagrammatic representation of the various types of forests of India is shown in fig.2.

3.3.1 Moist tropical forests

1. <u>Tropical Wet Evergreen Forests</u>

These include the tall, dense forest with mesophytic evergreens predominating in all canopy layers. On the mainland this type is found in regions with rainfall over 2500 mm. along the western face of the Western ghats and in strip extending south-west from upper Assam through Cachar.

In the Sub-Himalayan tract of Bengal and the adjoining part of Assam, the typical wet evergreen type is not, or is only very locally recognizable, despite the high rainfall. Sal forest has taken possession of much of the area, apparently due to burning, and with fire protection it has progressed to a semi evergreen type known as wet mixed forest. The edalphic types include the Bomboos.

2. <u>Tropical Semi evergreen Forests</u>

This type usually adjoins the tropical wet evergreen, forming a transition to the latter from the moist deciduous, much influenced by human activities. It is found locally along western ghats while a northern form occupied considerable areas in Assam and lower slopes of the Eastern Himalayas. Another form occurs in high rainfall areas in Orissa.

3. <u>Tropical Moist Deciduous Forests</u>

This type is generally referred as monsoon forest which are some of the most characteristic type of forests of India. It occurs as a strip along the foot of the Himalayas, with another along the east side of the Western Ghats. The typical rainfall is 1500-2000 mm with a dry season of 4-6 months. The moist teak forests are characteristic of the southern form whereas the moist Sal forests form the greater proportion of the northern half of the range. In the north, Sal usually always predominates and is often pure.

Table No. 1 : Land Use and Forest Area by River Basins in India (in '000 ha)

Sr.	Name of the River Basin	Geog. area	Reporting area	Area under forests	Area not available for culti-ivation	Uncultivated culturable area	Net area sown	Name of the States in which the basin lies
1	2	3	4	5	6	7	8	9
1.	Chambal	13,047	13,898	1,225	2,533	3,600	6,540	M.P. Rajasthan U.P.
2.	Yamuna	22,675	22,309	2,575	2,939	3,726	13,051	H.P., Haryana, Punjab, U.P. Delhi, M.P., Rajasthan
3.	Ramganga	3,249	3,221	700	443	236	1,842	U.P.
4.	Tons, Karamnasa and Others	2,857	2,833	516	420	417	1,480	M.P., U.P. & Bihar
5.	Gomati, Ghaghara and others	10,113	10,067	617	1,710	1,178	6,508	U.P. & Bihar
6.	Son	7,126	7,066	2,864	604	1,424	2,174	M.P., U.P. & Bihar
7.	Gandak and others	5,730	5,671	169	1,124	527	3,851	U.P., Bihar & W.B.
8.	Other Right Bank Tributaries of Ganga	9,710	9,643	1,603	1,311	2,066	4,663	Bihar & W.B.
9.	Main Ganga	10,733	10,629	1,953	1,798	941	5,937	U.P., Bihar & W.B.
10.	Brahmaputra	18,711	18,711	2,237	4,228	9,388	2,758	Arunachal, Assam, Meghalaya, Nagaland, W.B.
11.	Barak and others	7,815	7,774	2,977	3,683	370	744	Manipur, Tripura, Assam (inc Mizoram) Nagaland Meghalaya
12.	West flowing rivers beteween Kanyakumari and the Tapti	11,218	10,742	3,172	1,297	1,941	4,338	T.N., Kerala, Mysore, Goa, Maharashtra, Dadra & Nagar Haveli, Gujarat
13.	Tapi (including the Kim)	6,514	6,363	1,647	424	492	3,800	M.P., Maharashtra & Gujarat
14.	Narmada	9,800	9,867	3,167	799	1,402	4,499	M.P., Maharashtra & Gujarat
15.	Mahi (inc. the Dhadhar)	3,484	3,412	481	721	684	1,598	M.P., Maha M.P., Rajasthan and Gujarat
16.	Sabarmati	2,167	2,077	213	316	284	1,264	Raj., Guj.
17.	Luni and other rivers of Saurashtra & Kutch	32,185	31,678	794	7,437	9,288	14,159	Rajasthan, Gujarat & Diu
18.	Indus	32,189	14,375	3,061	1,562	2,669	6,969	J & K
19.	Sabarnarekha and other east-flowing rivers between the Ganga and the Baitarani	2,920	2,916	610	408	606	2,292	Bihar, Orissa, W.B.

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Sr.	Name of the River Basin	Geog. area	Reporting area	Area under forests	Area not available for culti-ivation	Cultivated culturable culturable area	Net area sown	Name of the States in which the basin lies
	1	2	3	4	5	6	7	8 9
20.	Brahmani and the Baitarani	5,183	5,173	1,225	747	1,772	2,029	Bihar, M.P., & Orissa
21.	Mahanadi	14,159	13,971	4,500	1,477	2,370	5,624	M.P., Orissa, Bihar, Maharashtra
22.	East flowing	14,159	13,971	4,500	1,477	2,370	5,624	M.P., Orissa rivers between Mahanadi and Godavari
23.	Godavari	31,281	30,784	9,119	2,734	4,496	14,435	A.P., M.P., Maharashtra, Mysore & Orissa
24.	Krishna	25,895	25,639	2,944	2,346	4,761	15,638	A.P., Maharashtra & Mysore
25.	East flowing rivers between Krishna & Penner	2,467	2,458	374	461	532	1,091	A.P.
26.	Penner	5,521	5,470	1,118	815	1,456	2,081	A.P. & Karnataka
27.	East flowing rivers between the Penner and the Cauvery	6,505	9,437	964	1,233	1,817	2,423	A.P. & Karnataka, T.N., Pondicherry
28.	Cauvery	8,79-	8,227	1,278	1,152	2,056	3,741	Kerala, Karmataka, T.N.
29.	East flowing rivers between the Cauvery and the Kanyakumari	3,509	3,493	307	550	980	1,656	T.N.

Notes I : Area not available for cultivation consists of (a) area under non-agricultural uses and (b) Barren and unculturable areas.

II : Uncultivated culturable area consists of

a) Permanent Pastures

b) Misc. tree crops and groves

c) Fallows.

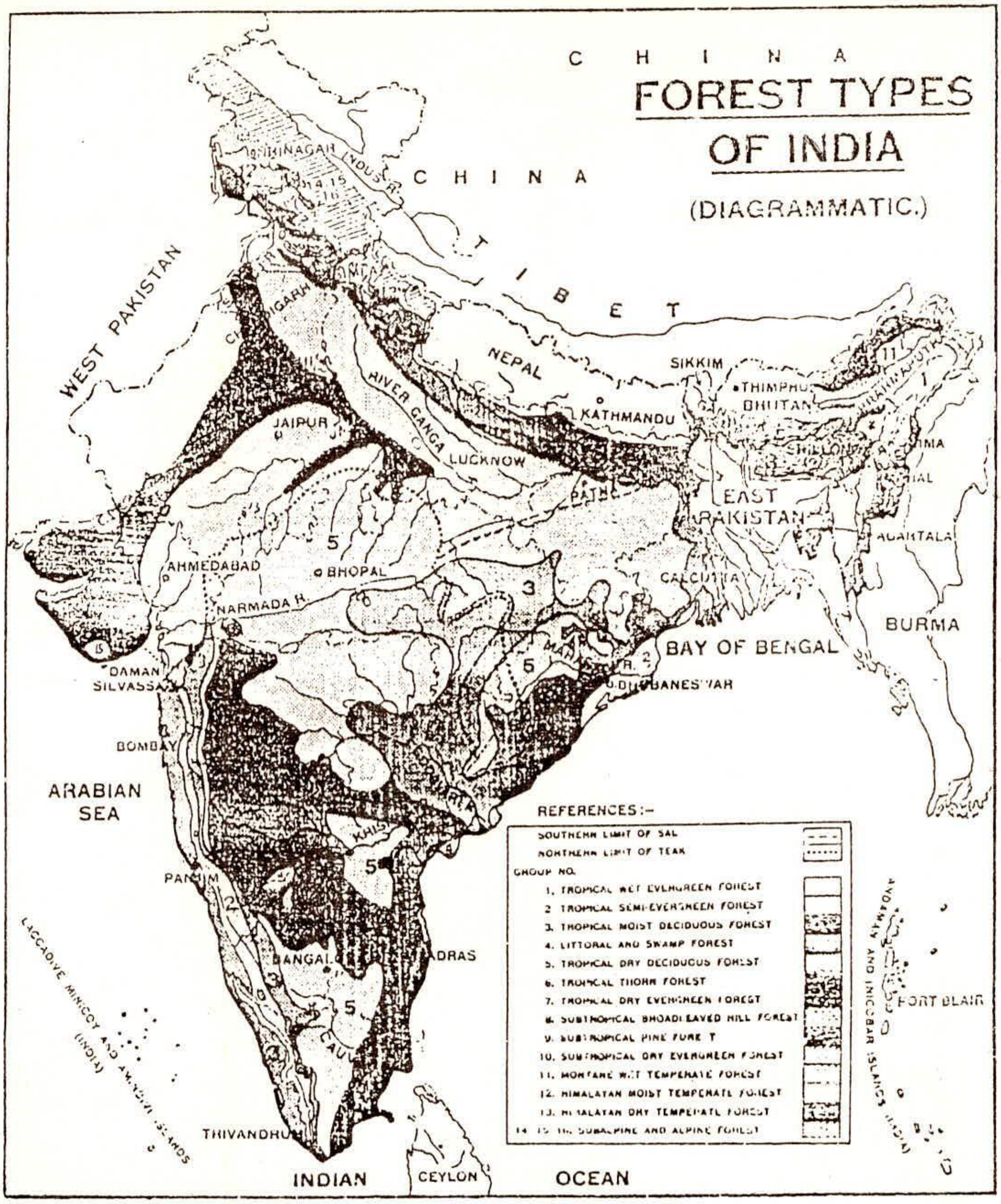


Fig.-2 Source: General Silviculture of India, Champion and Seth, 1968.

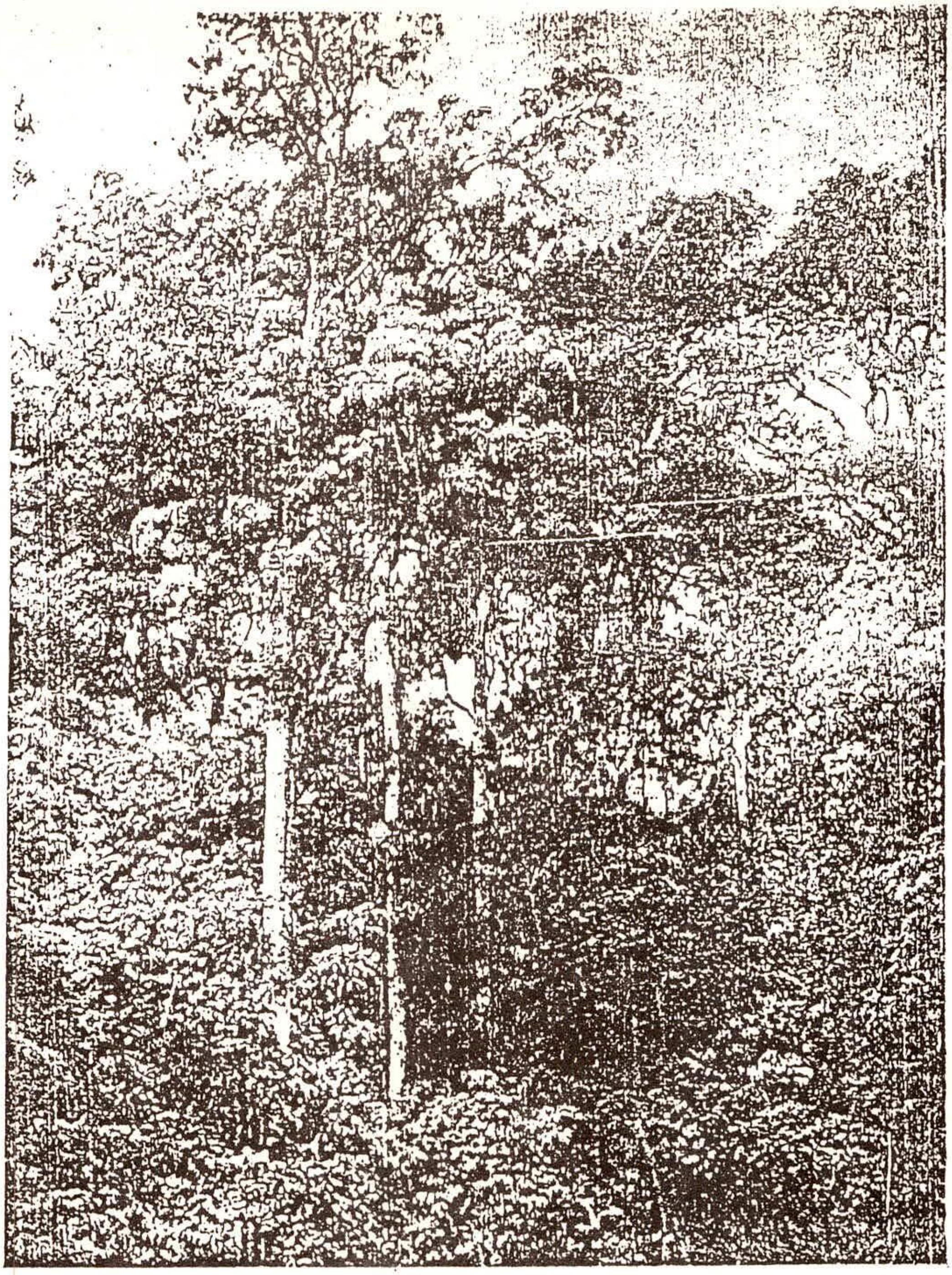


Plate 1 West Coasts tropical evergreen forest (with Dipterocarpus Indicus). Kanara East Division Mysore.

Plate 2 -Moist deodar forest. Lower Bashahr Division Himachal Pradesh.

4. Littoral and Swamp Forests

The littoral and tidal types occur all along the coast seaboard and only restricted to local occurance above Manglore, common near Bombay and extend upto Dwarka. The seasonal swamp forests are more characteristic of eastern North India.

3.3.2 Dry tropical forests

1. Tropical Dry Deciduous Forests

These area low forest, with a light top canopy almost entirely deciduous in all canopies. These occur almost all parts of India with rainfall in the range of 750-1250 mm. The common types include the Khair, Babul and Sissu.

2. Tropical Thorn Forests

These area mainly xerophytic forests occupying Indus basin in southern Punjab and Rajasthan where rainfall lies in the range of 250-750 mm. The tree species include Accacia planiforms and Accacia chundra.

3.3.3 Montane subtropical forests

1. Subtropical Broadleaved Forests

These are the luxuriant forest with evergreen species predominating. This type is limited to the lower slopes of the Himalayas in Bengal and Assam and local occurances on other hill ranges such as the Khasi Nilgiri and Mahabaleshwar hills.

2. Subtropical Pine Forests

This type is constituted by the Chir pine forests found between 1000 m and 1875 m. throughout the central and western Himalayas.

3.3.4 Montane temperate forests

1. Montane Wet Temperate Forests

These are evergreen or semi evergreen mixed broadleaved forests with dense undergrowth. The forests are characteristic of the E Himalayas between 1800 m and 2400 m and also occur at tops of hills of south India (Nilgiris). In north India they are mostly oaks and chestnuts.

2. Himalayan Moist Temperate Forests

These are evergreen forests of conifers and oaks, or a mixture of both. Undergrowth is rarely dense and partly deciduous. These are found between 1500-3000 m in the Central and Western Himalayas except where the rainfall is below 1000 mm.

3. Himalayan Dry Temperate Forests

These include the open evergreen with open scrub and lie in the inner ranges of the Himalayas throughout their length and are best represented in the north west.

3.3.5 Sub alpine forests

These are snow bound for most of the part of the year and include the conifers and evergreen broadleaved variety. These occupy mainly Himalayas at altitudes above 3000 m.

3.3.6 Alpine scrub

These are low scrub of evergreen conifers and mainly evergreen broad leaved species at altitudes of 5500 m. Others include the open xerophytic formation in which dwarf scrub predominate.

3.4 Forest Soils

There are about 27 Indian soil types broadly classified (Rayachandhani, 1962) under the forests. The chief types include the alluvial Saline and Alkali, Desert, Black, Red, hatritic, Montaine, and Skeletal soils. The various soil types, their location, mechanical composition and some properties under forest cover are shown in Table 2.

Table 2 : Analytical Data for Some Typical Indian Soils

Forest Type	Locality	Topography	Soil type	Depth (cm.) %	Mechanical composition: Coarse sand %	Fine sand %	Silt %	WaterMoisture Clay %	Nitrogen holding capacity %	Organic equivalent %	pH %	matter %	%
1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. West Coast	Comptt.14, Silent	Upper hill	Lateritic	0-7	27.9	15.65	30.0	25.0	64.2	31.5	0.274	6.52	5.9
Tropical ever-	Valley, Palghat	slope		7-36	27.6	16.1	27.5	25.0	60.1	25.6	0.154	4.10	5.8
green (IIAC4)	Division, Kerala			36-91	17.8	16.0	2.5	60.0	54.7	37.1	0.071	5.45	5.3
				91-175	23.1	13.3	10.0	50.0	49.4	29.3	0.062	1.03	5.2
2. Southern dry	Marsendra,	Plateau,	Red	0-8	39.5	14.0	25.0	20.0	30.2	18.7	0.038	1.35	4.9
mixed decidous	Bangalore	flat upland		8-56	28.3	15.2	5.0	50.0	37.5	19.9	0.036	0.93	5.1
(IIAC3) Casuarina	DivisionMysore .			56-102	25.7	14.5	10.0	47.5	40.8	22.2	0.032	0.69	6.2
plan-tation				102-165	30.7	12.0	15.0	40.0	40.5	21.9	0.013	0.28	7.2
3. Dry peninsular	Rambhadevi Block,	Plateau	Black (Stiff)	0-15	6.2	16.7	35.0	30.0	68.0	42.1	0.03	0.9	7.4
sal (5B Clc)	Deogarh Division,	undulating	(calcareous)	15-58	8.7	14.7	32.5	27.5	75.7	63.5	0.03	0.6	7.7
Orissa				58-92	19.3	13.0	32.5	27.5	69.2	41.1	0.01	0.6	7.6
				92-122	49.3	13.4	12.5	12.5	54.5	30.2	0.01	0.3	7.5
4. Moru oak	Lurli 1, Chakrata	Hilly	Brown	0-16	2.3	25.3	45.0	22.5	88.3	61.2	0.308	6.4	5.8
Q dilatata)	Division, Uttar		forest	16-60	11.4	26.0	30.0	30.0	66.7	40.1	0.069	1.5	5.5
(B Clb)	Pradesh			60-102	0.3	20.4	27.6	32.5	55.9	34.5	0.037	0.7	5.2
				102-183	0.8	24.8	20.0	47.5	48.6	32.9	0.030	0.6	4.0
5. Moit Deodar	Borsu 1/81 Comptt.	Hilly	Podsol	0-10	5.4	19.6	45.6	8.3	-	-	-	16.0	6.4
Calrus Deodara	Kulu Forest Division			10-36	11.4	25.3	47.9	7.5	-	-	-	5.8	6.0
12 Clc)	Punjab			36-44	5.9	17.7	50.4	8.7	-	-	-	11.7	6.5
				44-67	4.9	17.5	52.1	13.3	-	-	-	8.0	6.3
				67-below	7.1	24.9	53.2	26.8	-	-	-	4.0	6.1
6. Desert thorn	Bassi, Jaipur Division.	Flat upland	Saline alkali	0-10	25.8	47.8	5.0	10.0	35.8	16.4	0.03	0.21	9.5* (1.2)
(6B Cl)	Rajasthan		(calcareous	10-10	14.4	43.9	5.0	15.0	63.2	28.2	0.01	0.07	9.3 (.6)
			throughout)	10-75	15.1	24.3	5.0	12.5	50.6	27.3	0.01	0.22	9.2 (.3)
				75-below	18.5	18.3	5.	10.0	74.9	22.1	0.01	0.21	9.1 (.3)
7. Desert thorn	Guda-Andla,Jodhpur	Valley	Desert cal-	0-7	31.6	31.9	17.5	17.5	40.5	24.1	0.07	1.2	6.7
(6B Cl)	Division, Rajasthan	bottom	careous	7-61	37.3	22.6	12.5	22.5	45.5	24.8	0.12	0.5	7.2
			below 60 cm)	61-91	44.5	15.6	5.0	15.0	37.1	15.1	0.03	0.5	7.7
				91-130	38.6	14.2	2.5	15.0	48.5	19.8	0.05	0.5	7.8
				130-154	47.1	13.6	5.0	15.0	48.9	22.6	0.02	0.6	8.7
				154-183	17.0	7.20	2.5	17.5	49.2	24.5	0.02	0.2	8.6

*% of water soluble salts.

4.0 EFFECT OF FORESTS ON VARIOUS HYDROLOGICAL PARAMETERS

4.1 GENERAL

The effect of forests on important hydrological parameters are discussed here in. All forms of precipitation rain and snow falling on vegetation are intercepted, evaporated and transpired and so on as a part of water cycle. The amount of precipitation reaching the ground as a proportion of the total is an important point of consideration in water shed management.

4.2 INTERCEPTION

Intercepted precipitation is that portion of the precipitation which is caught on the surfaces of the trees, and evaporates into the atmosphere without ever reaching the ground. The amount of intercepted precipitation is thus approximately equal to the difference between the precipitation falling on open, unprotected land and the precipitation that reaches the forest floor by penetrating the canopy or running down the branches etc. The crowns of different species of tree can therefore be assigned a wetting factor, defined as the amount of precipitation required to create a surfaced film such that further droplets lose the adhesive effect of surface tension and thus slide off or run down to the ground. Wetting factors depend on the characteristics of the leaf and bark surfaces, and the shapes of leaves. Many other factors are involved in determining how much precipitation is intercepted viz. Canopy density and pattern of the branch system, precipitation intensity and duration, air humidity, exposure of the site, solar radiation, air temperature and wind speed. The loss by evaporation of water adhering to the leaf surfaces represents a considerable amount, since precipitation water intercepted in this way is spread over a large area larger than that covered by the same amount of precipitation falling directly on ground.

According to measurements made in the period 1965-70 at kychova in czechoslovakia, the amount of precipitation required to keep the tree canopy completely wetted varies from 0.5 to 1.0 mm per day. When the rainfall is heavy 0.5 mm per day is sufficient, but if the rain is gentle about 2 mm per day is required although some authors mention as much as 4.8 mm. On foggy days with a high relative humidity, there may be no evaporation of intercepted water.

4.2.1 Interception of rain water

During heavy rainfall, more of rain penetrates the tree canopy and reaches the ground, and temperature does not influence interception so much under these conditions as during gentle rain. Making a very rough generalisation, it may be said that interception losses amount to 70 to 80% during gentle rain, and about 5% during heavy rain.

4.2.2 Influence of different species and the age of the trees

In order of decreasing magnitude with respect to there ability to intercept precipitation, forest species can be listed as follows : spruce, fir, pine, broad leaved species and finally the horn beam with an annual mean interception of 8.6% and a winter interception of 5.8%. Accordingly to Zeleny (1966) interception in forests of mature felling age is double that of young stands.

Pasak (1966) reported in an unmixed spruce stand 1 mm of precipitation is retained daily. If deciduous trees are added, 0.5 mm rain penetrates per day, and in a mixture of oak pines, the penetration is 0.4 mm per day.

Valek (1962) found that 12 - 23% were intercepted by fir trees and 5 - 15% by oaks.

The runoff from the branches and the trunks of trees is largely influenced by the smoothness of the bark and the branching pattern. Water flows more easily down the smooth bark of the beech and the hornbeam than it does down the cracked bark of the spruces and oaks. The sharp angle between the branches of a beech and its trunk contributes more to the amount of water running down the tree than branches which project horizontally.

Interception of precipitation by agricultural crops and grasses varies from 25 to 50% short turf retains about 6%. According to measurements made by Sedlak (1968), the amount of water intercepted by sugar beet is 0.2 - 0.3 mm, and the amount retained by maize is 0.62 mm, the leaf wettability of potatoes is 13.5 mg/cm^2. Grains and cloves intercept 19 - 22% and herbage 26% of the precipitation, weeds can intercept upto 50%.

4.2.3 Effect of felling and cultivation

Any changes made which affect the forest canopy. Even the elimination of individual trees, must necessarily change the degree of interception so that more precipitation reaches the ground.

An average of 26% more precipitation reaches the ground in a thinned stand compared with non thinned stand and therefore there is greater run off from thinned forests. It was found that interception in summer and autumn was increased by 35% by removing trees of trunk diameter 24 cm and over from non thinned stand, and in young stands even a slight thinning significantly reduced interception.

The small amounts of summer and autumn precipitation contribute little so the surface and ground water regime because they are lost by evaporation. Only the last autumn winter and spring rains are of significant to the water budget of the water shed, and therefore reduction in the degree of interception. The relationship between the degree of interception and canopy density is not linear (Table 3), nor is the canopy density directly related to the density of tree planting.

Table 3

Relation between precipitation and interception for spruce of canopy density 0.9

Precipitation (mm)	2-2	2-4	4-6	6-8	8-10	10-12	12-14
Interception %	80	65	50	40	33	27	24
Precipitation(mm)	14-16	16-18	18-20	20-22	22-24	24	
Interception %	21	18	16	15	15	15	

Table 4

Amounts of precipitation reaching ground according to the tree crown area

Tree crown area (m^2)	14.8	8.9	6.1	6.0	3.7
Precipitation reaching ground (mm)	178	204	222	245	247
Degree of interception according to forest density					
Interception % of 25mm precipitation	23	15	22	10	3
Cross sectional area of trunks	382	223	206	181	147
experimental area (m^2)	159	96	66	65	40
Growth density index	310	188	134	134	86

Source : Role of forest in water economy -Otakar Riedl.

4.2.4 Interception of snow and snow melt

Forest trees are able to retain various amounts of snow on their foliage and branches, the amount depending on the species, the canopy density and the degree of foliation. The amount of snow captured and the duration of capture are influenced by air temperature, direct solar radiation wind speed and site exposure. The role of evaporation of snow caught in the crowns of trees is governed by the same meteorological factors as those determining evaporation in open ground. Direct sunlight gives rise to thawing and breaking up of snow cover, so that some of the captured snow falls to the ground and the reminder then melts and drops to the ground more rapidly. Some evaporates directly.

Leaves and especially the needles of conifers, offer an effective support system for snow flakes. Snow flakes are larger than rain drops and adhere to the surface of contact thereby increasing the overall surface area offered to further snowflakes. According to observations made in USA, snow interception was 5.4% in a young forest stand 24.5% in an old pine forest without undergrowth and 29.8% in same pine forest with undergrowth.

Interception by coniferous trees is smaller in winter (e.g. 16% for an old stand of spruce) than in summer (42% for the same spruce). In some winters the interception of snow can reach large proportions, especially if conditions are such that the snow does not melt, but nevertheless evaporates from the trees. Under more moderate conditions with fluctuating tamps. through the winter, the snow thaws on the trees and the melt water reaches the ground. Water arriving in this way makes an important contribution to the ground water reserves and the advantage of slow thawing of snow captured in the trees of the watershed is that it prolongs and evens out large discharge of water in to the waterways.

At the same altitude above sea level, the thickest layer of snow can be found on clearing and pastures sheltered from the wind followed by beech and oak forest and then coniferous forest. The thickness of the snow layer depends on the age of the trees and the density of the tree canopy.

In the forested watershed of Kychova, the following thickness of lying snow were recorded on open unprotected soil 30 cm in nearby spruce forest, 13 cm, in a dense fir forest, 7 cm, and in young beech wood 4 cm.

On agricultural land at lower altitudes, falls of snow recorded immediately after it has stopped snowing are found to be deeper than falls on less open land. In open sites, however, the wind and the process of evaporation makes the greatest impact in reducing the snow cover so that often before the thaw sets in, there is less snow remaining on these open sites than there is in the forests.

According to a study by the US Army Corps of Engineers (1956), the daily spring time snowmelt 'M' in inches may be estimated by the following correlation equations as a function of mean daily temperature T mean the maximum daily Tmax, and the relative forest cover:

$$M = 0.05\ (T_{mean} - 32) \qquad \text{(i)}$$

$$M = 0.04\ (T_{max} - 42) \qquad \text{(ii)}$$

The equations are applicable for Tmean in the range of 34 to 66°F and for Tmax in the range of 44 to 76°F. There is a wide variation in melt rates between periods, because air temperature alone does not adequately represent the entire melt process. The above relations however represent the average relationship between air temperature and snowmelt during active spring snowmelt period for extremes of the forest cover.

4.3 INFILTRATION

The infiltration of water into forest soils differs in some respects from the infiltration of water on agricultural lands. This is because forest soils are usually not homogenous, and deviation from homogenity is increased further by timber handling.

The following examples are given to illustrate the range of infiltration rates in different forest soils. In an 80 year old beech and fir forest in Kychova, 500 cubic cm infiltrated soil in 72 secs, the expt. was carried out over a layer of humus 3-5 cm thick. The same amount of water took 24840 secs to infiltrate (345 times) in the close neighbourhood of the same forest, but at site where soil compaction had taken placed after a land slip. On the forest track there was no infiltration even after 3 hrs. and in a forest glade with a thick layer of moss, the infiltration of 250 cubic cm took 10800 secs. In a spruce stand with a humus layer 5-7 cms deep, situated next to the beech and fir forest, the infiltration of 500 cubic cm of water took 51-124 secs.

In a properly managed forest with a well distributed layer of shed leaves and branches, the latter layer not only provides excellent ground cover and soil protection, but also acts in sponge like fashion, making for the rapid infiltration of water which then accumulates in the layer and from there infiltrates more slowly into the deeper layers of the ground. The permeability of the forest soil and the thickness of the covering layer of fallen leaves and branches are therefore important factors governing the water economy of the forest. The upper humus forming layers provide an effective insulation barrier against drying out of the soil, which therefore maintains a high capacity to take up water by infiltration. Heaps of leaf litter which has not been evenly distributed over the ground can be compressed under the weight of snow and further compacted by rain developing a surface from which water largely runs off.

4.3.1 The role of plant roots

Water movement in the ground under forest is greatly facilitated by the roots of the trees. As the root tips ramify through the ground they enter the soil pores both capillary and non capillary as well as entering the larger aggregates and displacing the primary soil particles. Thus roots have the effect of reducing the free space and porosity of the soil. As roots expand in dia-meter the surrounding soil is compressed and the pore volume is further reduced thus limiting the passage ways available to the movement of ground water and soil atmosphere.

The stress resulting from the pressure of expanding roots on the surrounding soil spread more in a horizontal direction then vertically. The root pressure tends to close the soil pores and squeeze the waterout of the soil, but the fact that the root volume increases very gradually means that the stresses set up in the soil are less than those which would result from a similar, but sudden increase in volume. This is because under slow compression, the soil yields as the particles become more tightly bound together. The yielding process depends very much on the water content of the soil, especially in the case of clay soils, with increasing moisture content, the compressibility of the soil increases.

Soil particles are displaced radially under the pressure of a growing root, in the same way as the soil is affected by the penetration of a pile into the ground. The displacement near the root in any direction equals a half of the overall expansion of the root. According to field measurement, the distance from the root beyond which displacement of the soil is no longer discernible is about six times the root radius. At the surface of the root, a shear stress appears which is small for roots in moist loam, and reaches the highest values around roots growing in gravel.

According to the conformation and growth pattern of the root system, the displacement of the soil is different in different directions. For example, spruces have horizontaly directed roots, and the displacement of the soil is therefore rather different from that caused by trees with downward projecting roots. The roots of a spruce, which are from 5 to 50 cm below the ground surface, give rise to a displacement towards the surface and lifting of the surface, the extent of this depending on the depth of the roots.

The effect of root pressure against the resistance of soil, the creation of tangential stresses around the root surface, and the overcoming of the shear resistance, cause cracks to appear in the ground around the roots. The orientation of the cracks depends on the orientation of the roots, the magnitude of the pressure and the granular composition, moisture content etc. of the soil. Generally, the cracks follow the direction of the roots. The area of the cross-section of axially parallel cracks is determined by the above mentioned factors; as pressure increases with growth of the roots, the cracks are widended and new ones develop.

The cracks thus formed enable water to move along the surfaces of the roots, into the ground, and the spaces of the cracks compensate for the pore volume that was lost by compression of the soil. However, the original pore volume was made up of a larger number of capillary spaces in which water moved by the action of capillary forces, while in the newly created which are smaller in number and larger in volume than the capillaries, the water moves predominantly under the influence of gravity.

Since the cracks are interconnected along the entire root length, they form an uninterrupted system of small channels along which water moves much more rapidly than through soil pores. Thus the rate of infiltration is much enhanced by the formation of the cracks, which have a lower tortusity factor than soil capillaries.

4.4 EVAPORATION FROM THE GROUND WATER AND TRANSPIRATION OF FOREST TREES

4.4.1 Evaporation from the ground

Evaporation from the soil affects the upper most layers to depths of 10-25 cm, though in dry soils water vapours may reach the surface from sources as deep as 70 cm. It takes 20-80 days from the start of the evaporation process before water enters the deepest affected layers begins to move towards the surface, the water moving either in liquid or vapour form. At the outset of the drying of a soil, water movement in the surface is at its most rapid, subsequently slowing down to a constant, rate as the thickness of the dried out zone increases. Water loss by evaporation reaches 18% of the original moisture content in sandy soils, while in loamy soils and stable soil, only 10% may be lost by evaporation. The difference is explained by the fact that water is more tightly bound in the pores and capillaries of soils with good aggregate structure.

On very wet soils not protected by tree canopy, the rate of evaporation remains to a constant proportion of the rate of evaporation from a free water surface; sandy soil, medium heavy soils and heavy soil, this proportion is about 10.09, 0.75 respectively.

If the relative humidity of the soil atmosphere is 100% evaporation occurs more rapidly than evaporation from a free water surface, although if the water table is at the ground surface, evaporation is about the same as that from an open expanse of water. The rate of evaporation is much slower from the bound, or capillary water content of the soil.

4.4.2 Transpiration

Transpiration is a physiological process which differs from the simple physical evaporation in that transpiration rates are sometimes larger and sometimes smaller than the rates that would be expected if the phenomenon were a purely physical one. Generally, transpiration is influenced by radiation, Temperature the relative humidity of the air, the wind speed and mobility of ground water. The depth of the water table also has as strong influence on the rate of transpiration it was found, for example, that evapotranspiration from a meadow increased by 31% when the water table rose from a depth of 1.8 m to 0.5 m.

In soil which is penetrated by roots, water moves towards the roots in a direction normal to the root axis as the process of extraction continues. Dense root system give rise to intense drying of the soil in the layers occupied by the roots, while deep roots systems spread the drying effects more gradually over a greater part of the soil profile.

The transpiration rate of individual trees depends not only on environmental factors, but also on the total leaf area. The leaf area of broad leaved trees is at its largest at the time of most rapid growth of the foliage of the tree i.e. at about 60 years of age for the oak, 20-40 years for the popular and ash, 40 years for the pine, and 60 years for spruce. There after the leaf area decreases again.

One hectare of 60 years old oak or beech forest is estimated to have a total leaf area of 15-20 hectares. While the corresponding figure for Douglas fir is 18-27 hectares. By comparison, leaf area of one hectare of grass-lands ranges from 20-50 hectares, and that of lucerne can be as much as 85 hectares.

Table 5 : Annual Water Consumption for Transpiration and Evaporation by different Tree Species

Tree species	Annual precipi-tation (mm)	Consumption process	Age of trees							
			20	40	60	80	100	120	140	160
Pine	550	Transpiration	236	250	200	185	170	158	146	125
		Evaporation from ground and ground cover	48	67	87	100	100	100	103	105
		Interception in crowns	127	150	140	135	120	105	100	97
		Total	**411**	**467**	**427**	**420**	**390**	**333**	**349**	**327**
Oak	523	Transipiration	310	342	352	323	289	263	255	252
		Evaporation from ground and ground cover	65	78	84	90	94	98	104	104
		Interception in crowns	49	63	64	60	58	58	60	60
		Total	**424**	**483**	**500**	**473**	**441**	**419**	**419**	**416**
Spruce	580	Transpiration	203	291	300	278	219	193	188	188
		Evaporation from ground and ground cover	60	55	55	60	58	75	80	83
		Interception in crowns	158	175	185	180	170	160	144	128
		Total	**421**	**521**	**540**	**518**	**447**	**428**	**412**	**399**

Source - Role of forest in water economy - Otakar Riedl

Evaporation from the forest or woodland floor increases with the age of the stand while the transpiration rate increases the first, reaches a maximum with the maximum leaf area, and than gradually decreases.

The greatest water consumption occurs when the water reserves of the ground amount to about 180 mm, the optimum ground conditions for transpiration involving not only a certain supply of water, but also the presence of air in the ground and an optimum ground temperature for transpiration.

The figures given in table 5 show that the largest part of the water that is taken up is used in transpiration.

In dense forest stands, the water consumption is greater then the thinned stands, but when the tree canopy is very much reduced, consumption increases again as evaporation from the ground increases significantly. Evaporation in the forested watershed of Kychova in the Beskydy was calculated as the difference between in precipitation and the outflow of water in the waterways, and was found to amount to 380 mm. (40% of the beeches and 60% of the spruces in this area were over 60 year old). Monthly amounts of evaporation in a beech forest expressed as a percentage in of the annual evaporation, were obtained from daily measurements of the relative humidity, as follows (Riedl 1986):

Months	1	2	3	4	5	6	7	8	9	10	11	12	Total
Evaporation	1	1	2	4	12	17	22	17	17	6	1	0	100%

Rates of transpiration or evapotranspiration can also be estimated from fluctuations in the height of the water table ; during a period without precipitation, water uptake causes the water table to drop continuously, and there is a daily fluctuation of this process as the rate of transpiration varies on a daily cycle. Water consumption is greatest in the first hours of the afternoon, and least at night, when the water supply is able to recover to some extent from water contained in the soil pore spaces and capillaries, and water gained condensation. According to BIELECKY (1969), the daily fluctuation can amount to as much as 37 mm, although during measurements made for a period of a month in a forest, daily difference of 4.6 to 81.3 mm were recorded, and for a field observed during the same month the difference were 119 to 149 mm per day.

Evaporation from the ground cover in an oak forest (MOLCANOV 1961)

Age (years)	4-10	15-21	22-28	33-39	42-48	56-62
Evaporation	205	67	62	70	81	84

Table 6

Water consumed by transpiration in a pine forest according to the water reserves of the ground

Ground water reserve (mm)	60	100	140	180	220	260	300	380
Pine forest transpiration uptake (mm)	234	250	270	275	260	245	205	176

Similar fluctuations occur where the water table is at a greater depth, and fluctuations tend to be less pronounced in forests than in open fields. Seasonally, the smallest fluctuations occur in October, and the largest in the period of fastest vegetative growth.

Evapotranspiration in forest stands has to be considered in terms of factors over and above the characteristics of the various species and the influence of leaf area. Trees show the greatest water demand when the foliage is fully developed, and when the day length and hours of sunshine per day are maximum. Average figure for daily water consumption in forest stands in July and August are 2-2.5 mm and 3-3.5 mm respectively. During the day, the highest rate of uptake occurs just afternoon, while during the night, the consumption may vary from nil to 0.2-0.3 mm. Comparing evaporation from a free water surface with evapotranspiration from meadowland, there is little difference under the overcast sky, but under bright sunshine the latter is greater than the former.

4.5 THE INFLUENCE OF THE FOREST IN REDUCING FLUCTUATIONS IN THE OUTFLOW OF WATER FROM THE WATERSHED

Precipitation water which reaches the forest floors is partly absorbed by the surface layers of humus and litter, from which it gradually infiltrates into the ground. That part of the precipitation water which does not enter the ground during conditions of intense afflux begins to flow over the surface. The ground cover of litter, fallen branches, accumulated heaps of fallen leaves, etc. presents an obstacle to the free flow of the surface water, and this flow is further retarded by unevenness of the ground, the presence of mounds or troughs and hollows filled with litter causing the water to be diverted and a large amount of it to be retained.

Research studies carried out in Kychova have shown that on hillside experimental cultivation plots (slope angle 30) protected by a good ground cover and surface layer of humus, all the precipitation that fell during a 10-year observation period was completely absorbed and no surface runoff occurred. It may be inferred from this that in a well maintained forest, surface runoff only occurs if the soil is already saturated and may thus develop after some delay during exceptionally heavy rainfall. The greatest degree of runoff occurs in the open parts of the forest the tracks, log heaps, felled and ploughed areas, and areas with a poor surface humus layer. Generally, however, surface runoff from forested watersheds is less than that on non-forested watersheds; also the forest has the additional effect of retarding the runoff process and slowing down the outflow of ground water from the watershed. This retardation depends on the distance of travel downhill, the angle of inclination of sub-soil strata, the permeability of the ground, the depth of the soil profile, the soil porosity, the soil water content at the start of the period of precipitation, and the soil temperature. As a rough guide to retardation times, these may be 3-5 days in a catchment area of about 5 Sq.kms., although under exceptionally favourable conditions the retardation can be as much as 25 days.

Capturing large amounts of water from voilet cloudburst and providing the conditions for this water to find its way into the ground, is therefore a very important function of the forest. The soil, which is the principal supplier of water in terrestial environments, is improved structurally by the root system of forest trees, which thus enhance the properties of the soil and increase its water supply capacity.

4.6 PROTECTIVE FOREST BELTS

Apart from providing a source of timber, forest stands perform other functions which in overall economic terms may be of greater value than the commercial timber value of the forest. These other functions include water conservation, soil protection and soil improvement, are realised not only by large expenses of forests, but under suitable conditions by narrow forest belts also. The narrow forest strips enable forests in creating conditions for moderating air movements, reducing wind erosion, reducing the harmful drying effects of wind on soil and combating the undesirable effects of industrial pollution of the atmosphere. Accordingly forest belts may broadly be divided to perform two main functions:

1. Belts with soil conserving function - wind break belts.

2. Belts which are intended to provide a partial protection of land against industrial atmospheric pollutants -environmental enhancement belts.

In 1934-35 millions of tons of soil in USA were carried away and deposited in ocean. It was this event that promoted the widespread introduction of forest belts over whole of USA, the north south oriented belts having the function of interrupting the continuous air flow from ocean to ocean. Nowadays this is widely practiced in all European countries including USSR.

The reduction in wind velocity and turbulent exchange obtained in the vicinity of wind break belts have both favourable and unfavourable effects on meteorological conditions, soil water reserves and soil properties. The favourable effects includes:-

- air temperature increased
- an increase in air humidity
- a reduction in evaporation from the soil and vegetation
- increased dew formation
- increased capture of snow
- higher agricultural yield

The increase in snow capture in south Moravia (Europe) is illustrated in graph of fig.3, as a result of a protective forest belt.

Shrubs are more effective than trees for bringing about deposition of wind borne material in drifts. The large number of growing stems of shrubs swaying in the wind from a screen near ground level which is less penetrable than that formed by tree at the same level.

Obtaining the best distribution and positioning of forest belts requires that the prevailing wind direction and max wind speed are known for the times of the year when the strongest winds are expected and soil is most vulnerable to wind erosion. The inter belt spacing should be such as to ensure that the wind speed between successive belts does not exceed the threshold speed for displacing soil particles. For greatest effectiveness the axis of the belts need to be perpendicular to the direction of the prevailing wind. On undulating terrain, protective forest belts are preferably positioned near or at the tops of slopes. On leeward slopes of less than 5o angle of inclination the distribution and spacing of belts may be level areas. Where the slopes are steeper, the belts are positioned where air currents over the top of the hill decent to meet the ground. The interbelt distance on the upper third length of leeward slopes should be smaller than that on plateaus.

The industrial exalations is a potential threat to public health and is undoubtedly damaging to agricultural forestry terrestrial and aquatic environments. However it is a doubtful whether narrow forests belts can make any contribution towards purifying the atmosphere simply by their wind moderating action. Indeed entire forests may die under constant exposure to toxic emissions. The extent of the damage suffered varies according to the species and the age of the vegetation, and depends very much, of course, on the particular pollutant involved and its concentration. The protective forest belts provide filtering effect to a polluted environment.

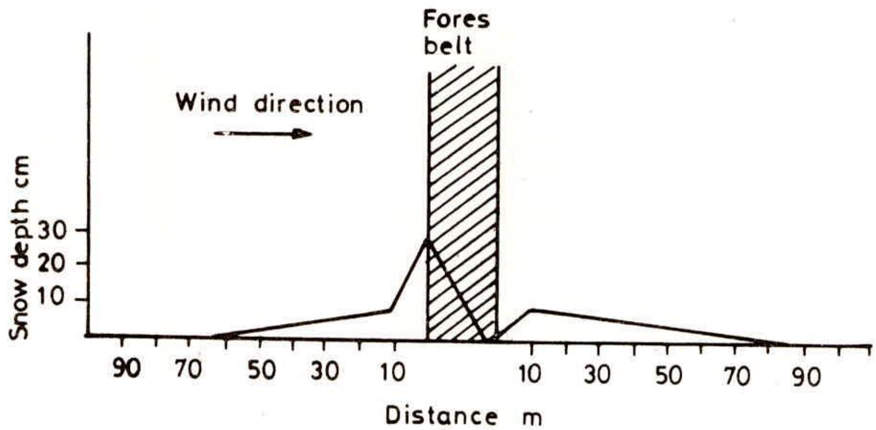


Fig.-3 Capture of snow due to a forest belt.
Source: Protective forest belts by Otaker Riedl.

5.0 STATUS OF RESEARCH IN INDIA AND VARIOUS RESEARCH NEEDS

5.1 ORGANISATIONS AND MANPOWER INVOLVED IN FOREST HYDROLOGY

The studies concerning forest hydrology have not been done on a large scale in India. The limited number of studies which have been done by the central soil and water conservation research and training institute and some other organisations have been mostly on small watershed varying in size from 0.21 Ha to 84 Ha with exception of very few studies which have been recently initiated on large watersheds (370 to 1754 Ha).

The organisations working in the area of forest hydrology include:

1. Central soil and water conservation research and training institute, Dehradun. (also at Chandigarh, Agra, Kota, Ooty and Vasad).
2. Forest research institute, Dehradun (Experimental research stations at Simla, Tehri, Garhwal, Ooty and Kurseong).
3. Central water and power research station, Pune.
4. Damodar valley corporation, Hazaribagh.
5. Ramaganga project division, Ramaganga.
6. Forest deptt., Chandigarh.
7. Central water commission, New Delhi
8. Central unit of soil and water conservation, MOA, New Delhi
9. Central arid zone research institute, Jodhpur.
10. National remote sensing agency, Hyderabad and State Centres.

Apart from central and state governmental organisations a number of autonomous agencies such as universities of agriculture and other related organisations are taking up research in the area of forest hydrology, thus involving a large number of scientists and academicians. Several small representative basins and experimental basins studies have been initiated since 1960. Appendix 1 shows the details of organisations involved in such basin studies.

5.2 STATUS OF RESEARCH IN INDIA

Presently the type of studies taken up in India include:

(i.) to evaluate the effect of various land uses and vegetative covers on various elements of hydrologic cycle e.g. interception, infiltration, soil moisture, runoff and soil loss. (ii) to study hydrological behaviour of natural and man made forests, (iii) to study hydrological behaviour of natural forest watersheds under permanent vegetation and grass cover, (iv) to study influence of various forests management practices and biotic interference on hydrologic cycle, (v) to establish rainfall runoff and sediment yield relationships and develop runoff prediction models for small watersheds, (vi) to assess the impact of soil conservation measures of runoff and soil loss, (vii) to identify suitable tree species and management practices from conservation point of view, and (viii) to study hydrological behaviour of revinous watersheds.

The effect of forests on important hydrological parameters viz. rainfall, interception, infiltration, soil moisture, evaporation, ground water, water yield, sediment yield, water quality and floods have been discussed here briefly.

5.2.1 Rainfall

In India, systematic and scientific studies have not been done in a planned way to study the effect of afforestation on rainfall. The experience in India on the basis of few observations tends to suggest that forests do not have appreciable effect on rainfall over a wide area whereas they may have limited effect on local rainfall due to high rate of evapotranspiration taking place from vegetation cover. The result of an enquiry initiated by Government of India in 1906 (Lal and Subba , 1981) also concluded that the influence of forests on rainfall was probably small.

However, Dr. Voelekar published interesting data pertaining to the areas of Nilgiri hills which was later updated suggesting that the number of the rainy days increased with the increase of forests, excluding the month of June, July and August as the rains during these months are not of local origin (Ranganathan, 1964 cited from Lal and Subba , 1981). Martin (1944) in a study on the influence of forests on rainfall observed that forest increases rainfall as a whole over large area owing to increased humidity and forests make rain more frequent and gentle. While studying the effects of deforestation on the intensity and frequency of rainfall and floods in Pathri, Ranipur and Ratmau torrents, Bhattacharya (1956) found that the planned deforestation in either of the catchments was not having any significant effect on rainfall which did not exhibit marked change in either its intensity or distribution. It may thus be concluded that the results of limited studies indicate that large scale afforestation may locally affect the incidence and distribution of rainfall and even increase it, but these effects on a regional scale may not be significant. In case of coastal forests, the precipitation is more because of interception and then condensation of fog by forest vegetation. Studies on large upland watersheds are required to be taken up to get a better understanding on the effects of forests on rainfall.

5.2.2 Interception

Studies carried out by FRI, Dehradun on the interception losses of Chir, Teak, Sal, and Khair indicate the canopy interception as 22.1, 20.8, 38.2 and 28.5 percent of rainfall respectively (Qureshi and Subba , 1967, Dabral and Subba, 1968, 1969 Gosh et al. 1980).

The CSWCRTI has carried out interception studies at Chandigarh, Dehradun Ootacamund and the results are presented in table 7. The regression equations have been also developed between precipitation and interception at Chandigarh and Ootacamund (Tejwani et al. 1975 and Annon. 1982) on couple of important tree species. Based on the figures available from experimental studies the interception losses could be assumed to be around 20% for dense canopies for all the preliminary purposes. There are no details available for interception by ground vegetation which could be conservatively assumed around 10%. There have been very few studies on interception by leaf litter. Dabral et al. (1963) found the litter interception in the order of 5 to 8% of rainfall. In summary it could be safely said that the average total interception by forest cover (including top/middle storey, undergrowth and litter interception) appears to be around 35% of rainfall.

Table 7 : Interception by Forest Cover

Species	Stand density (trees/ha/ or age	% of rainfall throughfall	stemflow	interception	Remarks
Babul (Acacia nilotica)	7 years	-	-	26.00	(Tejwani et al, 1975)
Khair (Acacia catechu)	574	67.30	4.20	28.50	(Dabral et al, 1963)
Teak (Tectona grandis)	1742	73.20	6.00	20.80	(Dabral & Subbarao, 1969)
Chir (Pinus rexburghii)	1156	74.30	3.60	22.10	(-do-)
Sal (Shorea robusta)	1678	66.40	8.30	25.30	(Dabral et al, 1963)
Black Wattle (Acacia mearsnii)	31.5*(15 years)	70.50	4.30	25.10	(Samraj et al, Anon, 1982)
Bluegum (Eucalyptus globulus)	12.1*(15 years)	76.70	1.50	21.90	(-do-)
Natural Shola Forest (Age indeterminable)	30.6*	65.00	1.30	33.80	(Singh & Prajapati, 1974)
Sisham (Dalbergia sissoo)	10-14 years	-	-	6.50	(1971)+

* Average canopy m^2/tree

+ Citation from the annual reports of the Central Soil and water conservation Research and Training Institute, Dehradun, for the corresponding years.

++25 years of research on Soil and Water Conservation in Southern Hilly High Rainfall Regions CSWCRTI, Research Centre, Udhagamandalam (ICAR), 1982.

5.2.3 Infiltration

Infiltration, an important element of hydrologic cycle is amendable to vegetation manipulation by virtue of its effect on soil structure. The forest cover provides a layer of decaying organic matter associated with deep roots which helps in making the soil structure more conducive to infiltration. Tejwani et al. (1975) reported average infiltration rates under different types of site conditions which are given in table 8.

Table 8

Hourly and Average Infiltration Rates for Different Sties under Forest Area in HimalayanUpland (Foot Hills Slopes)

Site	Site description	Elevation above MSL (Metre)	Infiltration Rates (cm/hr.) I hr.	2nd hr.	3rd hr.
13	BIDHAULI-Sal forest with good leaf little	838	8.95	5.90	5.85
14.	HORAWALA-Satl forest with very little leaf little and compact surface	671	3.65	2.0	2.20
15	MADARI R.F.-Sal forest with litter leaf litter and compact surface	567	4.55	2.45	2.50
16	CHANDUR R.F.-Sal forest with little leaf litter	533	4.85	2.53	2.88
17	DHULKOT R.F.-Sal forest with good leaf litter average	...	5.87	3.78	3.83

Source : Tejwani et.al. (1975)

The results of infiltration studies conducted at Bellary and Ootacamund under different vegetative covers as given in table 9. (Tejwani et al. 1975) indicate maximum infiltration rates for wood lands in Bellary (17 cm/hr.) and Shola forest i.e. miscellaneous vegetation in Ootacamund (12.5 - 16.8 cm/hr.). The analysis of data from small forest and agricultural watersheds of Doon valley done by Dhruvanarayana and Sastry (1983) indicate that the rate of infiltration is twice in forest watershed (Shorea robusta) as compared to agricultural watershed as shown in figure 4.

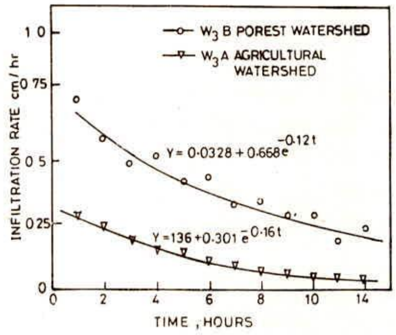


Fig.-4 Infiltration characteristics of forest and agricultural watersheds.
Source: Dhruvnarayana and Sastry (Anon., 1983)

Table 9

Infiltration Rate under Different Vegetative Centres

Vegetative Cover of land use		Infiltration rate (cm/hr.)	Remarks
Bellary	Woodland	17.00	For one hour run
	Grass land	2.60	"
	Agricultural land	1.00	"
Ootacamund	Study No.1		
	Shola forest	16.84	For three hours run
	Bluegum plantation	20.69	"
	Grazed grassland	5.13	"
Ootacamund	Study No.2		
	Shola forest	12.50	"
	B ROOM(Cytisus scoparius)	11.25	"
	Grazed grassland	6.25	"

Source : Tejwani et.al. (1975)

A comparative study of infiltration rates conducted by FRI at Dehradun in Eucalyptus, Sal, Chir, Teak, Bamboo and grassland gave 54.0, 12.0, 9.6 and 7.6 cm/hr. Chir plantation after fire gave significantly reduced infiltration rate i.e. 3.6 cm/hr. The studies at experimental research station (ERS) at Simla under forest and agricultural lands both under snow and without snow also confirm that forest land has higher initial infiltration rate. Maximum infiltration rate was obtained under Shola forestry (30 cm/hr.) followed by Bluegum (23.6 cm/hr.) and grassland (8.7 cm/hr.) at Ootacamund by ERS in their preliminary studies (Personal communication). In Bihar, Mistry and Chatterji (1965, cited from Gupta, 1980) recorded infiltration rates under forest land, permanent grass and arable crop lands as 26.12 and 9 cm/hr. respectively.

The infiltration studies conducted in India at various places under different vegetation covers confirm that infiltration rates are higher under forests. The percentage increase would vary depending on soil type, species and biotic interference. It appears very little work has been done in this field and there is a need to carry out field infiltration studies under different forest types, sub types, and associations. The efforts must be channeled to evaluate the effect of species changes, burning, logging, extensive soil working, grazing etc. on the infiltration so that the possibilities of manipulating infiltration rates can be explored for improving hydrological regimes of watersheds. Appropriate values of infiltration for different forest cover could, therefore, be used for estimating water yield from forest watersheds.

5.2.4 Soil moisture

The ability of soil to store moisture works as a reservoir during heavy rainfall and influence the peak discharge and floods. The slow releasing mechanism from the soil moisture storage increase the lean season flow in stream which could be of great help during drought situation. The sporadic soil moisture monitoring (measurements) under forest cover has been done by CSWCRTI and its centres, FRI Dehradun and CWPRS at Khandala.

It has been recorded (Gosh and Subba , 1979 cited from Gupta, 1980) that soil moisture remains at a higher level under forest than grass e.g. bamboo (14-102), teak (30-73) Chir pine (20-77), Sal (20-108) and grass (9-95). In a study at Dehradun, the forest watershed gave relatively higher soil moisture values in top 45 cm soil depth as compared to agricultural watershed as analysed by Dhruvanarayana and Sastry, (Anon, 1983). The burning of leaf litter and its removal for manure as is being practised in hills results in low soil moisture conditions. Whereas a better moisture regime has been found when leaf litter is burnt but not removed from forest floor.

In India much efforts have not been made to quantify soil moisture storage of forested land, water holding capacity of forest soils etc. Under a forest cover soil moisture content is not uniform due to uneven wetting resulting from stem flow and interception. Desk studies (calculations) indicate that the forest areas of India has a soil moisture storage capacity (water holding capacity) of about 447.6 m ha-m on a temporary basis and 223.8 m ha-m a prolonged basis (Mathur 1982). Thus there is an urgent need to determine soil moisture storage of forested catchments and to evolve ways and means to improve over the present status. The regular soil moisture monitoring of forested catchments is becoming increasingly essential in forest hydrology.

5.2.5 Evapotranspiration

Very little has been done to work out evaporation and transpiration losses from forested watersheds in India. It has been observed that the albedo of forest areas are different as compared to other areas which has its effects on evaporation losses from forested watersheds. Dabral et al (1965) gave the following rough estimates of annual evapotranspiration losses as observed at Dehradun (upto soil depth of 1.22 m) on the basis of one year's observation.

Chir	(Pinus roxburii)	25 years	=	840 mm
Teak	(Tectona grandis)	35 years	=	840 mm
Sal	(Shorea robusta)	37 years	=	560 mm

The evapotranspiration losses of Eucalyptus citridora, Populus calale, Dalbergia latifolia and pinus roxburii in juvenile stage were reported to be 5526, 2704, 1143 and 536 mm respectively from Sept. to June at FRI using lysimeters by Dabral (1970). Banerfu (1972) reported evapotranspiration loss to be 1136 mm for Eucalyptus plantation in West Bengal during the period from October, 1970 to October, 1971. Evapotranspiration of some of the species of forests is indicated in table 10.

Transpiration is more important during the growing season than the evaporation. It depends on the type and species of the plant, characteristics of soil, water table and treatments of vegetation e.g. frequent cutting etc. In an experiment at Ootacamund carried out to work out transpiration of bluegum (E. globulus) in Nilgiris by calcium carbide method, the annual transpiration rate was estimated to be about 34.7 cm at an average annual rainfall of 130 cm. Some work has also been carried out at Calcutta University on leaf area, no of stomata and stomatal area as reported by Mathur (1980). Rajgopalan et al. (1985) reported annual consumptive use crop coefficient for forested catchments in Khandala to be 0.542 which is on the lower side of crop coefficient of deciduous orchard. Such studies have been desirable in different vegetation types to arrive at appropriate coefficient values under different forest mixtures.

It would be desirable to carry out evapotranspiration studies of different tree crops and forest types all over the country so that correct estimates of water use by forests can be assessed. Studies are required to be done to observe the effects of changing forest structure and composition including clearing or thinning overstoreys evapotranspiration losses. Efforts are required to initiate research on the use of anti-transpirations so as to reduce evapotranspiration loss and increase stream flow. This could be of great use for improving municipal water supplies by properly manipulating the vegetation in municipal watersheds. The application of Bowen ratio energy balance method may be explored for estimating forest ET as being done in other countries as reported by Black and Mc Naoughton (1971). Mc Naoughton et al (1973), Gay and Fritschen (1979), Spittelehouse and Black (1979) and many others.

5.2.6 Ground water

The effect of forest cover on ground water storage can be inferred from evapotranspiration, soil moisture and discharge relationships. It depends partly on the depth and proliferation of the rooting system and growing season length. It is generally believed and has also been experienced in some countries that in areas where the ground water table is near the surface, forest cutting will cause it to rise. Conversely reforestation can eliminate water logged or semi swamp conditions. But in India, no efforts have been made to study the influence of forest on ground water. Recently the ERS (FRI) has taken up projects to evaluate the role of land use and difference forest covers on ground water table through regular ground water monitoring at Siliguri under cryptomeria and under Bluegum. Shola and grassland at Ootacamund centres. The increase in water table due to afforestation and other soil conservation measures in a water shed of 314 Ha has been evidenced in GR.Halli, chitradurga (Anon, 1983) and elsewhere. In most of the watershed hydrology research studies, the ground water component is normally not being mentioned which is considered to be an important component for studying the complete hydrology of a watershed. There has been a recent trend to plant fast growing tree species but as on today there has been no systematic study on the impact of the fast growing trees like Eucalyptus etc. on ground water recharge.

Table 10

Effect of Forests on Evapotranspiration

Forest type/ Land use	Evapotranspiration (mm)	Transpi-ration	Reference
Chir	840	-	Dabral et.al.(1965)
Teak	840	-	-do-
Sal	560	-	-do-
Eucalyptus	268-5526	-	-do-
Forest	50% of precipitation	100	Kunlcle (1975)
Grasslands	38% of precipitation	22	Gupta (undated)
Cropland	-	43	
Eucalyptus Globulees	38% of precipitation	-	Thomas (1972)
Dry Deciduous Forest	560	-	Mishra (1968)
Pinus	536	-	Dabral et.al.(1965)
Radiata	760-885	-	
Finester	149	-	
Macarthuri	268	-	
Stuartiana	1200	-	
Diversi Colour	1248	-	

5.2.7 Water yield and soil loss

Experimental studies have been conducted at various places in India to assess the effects of forests and forest management practices on water yield, peak flows and soil loss. Studies under different vegetative covers like Kudzu (pueraria hisusta), Dichanthium annulutum, chryspogan fulvus, and Eulliopsis binta (Bhabhar grass), on 11% siope gave minimum runoff and soil loss under Kudzu where as Bhabhar grass produced maximum runoff during the observation period from 1961-66 (Tejwani et al., 1975). Mathur et al (1976) reported that reforestation of a small watershed (1.45 Ha) by Eucalyptus grandis and Eucalyptus camaldulensis (replacing the brushwood reduced volume and peak rate of runoff by 28 & 73% respectively from 1969 to 1973).

The runoff and soil loss data collected from 3 Doon valley watersheds (4.42 to 83.4 Ha under agril, forest and combination of both) from 1960-1983 indicate minimum runoff (0.8% of monsoon rainfall during 1983) from agricultural watersheds (54.6 ha) where binding has been done. Relatively high seasonal runoff (15.1% of rainfall was recorded in forest watershed (5.3 ha), perhaps due to the fact that no mechanical soil conservation measures were implemented (Anon, 1983). However, peak rate of runoff was also maximum from forest watershed which could be due to relatively high drainage density, relief ratio and low time of conservation. A forest area in the lower Himalayan at Bemunda (Tehri-Garhwal) is also being gauged with the R.C.C. trapezoidal flume since 1980 to study the hydrological behaviour of forest watershed and develop rainfall-runoff relationship (Puri et al. 1982). The first two years of data indicated that the total runoff (including base flow) was observed to be 69% and 79% of the total precipitation during the main rainy months of July and August in water year 1981-1982 indicates 54% of the total precipitation going as total runoff from the catchment. The hydrological monitoring is also going on since 1975-76 at two sites in the Bhaitan watershed (370 ha) to study the hydrological behaviour of watershed before and after the watershed treatments at Fakot (Tehri-Garhwal).

Data on the peak discharge computed for selected storms of some agricultural and forested watersheds (sal forest) at Dehradun has shown 10% less peak discharges and 38.5% less soil loss in forest watersheds than agricultural watersheds (Ghosh and Subba, 1979). The results of a study carried out by FRI in two experimental watersheds (6.5 ha each under coppiced Sal deciduous moist forest) at Rajpur gave runoff as 42% of rainfall and soil loss of about 91 t/sqkm as observed by Subba et al (1973). A treatment of 20% thinning and imposed subsequently in one of the watersheds which showed that the peak rate of flow increased by 8.6% in the first year which later on subsided in subsequent years (Subbarao et al. 1984). At Chandigarh results of microwatersheds (0.7 - 4.15 ha) studies indicated that (i) burning (ii) cutting of trees (iii) overgrazing increased peak discharge by 73% (Anon, 1975). The contour trenching and afforestation with (Acacia catechu (Khair) on slopes and Sisham in low lying areas in a highly denuded siwalik watershed (20 ha with 9% slope) supported by check dams, staggered contour trenches and dabris basin reduced the sediment yield from 80 t/ha/year to 7 t/ha/year within the first four years of treatment (Misra et al. 1976).

The studies have been also conducted at few places to evaluate the effect of management of grasslands on runoff and soil loss. The experimental studies have been carried out at Deochanda (DVC) to study the effect of grazing on runoff and soil losses. The five year of data (1955-60) indicated runoff as 27, 19 and 11% of rainfall and soil loss as 2.37, 0.79 and 0.40 t/Ha from overgrazed, properly grazed and ungrazed areas respectively (cited from singh, 1985). This clearly indicates the gross effects of overgrazing on hydrologic behaviour of a watershed.

Studies at Ootacamund on peak discharges from different land uses indicate that the plantation of Euclyptus and Wattle reduced the peak discharge by merely 62% as compared to agricultural land (Lal and Subba Rao, 1981). Studies on the amount of runoff and soil loss under different vegetative covers e.g. Shola (i.e. natural forest), bluegum, wattle, broom and grasses carried out on 0.02 ha plots on 16% slope indicate highest water loss (runoff) amounting to 1.27% of total precipitation from wattle and Shola covers whereas in bluegum runoff is recorded to be 1.08% of total precipitation. It reveals that there was not much difference in runoff between different vegetative covers. The soil loss was also negligible (Anon., 1982). The runoff and soil loss data obtained from 0.09 ha plots with different treatments in natural Shola forest at Ootacamund (i.e. Sholas in treatment A, B and C were clearfelled in 1965 and planted with bluegum, Blackwattle and mixture of these two in1968) are given in table 11 (Anon, 1982). The results do not show any appreciable change in runoff and soil loss pattern even after the application of treatments.

Table 11

Effect of Plantation on Runoff and Soil Loss

Year	Mean Annual rainfall (mm)	Runoff as % of total rainfall A mixed plan-tation	 B Acacia mearnsii	 C Eucalyptus globulus	 D Shola	Soil loss kg/ha	Remarks
Calibration of 9 years before felling (1957 to 1965)	1361	0.01	0.01	0.03	0.05	Nil	**Mean for 9 years**
Calibration period of 3 years after felling (1965 to 1967)	1191	1.02	1.05	1.05	1.02	Nil	**Mean for 3 years**
Man-made forests in the first rotation (1968 to 1977)	1138	1.05	1.03	1.03	1.04	Nil	Mean for 10 years

Source : 25 years of Research in Soil and Water Conservation, CSWCRTI, Res. Centre, Ootacamund (1982).

The hydrological studies conducted on two identical watersheds (32 ha eacn) at Glemorgam (Ooty)_ to study the behaviour of watersheds with natural as well as introduced plantation of bluegum indicates that the observed discharge from natural vegetation (grasslands, sholas and swamps) and grass land with bluegum were 31.4 and 29.9% of total precipitation respectively (from 31.4 and 29.9% of total precipitation respectively (from 1972-76) and the soil loss was zero (Anon, 1982). However there are limitations of small plot studies. The preliminary analysis of runoff data of Glenmorgan water sheds indicates that at the end of 10 years rotation the watershed planted with bluegum (Eucalyptus globulus) produced

16% less annual water yield as compared to natural watershed (Research highlights CSWCRTI, 1983).

In the revinous areas of Yamuna, Chambal and Mahi rivers also the decreasing trend of runoff and soil loss has been noticed under forests and grass lands. Sharada et al (1982) conducted hydrological studies on to revinous watersheds (0.2 and 0.29 ha) at Agra and observed reduction in runoff as percentage of rainfall from 32.02 (1966) to 23.45 (1970) and 17.65 to 6.88 under grass cover alone (Cenchris Cilliaris) and Shisham (Dalbergia sissoo) with grass cover respectively. The comparison of the two indicate that grass cover alone is not as effective in checking runoff as Sissoo plantation with natural grasses. The two revinous waterhseds (10 and 4.8 ha) under mixed land use (forest + agri) being gauged at Vasad from 1961 also indicate the runoff volume and peak rate both decrease progressively as the vegetation in the watershed increases due to the closure against biotic interference. The average value of runoff coefficient is estimated as 0.20 (using data from 1961-1981) which seems to be in close agreement with the value of USDA (0.18) given for such land use (Anon, 1981). The experimental studies conducted at Kota (1979-82) on small watersheds (0.4-1.45 ha) showed that runoff and soil loss were maximum from agricultural watersheds (15.1% and 3.83 t/ha) as reported in Annual Report (1982) of CS&WCR&TI, Dehradun.

The hydrological studies have been carried out by pathak et al (1984) on six forested sites in microwatersheds of 25 square meters in Kumaun Himalayas. Overland flow was found to be negatively related with tree canopy and ground vegetation cover. The overland flow was maximum (1.24% of rainfall) for pine mixed broad leaved forest and minimum (0.38 of rainfall) for mixed oak, Tilong dominated forest with average value of 0.68% of incident rainfall. The sediment yield was maximum (57.2 kg/ha) for sal forest and minimum (15.3 kg/ha) for mixed oak-pine forest with average value of 32.5 kg/ha for all the six different forest sites. These results are obtained from very small plots, however, their applications on watershed basis may be doubtful.

In watershed management programmes, the afforestation and bunding measures have been considered as effective measures in areas where major contribution of sediment is in the form of sheet erosion. Hydrological monitoring of Sukhana lake catchment of Kansal, Ghareri and Nepli (from 1979 onwards) have also shown considerable reduction in sediment yield due to afforestation and other watershed measures. The hydrological data collected by the kalagarh project Authority before and after the commencement of soil observation works in the catchment (307644 ha) was recorded as 0.1795 ham/sq. km. (1958-62) and 0.1444 ha m/sq. km (1967-71) which means a reduction in silt load of 0.0351 ha/m/sq.km. of the catchment (Pathak, 1974). The reduction in silt load mostly appears to be due to afforestation as the cultivated area treated was comparatively very less till then. Recently, CWC, New Delhi also sponsored a project in collaboration with G.B. Pant University, Pant Nagar and I.I.T., Delhi to evaluate the effects of soil conservation measures on hydrology and sedimentation of the Ramaganga river. The data adequacy reports were yet to be completed and reviewed before making any conclusions.

5.2.8 Water quality

Water quality is as important and vital parameter of forest hydrology as because nearly 80% of the human diseases are attributable to drinking of polluted water and most of the population living in rural areas gets water from natural streams. The silt content in streamflow depends upon the vegetative cover conditions. Besides this, there are other quality parameters like common particulates, dissolved substances and gases which are significantly responsive to forest cover. Temperature directly affects the biological productivity of the stream and the temperature is very much influenced by forest due to changes in micro-climate. Dissolved solids are usually small from forested areas and primarily reflect the geology of the area. Nitrogen concentration may be an element to be watched in the flow from forested watersheds.

Very few studies have been done in India to see the effects of forest cover on water quality. In Doon valley, water quality studies have been taken up by ERS of FRI in relation to forest cover and the management. Parameters like colour, odour, temperature, electrical conductivity, sediment concentration pH. calcium, sodium, potassium, phosphate, iron, chloride, dissolved oxygen (Do) and biological oxygen demand (BOD) are being determined on monthly basis at eight sites located on 3 streams. Water quality of stream affected by mining is also being carried out. Study on some aspects of water quality has been initiated by CS&WCR&TI, Dehradun at Sahadra mine area in a watershed of 64 ha. The preliminary data analysis indicate that Ca, Mg, sulphate and suspended sediments are very high. Mine rehabilation through afforestation and mechanical measures is underway. There is an urgent need to study the influence of different forest covers and forest management practices on water quality of streams like clearfelling, forest fire, logging etc. Experimental watershed studies are required to be carried out in this direction.

5.2.9 Floods

It cannot be denied that forests considerably modify the water yield, peak runoff, sediment yield and regulate the stream flow. Admittedly flood occurs when there is excessive or intense rainfall over a short span of time associated with saturated watershed conditions (that the bulk of rainwater is not retained by the watershed). Under such conditions the presence of forest cover may not prevent large floods but retards erosion and debris flows to down stream reaches. The same view was expressed by the National Flood Commission (1980). It was found that the effect of forest in intercepting rainfall gets saturated and forest cover may not have any significant control on floods.

Examination of soil moisture data under forest and other vegetative cover did not corroborate with the belief that soil gets often saturated even under vegetation and thus become ineffective in holding the runoff and flood waters (Das and Singh, 1979). Similarly observations also indicated that intense storm seldom covers the entire catchment and thus saturate the same simultaneously. It has been observed, the increased load of silt carried by the rivers of the Indian subcontinent raises their beds inducing annual flood water to spread outward more rapidly. Chairman, High level committee of flood (cited from Das and Singh 1979) also indicated that the flood problem is not so much due to excessive discharge in the rivers as due to excessive sediment load in them. Afforestation measures basically retard the speed of runoff, minimise soil loss and consequently the sediment load in the rivers. Such measures cannot entirely prevent the floods but however medium and flash floods can be moderated and thus their frequency lowered. The effect of afforestation on large floods may be insignificant.

5.2.10 Effect of Deforestation on hydrological regime

There seems to have been a limited study done in India to evaluate the extent of damage caused by floods due to deforestation in a large scale in some representative basin on the basis of which any significant conclusion could be drawn. In most of the studies carried on experimental watersheds, the results are extrapolated for large basin which may not be true. While studying the effects of deforestation on the intensity and frequency of floods in Pathri, Ranipur and Ratmau torrents. Bhattacharya (1956) found that the planned and limited deforestation did not have any untoward consequence for pathri and Ranipur catchments. Some effect was found on the frequency (and not intensity) of floods in the Ratmau, indicating that floods were recurring at somewhat more frequent intervals consequent upon deforestation.

Studies on impact of deforestation on hydrological parameters were carried out in small forest drainage basins in Western Ghats (E.J. James, et al. 1987). In the study, three sets of drainage basins of about 2 Km^2 were monitored for 2 years. Each set considered of separate dense forest, partially exploited and fully exploited basins. Unit hydrographs were evolved for each of the drainage basins and compared. The lag time for dense forest was about 35% more than that of the partially exploited basin. Further the sediment yield from partially and fully exploited basins was much more than that of dense forest basin.

Change in landuse arising due to urbanisation and afforestation in the hills of Bhavani were studied (Shaklivadivel et al., 1981). With the urbanisation of rural watershed the surface runoff peak was found to increase by 107% and lag time decrease by 17%. On the other hand afforestation reduced the peak by 80% as also increased the lag time by 28%. Similar studies carried out in the hills of Maravian - Silasian Bakey Czechoslovakia have indicated greater runoff yield due to deforestation (Mirosiew K, 1978).

5.3 FOREST & VEGETATION COVER MAPPING USING SATELLITE IMAGERY

Remote sensing has been gaining ground since the late eighties and is no longer a novel technology especially for the survey and mapping of natural resources. In India its principal and most useful applications have been in the identification and mapping of vegetation and forest cover. Recently it has been shown that AVHRR (NOAA) data in the spectral bands of 0.5 to 0.7 micrometer and 0.7 to 1.3 micrometer is also suitable for detecting the presence of vegetation and some of its characteristics.

Kawasa (1988) carried out extensive studies in the forested catchments of Himalayas using satellite data (landsat) for his dissertation work. Table 12 shows the path - row combinations of the landsat scenes covering Himalayas. The methodology is described briefly as under.

Identification of vegetation and other associated parameters :-

There are numerous factors which are important in determining the reflectance of the vegetation canopy under natural conditions. Reflectance of vegetation is determined not only by the physical and anatomical characters of the single leaves (Reeves, 1975) but also by the amount, the arrangement and overall vegetation structure (Gill, 1982), the background characteristics and other innumerable factors. The reflectance from each individual component will also vary with sun angle, aximuth angle, and the time. Difference among species and the dynamic changes due to growth, development, stress and varying cultural practices also cause difference in the reflectance spectra of the crops.

Green vegetation is highly reflective in the near infra red and it appears as various shades of dark against the light background of other surface objects in spectral band 5. Through the use of optical colour composite combiners, it is possible to take advantage of the differences in the tone by combining them in false colour composites (FCC). In FCC, the vegetation shows up in patches of various shades of red against the various shades of green

Table 12 : List of Path-row Combinations of the Landsat MSS Scenes Covering the Himalayas.

S.No.	Path	Row	Centre Coordinates	Cloud cover	Date of Image acquisition	Scene Identification no.	Spectral band
1	145	040	N 28°49' & E 094°55'	-	21.12.73	8151603394500	5 & 7
2	145	041	N 27°22' & E 094°36'	-	15.11.73	8148003404500	5 & 7
3	146	040	N 28°46' & E 093°27'	-	15.03.77	8278303204500	5 & 7
4	146	041	N 27°23' & E 093°10'	-	16.11.73	8148103402400	5 & 7
5	147	041	N 27°23' & E 091°41'	-	5.12.73	8150003520500	5 & 7
6	147	042	N 26°16' & E 091°19'	30	21.5.73	8130203551500	5 & 7
7	148	040	N 28°25' & E 090°02'	20	30.9.72	8106903591500	5 & 7
8	148	041	N 27°23' & E 090°26'	-	3-.9.72	8106903594300	5 & 7
9	149	040	N 28°93' & E 083°13'	10	16.7.73	8135604051500	5 & 7
10	149	041	N 27°20' & E 088°57'	-	13.10.75	8226403525500	5 & 7
11	149	042	N 26°07' & E 087°31'	00	23.5.73	8130404064500	5 & 7
12	150	041	N 27°76' & E 087°66'	10	23.5.75	8212103594500	5 & 7
13	150	042	N 26°33' & E 087°28'	-	21.5.75	8212104000500	5 & 7
14	151	041	N 27°30' & E 086°01'	-	14.12.72	8114404174500	5 & 7
15	152	040	N 28°47' & E 085°02'	-	16.9.72	8105504221500	5 & 7
16	152	041	N 77°26' & E 081°41'	-	4.10.72	8107304224500	5 & 7
17	153	040	N 28°78' & E 083°59'	20	17.9.72	8105604260500	5 & 7
18	153	041	N 27°16' & E 083°06'	-	28.11.72	8112804291500	5 & 7
19	154	039	N 30°08' & E 087°28'	-	11.11.72	8111104340500	5 & 7
20	154	040	N 28°85' & E 081°93'	00	5.5.74	8165104281500	5 & 7
21	154	041	N 27°41' & E 081°53'	00	5.5.74	8165104283500	5 & 7
22	155	039	N 30°14' & E 081°09'	10	19.9.72	8105804390500	5 & 7
23	155	040	N 28°96' & E 080°53'	10	11.6.74	8168804324500	5 & 7
24	156	039	N 30°40' & E 079°51'	10	12.6.74	8168904380500	5 & 7
25	156	040	N 28°98' & E 079°10'	30	25.5.74	8167104390500	5 & 7
26	157	035	N 37°52' & E 079°53'	00	27.10.72	8109604492500	5 & 7
27	157	036	N 34°30' & E 079°32'	-	16.3.79	82151404274x0	5 & 7
28	157	036	N 34°26' & E 079°76'	10	27.10.72	8109604495500	5 & 7
29	157	037	N 33°03' & E 079°08'	-	21.4.79	82155004290x0	5 & 7
30	157	037	N 33°01' & E 079°00'	00	27.10.72	8109604501500	5 & 7
31	157	038	N 31°43' & E 078°37'	-	12.2.73	8120401510500	5 & 7
32	157	039	N 30°38' & E 078°08'	10	13.6.74	8169004434500	5 & 7
33	158	035	N 35°76' & E 078°43'	00	18.6.75	8214704433500	5 & 7
34	158	036	N 34°28' & E 078°11'	-	9.11.80	83098004303x0	5 & 7
35	158	036	N 34°33' & E 078°83'	20	13.5.75	8211104434500	5 & 7
36	158	037	N 33°05' & E 077°35'	-	22.10.80	83096204313x0	5 & 7
37	158	037	N 33°09' & E 077°69'	10	22.9.72	8106104552500	5 & 7
38	158	038	N 31°60' & E 077°21'	20	4.9.72	8104304555500	5 & 7
39	158	039	N 30°22' & E 076°85'	00	22.9.72	8106104561500	5 & 7
40	159	035	N 3593' & E 077°06'	10	7.6.79	83045904491x0	5 & 7
41	159	035	N 35°52' & E 077°00'	00	16.11.72	8111605011500	5 & 7
42	159	036	N 34°50' & E 076°63'	10	7.6.72	83035904494x0	5 & 7
43	159	036	N 34°27' & E 076°33'	00	16.11.72	8111605013500	5 & 7
44	159	037	N 33°08' & E 076°18'	10	16.6.79	82160604424x0	5 & 7
45	159	037	N 32°59' & E 076°09'	20	1.6.75	8213004495500	5 & 7
46	159	038	N 31°36' & E 075°42'	-	16.11.72	8111605022500	5 & 7
47	160	035	N 35°94' & E 075°53'	10	6.9.79	83055004541x0	5 & 7
48	160	035	N 36°15' & E 075°43'	10	16.5.73	8129705070500	5 & 7
49	160	036	N 34°51' & E 075°16'	10	30.5.79	82158904473x0	5 & 7
50	160	036	N 34°49' & E 075°21'	20	6.9.72	8104505063500	5 & 7
51	160	037	N 33°08' & E 074°71'	10	30.5.79	82158904480x0	5 & 7
52	160	037	N 33°15' & E 074°07'	10	9.7.73	8135105071500	5 & 7
53	161	034	N 37°36' & E 074°65'	30	19.9.80	83092904484x0	5 & 7
54	161	034	N 36°48' & E 074°52'	20	7.9.73	8140605105500	5 & 7
55	161	035	N 35°95' & E 074°22'	10	7.9.72	8104506115500	5 & 7
56	161	036	N 34°51' & E 073°75'	10	16.6.81	83119904563x0	5 & 7
57	161	036	N 34°51' & E 073°77'	30	7.9.72	8104605121500	5 & 7
58	161	037	N 33°00' & E 073°31'	00	18.6.79	82160874542x0	5 & 7
59	161	037	N 33°07' & E 073°34'	00	7.9.72	8104605124500	5 & 7
60	162	034	N 37°21' & E 073°15'	-	7.12.79	83064205031x0	5 & 7
61	162	034	N 37°36' & E 073°31'	00	26.9.72	8106505170500	5 & 7
62	162	035	N 35°52' & E 072°57'	-	8.11.81	83134405053x0	5 & 7
63	162	035	N 35°94' & E 072°85'	00	28.9.72	8106505173500	5 & 7

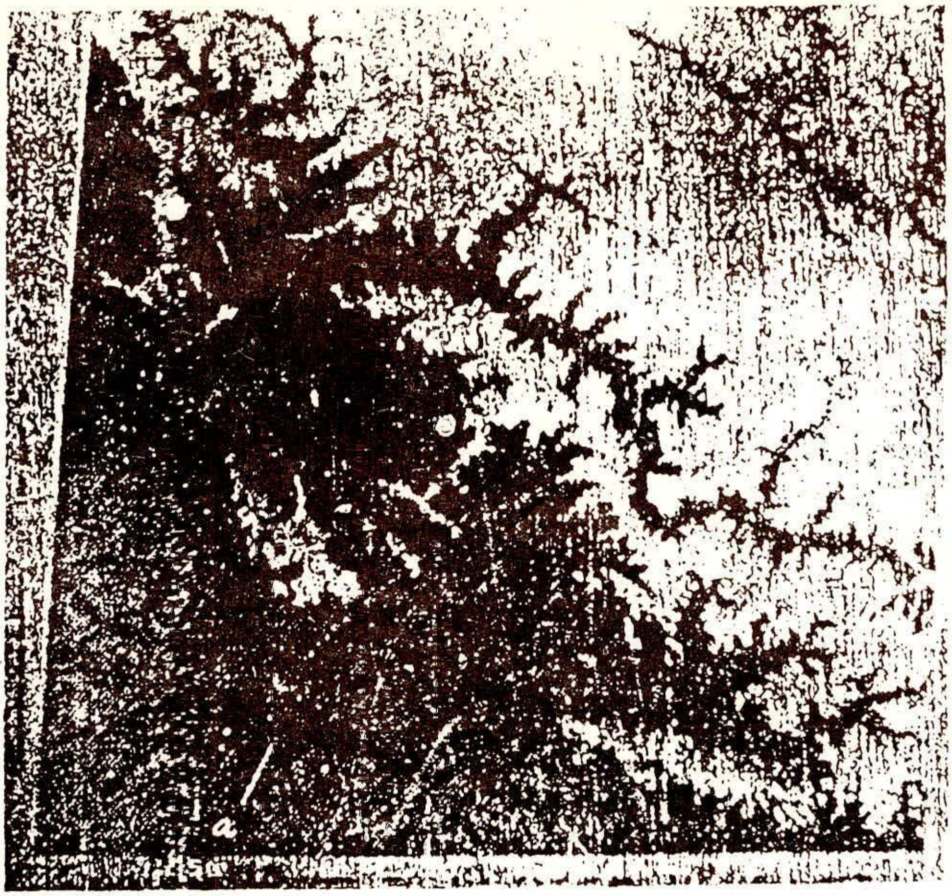


Plate 3 Landsat image of the Jammu region of Jammu and Kashmir Himalayas. The light grey shades in the image represent the non-vegetation areas.

background. These FCC are made by passing band 7 through a green filter and band 5 through a red filter on the spectral data viewer. The vegetation tones may be of different sizes, shapes and texture depending upon the extent and condition of the vegetation. When vegetation is homogeneous and occurring in large contiguous areas, it appears as a continuous structure with a single tone. The tone is based on manual interpretation and detailed identification. The details can be referred from Kawasa (1988).

5.4 PROBLEM IDENTIFICATION AND RESEARCH NEEDS IN FOREST HYDROLOGY

Research development in the area of Forest Hydrology is in its infancy in India. As already mentioned the influence of forests on their environment forms part of a complex relationship between environment and forest vegetation. The plant and animal communities which constitute the forest, form a very intimate, dependent and complex relationship with the non-living components of the environment such as geology, soils, climate etc. Forests even though has living components (plants and animals) have to replace the old and dying members with new young vigorously growing ones. This process is a continuous and gradual where nature follows its natural path but when man interferes with this process to achieve his set objectives the process varies from a slow/gradual to moderately fast to very sudden and severe changes in the ecosystem.

In the preceding sections the effect of forest on hydrological parameters and the status of research in India have been discussed in detail. Forest hydrology is mostly concerned with correct estimation of the hydrologic abstractions which have a major role to play in the hydrologic cycle. The hydrologic abstractions such as interception, evaporation, transpiration, infiltration etc., if properly understood in all its perspectives, an efficient rainfall runoff relationship can be evolved. The parameters effecting such processes have to be understood thoroughly. Today there is a general consensus that traditional formulae do not work well for forested lands. The need to develop comprehensive models is therefore to estimate the components of water budget of a forested catchment. Such predictions would go a long way in planning for efficient forest management and water resources projects. The problem areas, the parameters affecting, their data requirements and the processes involved are discussed through flow charts in figs. 5 - 11 (Mathur and Naithani, 1982).

5.5 DATA REQUIREMENTS AND DATA AVAILABILITY

The data requirements of forest hydrology include:

- i. Precipitation data
- ii. Climatic data
- iii. Discharge data
- iv. Silt and water quality data
- v. Forest cover data

These have also been discussed partly in section 5.4. The forest deptts. in India barring a few hardly maintain any hydrometeorological data observatories. The CWC and the state irrigation and flood control deptt. are collecting precipitation, discharge and silt data. The IMD and Agriculture deptts. collect and maintain data related to precipitation and climate. However in some of the states such as H.P., U.P. and Karnataka the forests deptt. are maintaining observatories in selected forested catchments and some of the above data is being collected.

CLIMATIC DATA NEEDED FOR RESEARCH IN FOREST HYDROLOGY

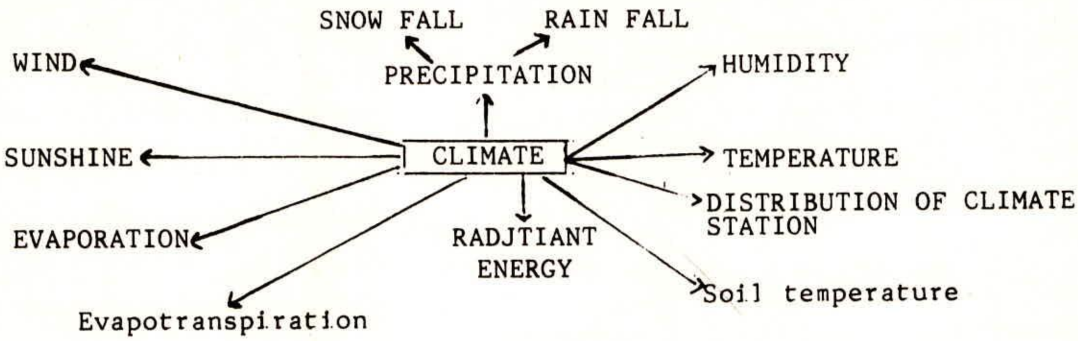


Fig. 5

SNOW AND RAINFALL MEASUREMENTS REQUIRED FOR RESEARCH IN FOREST HYDROLOGY

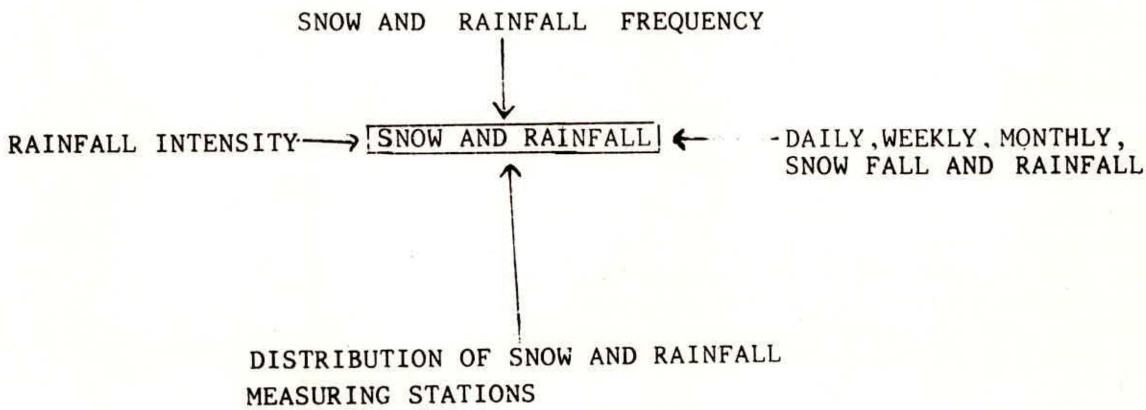


Fig. 6

INTERCEPTION PHENOMENA

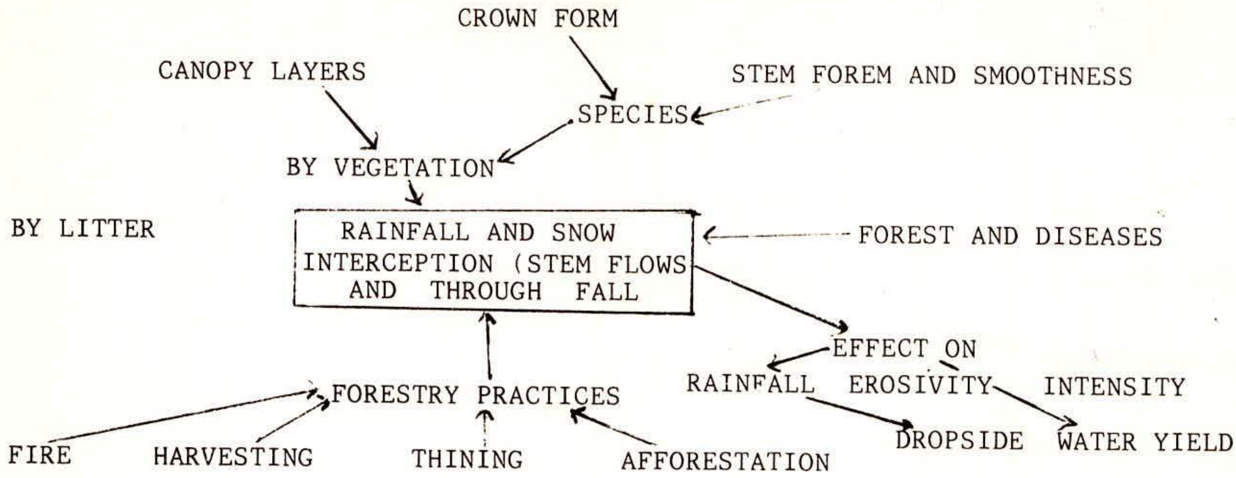
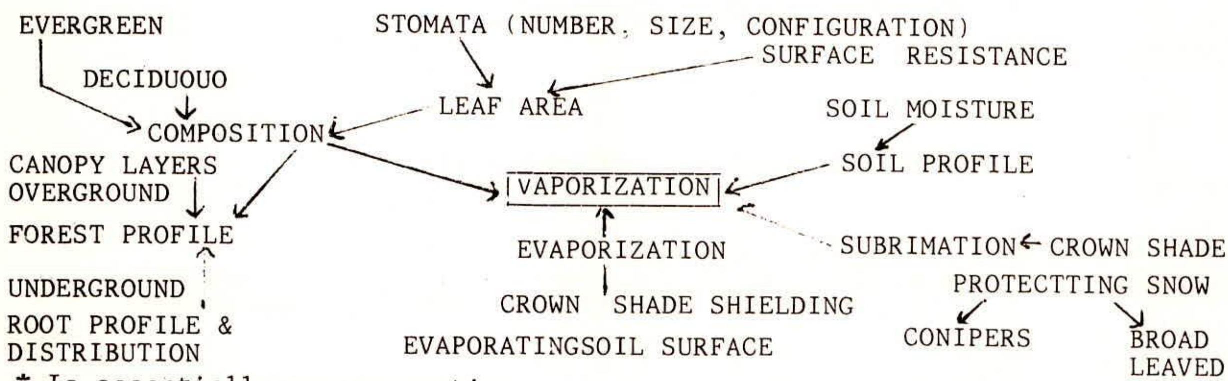


Fig. 7

VAPORIZATION PROCESSES AS INFLUENCED BY FOREST AND FORESTRY PRACTICES



* Is essentially an evaporation. procene and is controlled by thesame factors as evaporation but in this case the effective area for evaporation is much greater and surface resistance plays a much larger role Transpiration is a soil drying prooss

Fig 8

INFILTRATION AND GROUNDWATER RESEARCH NEEDS

IN FOREST HYDROLOGY

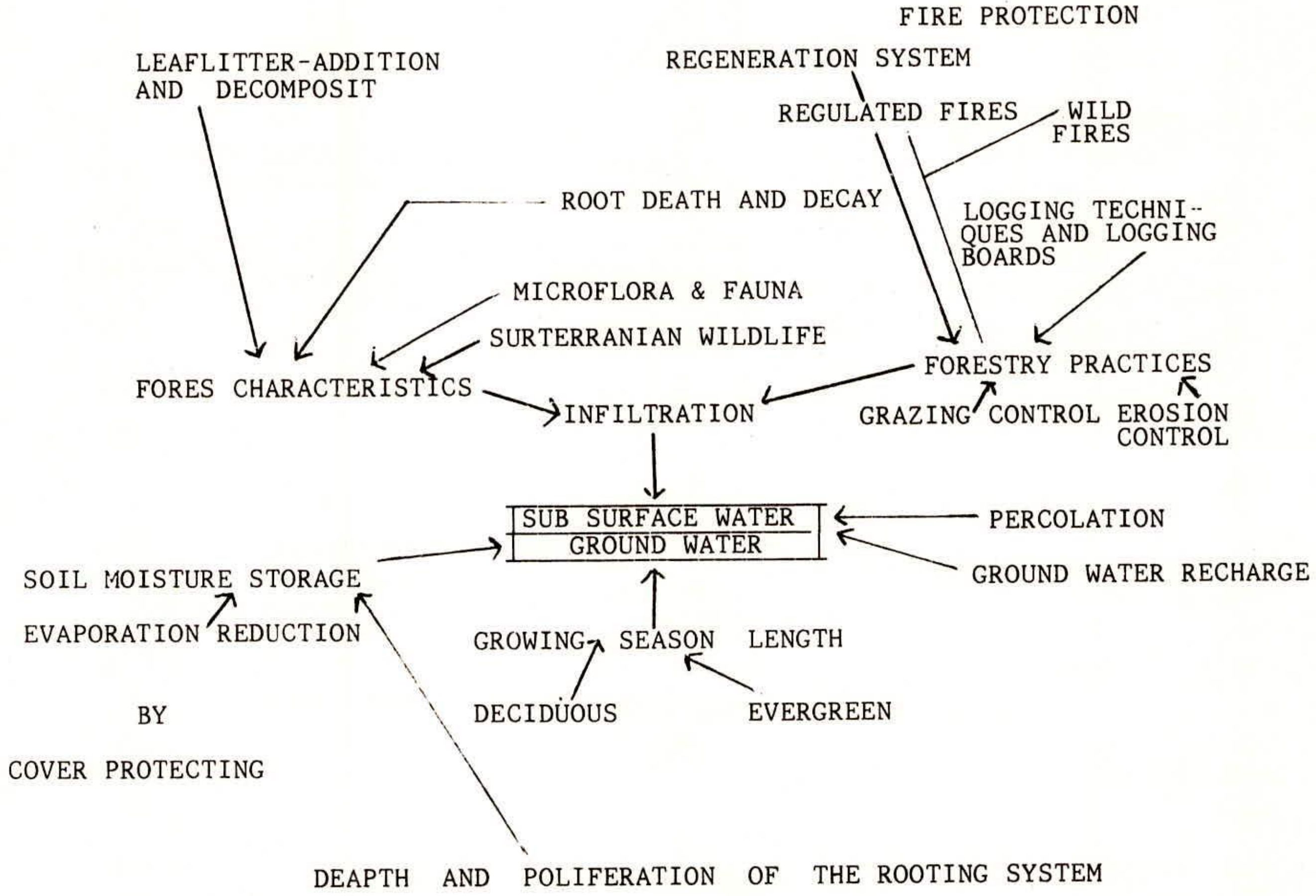


Fig. 9

EFFECTS OF FOREST CHARACTERISTICS AND PRACTICES ON WATER YIELDS/RUNOFF- NEED FOR QUANTIFICATION

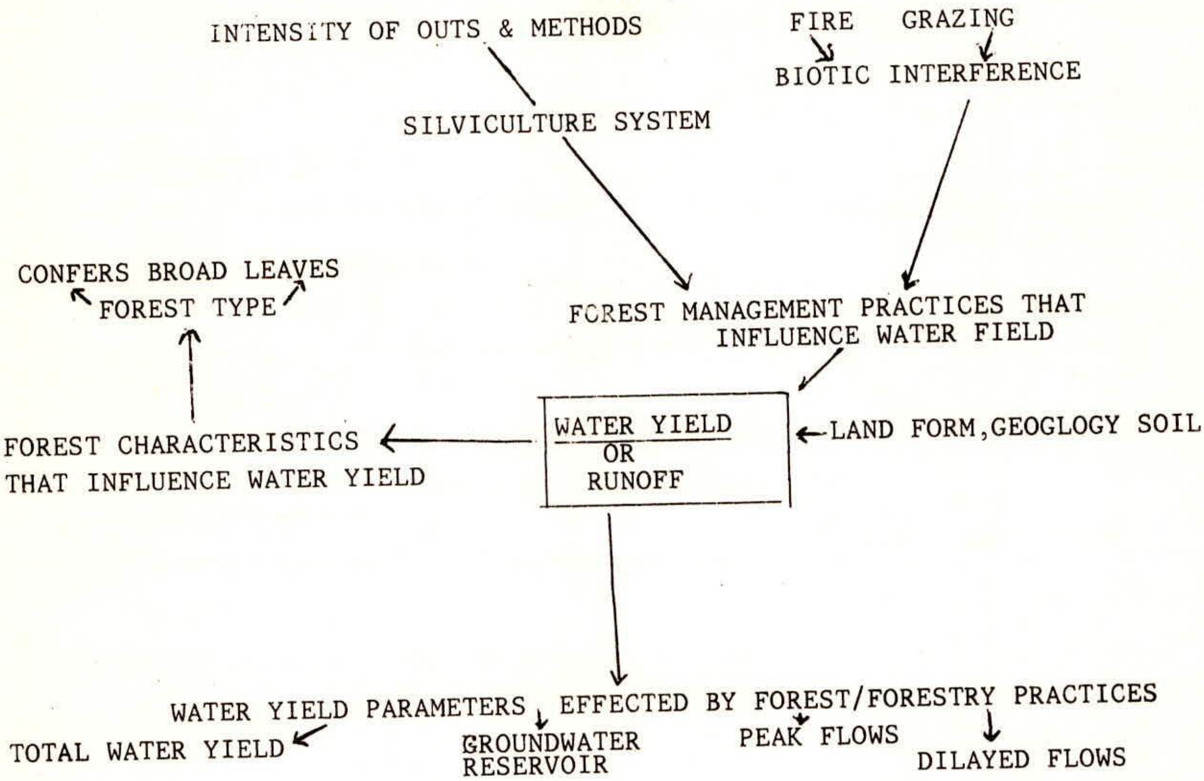
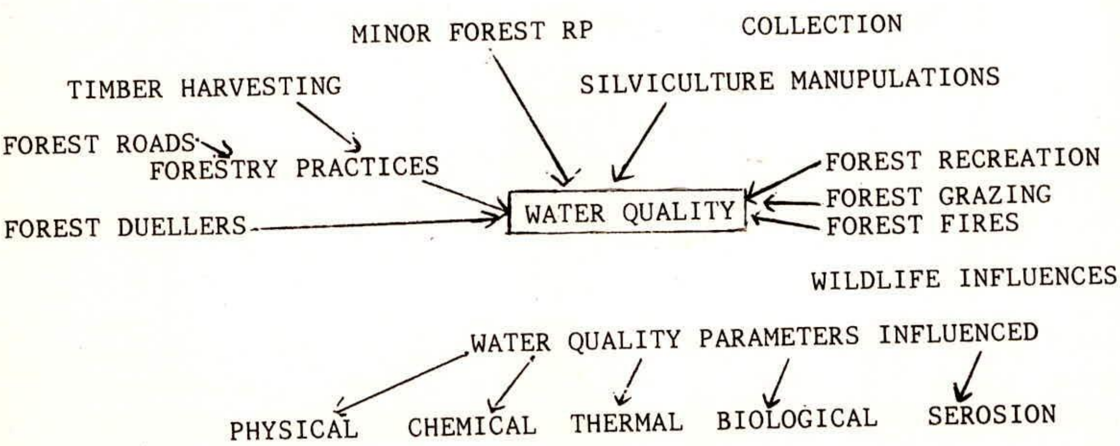


Fig 10

WATER QUALITY AS INFLUENCED BY FOREST AND FORESTRY PRACTICES



6.0 STATUS OF RESEARCH IN DEVELOPED COUNTRIES

6.1 GENERAL

The water balance is a central tool in any hydrological, climatological or meteorological study involving forest vegetation. Prediction of forest water balance has always been subject to the conflict between data availability and the desire to approach physical reality. Forest hydrology involving large number of parameters has of recent times been resorted to mathematical modelling and simulation in developed countries. Continuous monitoring of soil water pressure, rainfall and runoff under natural conditions to establish soil hydrologic characteristics are gaining ground. Remote sensing data from satellites are providing much useful information for hydrological modelling. The various hydrological processes interacting with forests such as interception, evapotranspiration, infiltration soil erosion, ground water etc. if properly understood with respect to water cycle, would enable a forest hydrologist in effective forest management.

Today there is a general consesus that traditional formulae do not work well in forested catchments. It is therefore felt the need to develop comprehensive models to estimate the components of water budget of a forested catchment.

A model is based on the fundamental principle that all its structural parameters must be possible to physically identify that can be measured independent of the final result and that it should properly represent only the fundamental physics of the system.

In water shed hydrology a number of mathematical and simulation models have been developed to suit the requirements. Several types of models have been developed. These include lumped, distributed, deterministic, stochastic and hybrid models. Of late physically based distributed models are gaining ground.

Physically based distributed models can in principle be applied to almost any kind of hydrological problems. Obviously there are many problems for which necessary solutions can be obtained using cheaper and less sophisticated empirical, lumped conceptual or statistical models. But, for the more complicated problems use of physically distributed models acquires great importance.

Physically based distributed models are based on our understanding of the physics of the hydrological process which control catchment response and use physically based equations to describe these processes. From their physical basis such models can simulate the complete runoff regime providing multiple outputs, e.g., river discharge phreatic surface level and evaporation loss. Physically based models are spatially distributed since the equation from which they are formed generally involve one or more space co-ordinates. They can therefore simulate the spatial variation in hydrological conditions within a catchment as well as simple outflows and bulk storage volumes. But these models require large computers, computational time and extensive data and are expensive to develop and operate. Unlike lumped conceptual models, physically based distributed models do not consider the transfer of water in a catchment to take place between a few defined storages. Instead the transfers of mass momentum and energy are calculated directly from the governing partial differential equations for example the St. Venant equations for surface flow, the Richards equation for unsaturated zone flow and Boussinesq equation for ground water flow.

A few important models developed and widely used in forest hydrology include Rutters (1971) evapotranspiration model, Gash (1979) analytical model, SHE model, USDAHL model, SSARR model, Leavesley model, TVA model, USGS model etc. Some of these watershed models are discussed in details to illustrate their application to forested catchment.

6.2 SHE MODEL

The system hydrologic European (European hydrological system, SHE) is an advanced physically based, distributed catchment modelling system. It has been developed jointly by the Danish Hydraulic Institute, British Institute of Hydrology and Sogreah, France.

6.2.1 Salient features

The SHE was developed from the perception that conventional rainfall/runoff models are inappropriate to many hydrological problems, especially those related to the impact of man's activities of land use change and water quality. These problems can be solved only through the use of models which have a physical basis and allow for spatial variation with in a catchment. The SHE is a physically based model in the sense that the hydrological process of water movement and modelled either by finite difference representation of the partial differential equations of mass, momentum and energy conservation, or by empirical equations derived from independent experimental research. Spatial distribution of catchment parameters, rainfall input and hydrological response is achieved in the horizontal by an orthogonal grid network and in the vertical by a column of horizontal layers at each grid square. River channels are superimposed on the grid element boundaries. Parameters must be evaluated as appropriate for each grid element, river link and subsurface layer. Basic processes of the land phase of the hydrological cycle are modelled in separate components viz. interception by the Rutter accounting procedure; evapotranspiration, b y the Penman and Jensen (1975); over land and channel flow by simplifications of St. Venant equations; unsaturated zone flow by the two dimensional Boussinesq equation and snowmelt, by an energy budget method.

The SHE has a modular structure in order to incorporate improvements of additional components such as irrigation return flow, sediment yield and water quality etc., in future. Considerable operating flexibility is available through the ability to vary the level of sophistication of the calculation mode to make use of as many or as few data as are available and also to incorporate data related to topography, vegetation and soil properties which are not usually incorporated in catchment models. The SHE does not require long term hydrometeorological data for its calibration and its distributed nature enables spatial variability in inputs and outputs to be simulated.

However, the operation methodologies must be evolved. Thus significant uncertainties in the values of the catchment parameters used in simulation. These uncertainties give rise to corresponding uncertainties in the prediction. However, the SHE is able to quantify these uncertainties by carrying out sensitivity analysis for realistic range of the parameter values, even when there is a lack of data. Therefore the SHE can act as a valuable decision support system (Abbott et al. 1986).

The SHE is designed as a practical system for application in a wide range of hydrological resource conditions. Its physical and spatially distributed basis gives it advantage over simpler regression and lumped models in simulating land use change impact, ungauged basins, spatial variability in catchment inputs and outputs, groundwater and soil moisture conditions, and water flows groundwater and soil moisture conditions, and water flows controlling the movements of pollutants and sediment.

The SHE is physically based distributed modelling system as each of the primary components of the land phase of hydrological process constituting the hydrological cycle, namely overland flow, unsaturated and saturated sub surface flow, evapotranspiration, snowmelt and canopy interception is modelled either by finite difference representations of the theoretical partial differential equation of mass, momentum and energy conservation or by empirical equations derived from independent experimental research. Spatial distribution of basin parameters, rainfall and hydrological response are obtained in the horizontal through the representation of the basin by an orthogonal grid network and in the vertical by a column of horizontal layers at each grid square. The river channels are superimposed along the boundaries of the grids. The schematic diagram of a catchment and a quasi three dimensional physically based distributed SHE model is shown in fig.12.

For simulation of the interception and evapotranspiration processes,SHE offers two models, in the first model the interception processes are modelled by a modified version of Rutter model, and the evapotranspiration is modelled by the penman-Monteith model. In the second model, a model developed by Kristensen and Jensen (1975) is used.

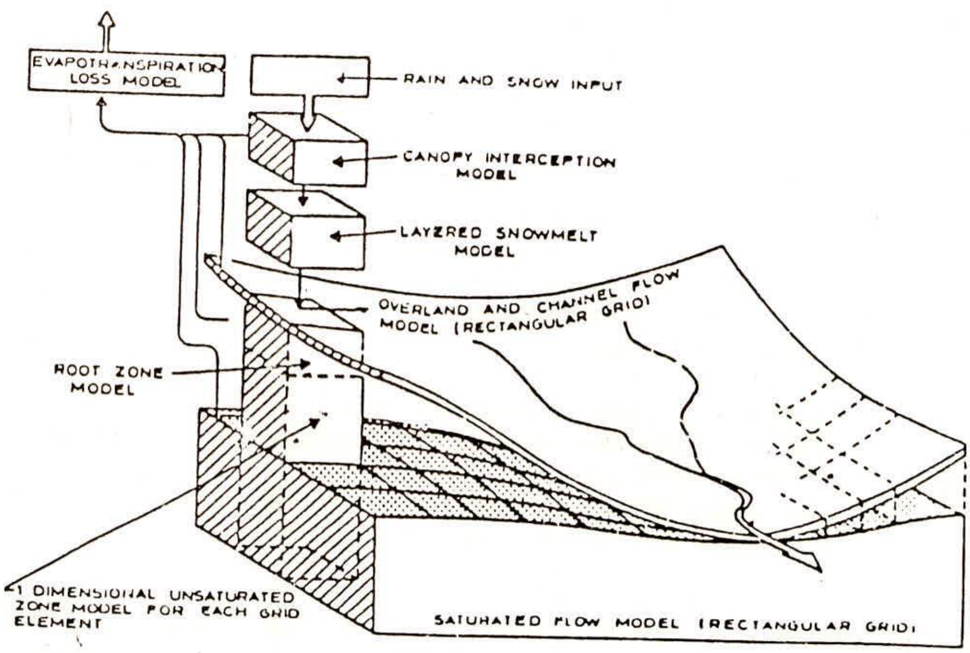


Fig.-12 Structure of the European Hydrologic System.

Interception

Meteorological and vegetative input data are used to simulate the total evapotranspiration and net rainfall amounts from the processes of :

1. Rainfall interception by vegetation canopy
2. Drainage from the canopy
3. Evaporation from the canopy surface
4. Evaporation from the soil surface
5. Uptake of water by plant roots and its transpiration

Net rainfall, transpiration and soil evaporation rates are supplied to the unsaturated zone component, which in turn gives information on soil moisture conditions in the root zone. It is assumed that the temperature is above zero degree centigrade and that there is no snowpack. Otherwise the process is modelled by the snowmelt component. As interception has significant effect on evapotranspiration the two processes are modelled within the one overall component.

The interception model calculates net rainfall reaching the ground through vegetation canopy, the amount of water stored on the canopy and evaporation from canopy. Interception modelled by modified Rutter model developed by Rutter et al. (1975), is an accounting procedure for the amount of water stored on the canopy. The canopy is considered to have a surface storage of capacity which is filled by rainfall and emptied by evaporation and drainage. This capacity may be regarded as the minimum depth of water required to wet all canopy surfaces. When the depth of water C on the canopy equals or exceeds S the evaporation from the canopy is assumed to occur at the potential rate, Ep. The rate of change of storage is when calculated as :-

$$\frac{\delta C}{\delta t} = Q - K e^{b\,(C-S)} \qquad (1)$$

where,

$Q = p1\ p2\ (P - Ep\ \frac{C}{S})$ when $C < S$

Q = $P1\ P2\ (P - Ep)$ when $C > S$

C = depth of water on the canopy

S = canopy storage capacity

P = rainfall rate

P1 = proportion of ground in plan view hidden by vegetation

P2 = ratio of total leaf area to area of ground covered by vegetation and

P1 P2 = P1 P2 when P2 < 1,

P1 P2 = P1 when P2 > , = 1 since P1 P2 cannot exceed P1, Ep = potential evaporation rate K & b drainage parameter and

t = time

This model is expected to work in a very satisfactory manner under conditions of a completely wetted canopy (C > or = S). However by introducing the ratio C/S the various terms can be modified so that the response from dry, though partially wetted, to fully wetted canopy is continuous. Equation 1 is solved by analytical integration.

Generally the canopy storage C and the model parameters S,k,b,P1 and P2 cannot be measured directly in the field but are estimated indirectly from measurement of rainfall, net rainfall below the canopy and evapotranspiration. Variation in vegetation in vegetative cover with time on account of seasonal growth or landuse changes can be incorporated by varying S,P1 and P2 with time.

The model discussed above was developed for trees, yet the model is used in the SHE for different types of vegetations. Since the physical principles remain the same. Further, interception is modelled for only one vegetation in each grid square. The effect of secondary vegetation is neglected. For example, if an area is characterised by trees, the grass below tree cover is ignored.

Evapotranspiration

The evapotranspiration model calculates actual evapotranspiration and translates it into a loss term, describing uptake of water by plant roots and its transpiration in response which is continuous as vegetation canopy varies from dry to partially wetted and fully wetted state. The loss term is then used in the calculation of soil moisture changes by the unsaturated zone component. Potential and actual evapotranspiration are calculated. When the supply of water to the plant or soil system with dry canopy is unlimited there occurs the potential evapotranspiration. On the other hand actual evapotranspiration should have the potential rate as an upper limit and otherwise be reduced by restriction in the supply of water from the soil to the plant roots or by stomatal resistance within the plants. Actual evapotranspiration in the SHE is calculated by using Penman-Monteith equation.

$$Ea = \frac{Rn\,\Delta + (\delta C_p\,\delta e) / \gamma a}{\Delta + (1 + \frac{\gamma c}{\gamma a})} \qquad ....(2)$$

where,

Ea	=	actual evapotranspiration
Δ	=	Rate of increase with temperature of the saturation vapour pressure of water at air temperature
Rn	=	Net radiation
δ	=	density of air
Cp	=	Specific heat of air at constant pressure
δe	=	vapour pressure deficit of air
γa	=	aerodynamic resistance to water vapour transport
γ	=	psychrometric constant
γc	=	canopy resistance of water transport

The parameter gc represents average stomatal resistance in dry conditions and is zero for a wet canopy since evaporation of intercepted water is already occurring at the potential rate. Due to difficulties in determining all the parameters in equation (2) particularly γc three modes of operation are specified for the calculations:

a. is constant for each type of vegetation.
b. varies as function of soil moisture tension as well vegetation type.
c. is zero.

Thus equation (2) then gives Ep the potential evapotranspiration rate. The ratio Ea/Ep is then used to calculate actual evapotranspiration rate Ea as a linear function of soil moisture tension (Feddes et al, 1976).

Total actual evapotranspiration calculated for each grid square is dependent on the extent of wetness of canopy and on degree of ground coverage by the canopy.

Et = P1 P2 Ep C/S + P1 P2 Eat (1/C/S) + (1-P1 P2)xEas ...(3)

where,

Et	=	total evapotranspiration
Ep	=	potential evapotranspiration
Eat	=	Total evapotranspiration from uptake through the roots.
Eas	=	evaporation for bare soil

Extraction of moisture for transpiration from the root zone is distributed according to the vertical distribution of root mass in the root zone. Soil evaporation moisture is obtained from the top of the soil column.

Interception (Option 2)

The second option offered in the SHE has been developed at the Royal Veterinary and Agriculture University in Denmark (Kristensen, Jense, 1975). In this option the actual evapotranspiration is calculated on the basis of potential rates which are required as input data and the actual soil equations is based on comparisons with actual measurements. The interception processes modelled by introducing the interception storage which has to be filled before through flow to the ground surface take place. The interception storage is diminished by direct evaporation. The size of the interception storage capacity, Imax, depends on the vegetation type and its stage is the ratio of the total area of leaves to the total ground are covered by the tree or vegetation.

$$I_{max} = C_{int} \ LAI$$

where,

C_{int}	=	interception parameter (mm)
LAI	=	Leaf area index

The parameter C_{int} is independent of vegetation type, but depends on the time resolution. On the basis of interception storage capacities given in the literature for different vegetation types a typical value of C is 0.05 mm. The leaf area index varies from 0 to 7.

Evapotranspiration

The transpiration from the vegetation, Eat depends on the density of the green crop material, described by the leaf area index and the actual soil moisture content in the nodes in the root zone. It also depends on the root density.

Eat = f1 (LAI) f2 (u) RDF Ep ...(4)

where,

Eat	=	transpiration
RDF	=	root distribution function
fs(LAI)	=	is a function of leaf area index and parameters C1 and C2
Ep	=	potential evapotranspiration
f2 (θ)	=	is a function of soil moisture for constant C3 and varying Ep

$$f(\theta) = 1 - \frac{\theta f - \theta}{\theta f - \theta w} \times \frac{C3}{Ep}$$

where,

θ	=	volumetric moisture content
θf	=	volumetric moisture content at field capacity
9w	=	volumetric moisture content at wilting point
C3	=	empirical parameter (mm/day)

Equation (4) is applied to all the nodes in the root zone. It is seen that the equation (4) includes the root distribution function RDF, which is calculated in the model assuming a logarithmic variation with the depth in accordance with the usual distribution of the root mass. It is seen that the evapotranspiration routine contains three empirical parameters, C1 C2 and C3. This approach is discussed in detail by Kristensen and Jensen (1975).

6.3 Stanford Watershed Model IV

Probably the most famous of ESMA (Explicit soil moisture accounting) models is the Stanford Watershed Model - IV (SWM IV) developed by Crawford and Linsley to simulate portions (the land phase) of the hydrologic cycle for an entire watershed outlet. A lumped parameter approach has been adopted due to which data needed is much less in comparison to distributed - parameter models. The flow chart of the model is given is fig. 13 and the complete details of the model structure are given in the subsequent paragraphs.

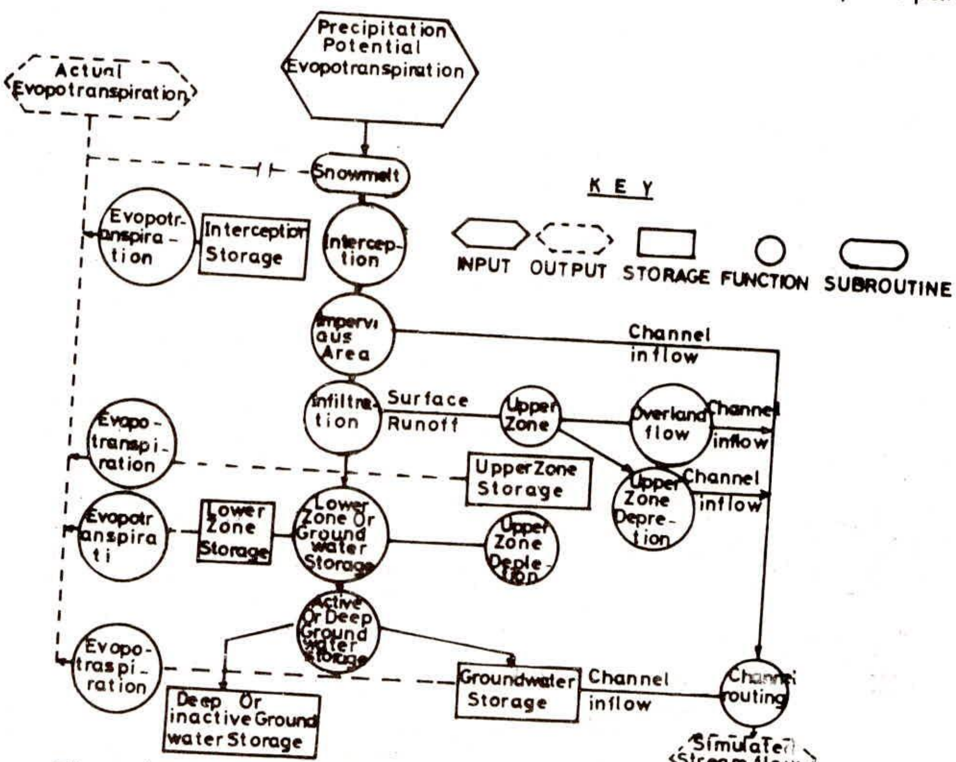


Fig.-13 Typical flow chart for a rainfall-runoff model of the explicit soil moisture accounting type, ESMA (After Crawford N.H. and R.K.Linsley. Jr.)

The model is based on the fundamental principle of hydrology to transform the input data to a runoff hydrograph at the watershed outlet. The soil moisture storage has been modelled with three reservoirs, namely the upper zone and deep groundwater storage. The rapid runoff response encountered in case of small watersheds is accounted or in the upper zone. While both upper and lower zones control the overland flow, infiltration and groundwater storage, the lower zone is responsible for long term infiltration and ground storage, which later is released as the base flow to the streams. The total runoff is the sum total of the overland flow, groundwater flow and interflow.

Model Structure

Interception in any time interval is governed by watershed cover and by current volume in interception storage. All incoming moisture enters interception storage until a preassigned volume is filled. This however depends upon the types of cover such as grasslands, moderate forest cover or heavy forest cover. Evaporation from interception storage is assumed to occur at a rate that corresponds to the current rate of potential evapotranspiration. Therefore interception will continue during a storm due to evaporation losses. The flow chart of the model for interception component is indicated in fig.13.

In the model evapotranspiration is considered to take place from:

1. interception storage
2. upper zone storage
3. Lower zone storage
4. Streams and lake surfaces
5. Ground water storage.

Evapotranspiration from interception and upper zone storage is considered to take place at potential rate, Ep, which is assumed to be the lake evaporation rate calculated as the product of a pan co-efficient times the input values of the evaporation data. The evaporation of any intercepted water is assumed to occur at a rate equal to the potential evapotranspiration rate and ceases when the interception storage is depleted.

Evaporation from stream and lake surfaces also occurs at the potential rate. The total volume is governed by the total surface area of streams and lakes (ETL).

The upper zone simulates storage in depressions and highly permeable surface soil while the lower zone is linkage to ground water storage. If interception storage is depleted the model will attempt to satisfy the potential for ET by drawing moisture from the upper zone storage at the potential rate. Once the upper zone storage is depleted, ET occurs from the lower zone a but not at the potential rate; the ET rate from the lower zone is always less than Ep. Evaporation opportunity is considered to control evapotranspiration from the lower zone. Evapotranspiration opportunity is defined as a maximum amount of water available for evapotranspiration at a particular location during a prescribed time interval.

The rate of evapotranspiration from the lower zone is determined from the shaded area as indicated in fig. 14.

$$E = Ep - \frac{Ep^2}{2r}$$

The variable r is the evaporation opportunity. This factor varies from point to point over any water shed zero to a max value of:-

$$r = k3 - \frac{lzs}{lzsn}$$

where,

lzs	=	The current soil moisture storage in the lower zone
lzsn	=	A nominal storage level, normally set equal to the medium value zone storage
k3	=	An input parameter that is a function of watershed cover.

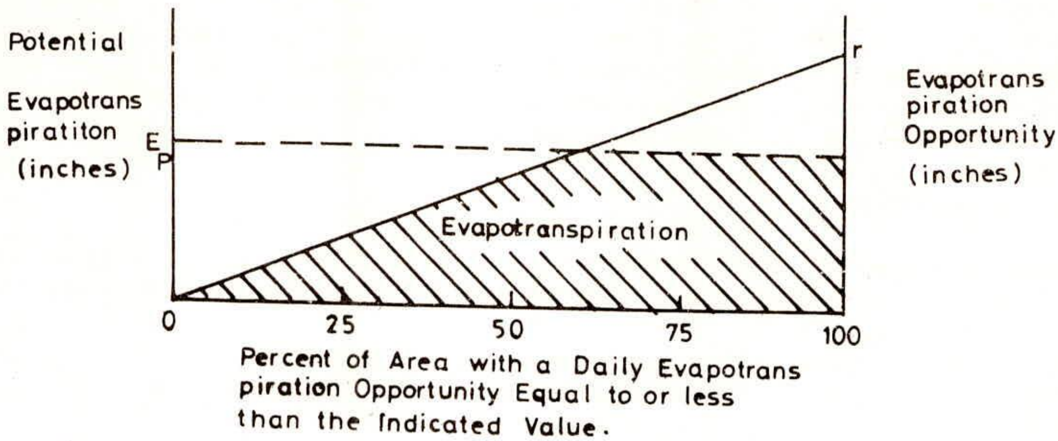


Fig.-14 ASSUMED LINEAR AREAL VARIATION OF POTENTIAL EVAPOTRANSPIRATION (SWM-IV Model)

The **ratio** (lzs/lzsn) is known as the lower zone soil moisture and is used to compare the actual lower zone storage with the nominal value at any time.

The model comprises of subroutines to carry out the computations of different phases of hydrologic cycle. Actual computations proceed from one circle process to another circled process as shown in fig.13. The continuity equation used during any time period is as follows:-

$$P = E + SRO + S$$

where,

P	=	Precipitation (cm)
E	=	Evapotranspiration (cm)]
SRO	=	Runoff
S	=	Change in storage in all three zones of soil.

The change in storage is calculated as the difference between the volumes of inflow and outflow. Further more all hydrologic activities are simulated in the time interval and balanced before proceeding to the next time interval to repeat the computations. The program terminated when no additional data is there for input.

6.4 USDAHL - 74 REVISED MODEL

The **USDAHL-74** is the revised version of the earlier model developed in 1970 by the US department of agriculture. This mathematical model is deterministic where in the input precipitation to the model consists of a continuous record of rainfall or snowfall weighted to represent the watershed. Variation in areal distribution must be accepted as error or it must be reduced by dividing the watershed into small areas and applying the model to rainfall measurements on each small area independently. Rainfall amounts can be determined for regular periods of time or they can be tabulated at break points in the mass curve in either case all periods of time must be accounted in the model.

The model estimates a number of parameters in the hydrological cycle such as evapotranspiration, infiltration hydrogeology, routing etc. in order to establish rainfall runoff relationship using several subroutines. The program is composed of 14 subroutines in addition to the main. However the discussions in the report are confined to evapotranspiration and infiltration pertinent to forest hydrology. The input parameters to model include watershed identity, periods of rainfall and snowfall records, soil zones, cropping pattern, land use and routing coefficients.

Evapotranspiration

Evapotranspiration (ET) potentials are estimated by coefficients applied to published pan evaporation data. The method is a combinations of techniques developed by Mustonen and Mc Guness (1968), Henson and Pruitt (1966). It is adopted for use with cardinal temperatures for crops which is easily available from any literature on crops for estimating plant growth. Fig.15 is a plotting of potential growth index (XGI), which is the cardinal temp. functions for Alfalfa and corn. This index is:-

(current temp. - low cardinal temp.)/(upper cardinal temp. - lower cardinal temp.). Cardinal temps are the upper or optimum and lower or minimum temp. for crop growth. When the current temp. exceeds the upper cardinal limit, the plant is assumed to suffer and XGI function is set less than 1.0 by a function of the amount of exceedance. If the current temp. is equal to or less than the lower cardinal limit, the XGI is set equal to a fixed minimum.

The growth index (GI) for a given crop is then computed from XGI graph for that crop as illustrated in fig.16 for alfalfa and corn. The GI follows the XGI if no cultural practices intervene. However, since the cultural practices that reduce the foliage also reduce the evapotranspiration, the GI for the crop is reduced following ploughing, planting, cultivating or harvesting if vegetation is abolished or reduced by such operations. After each practice the crop is assumed to recover in a specified number of weeks at which time the GI value is set at 1.0 and assumed to settle back to a bare fallow condition of low ET in 2 weeks where it remains a constant at 0.1 untill planting of a crop.

The evapotranspiration potential is computed from the following relation :

$$ET = GI \cdot K \cdot Ep\ (\ (S - SA)/AWC)^{x}$$

where,

ET	=	Evapotranspiration potential in inches per day
GI	=	Growth index of crop in percent maturity
K	=	ratio of GI to pan evaporation usually 1.0-1.2 for short grasses 1.2-1.6

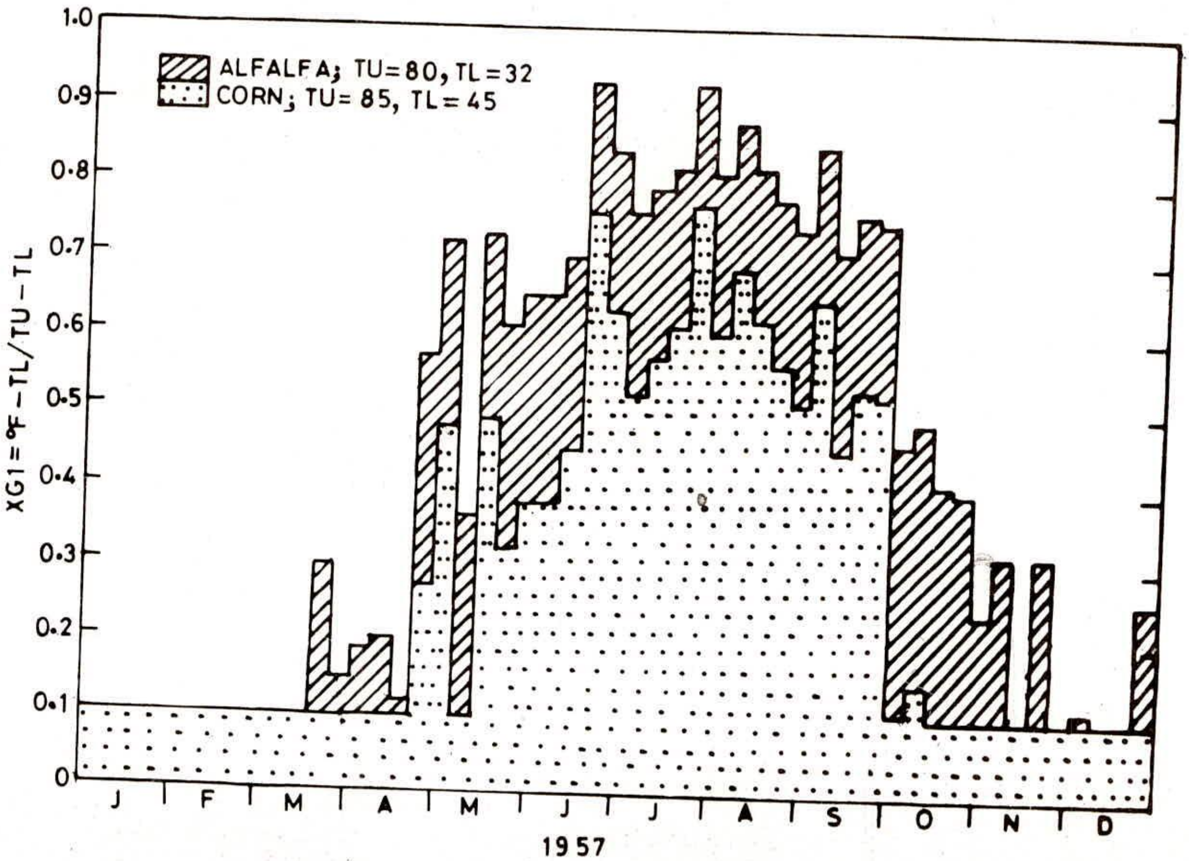


Fig.-15 Relative Potential growth (XG) graphs for alfalfa and corn computed from upper and lower cardinal temperatures (TU and TL)

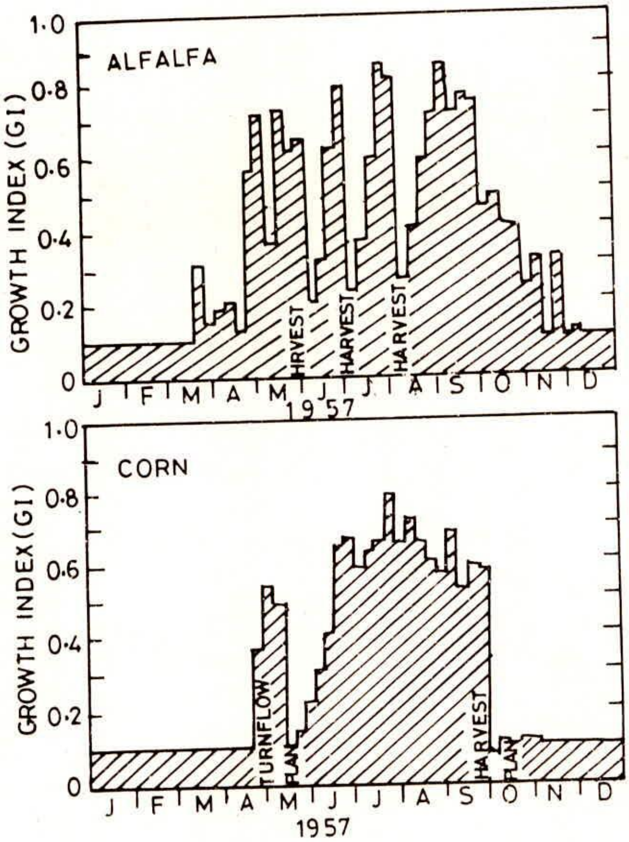


Fig.-16 Relative growth (Gl) graphi: Above, for alfalfa as modified by cutting; below, for corn as modified by tillage.

for crops upto shoulder height and 1.6-2.0 for forests.

Ep = Pan evaporation in inches per day
S = Total porosity
SA = Available porosity
AWC = Porosity drainable by evapotranspiration
x = set equal to AWC/G (G= Gravity of free water)

Input to the model includes 52 weekly averages of air temp. in place of air temp. in place of the cumbersome GI graphs required for each crop in USDAHL 70 model. Here the use of temp. is designed to individualize plant growth estimates for each year.

Infiltration

The model utilizes the infiltration capacity expressed by Holten (1961) as:

$$f = a\,Sa^{1.4} + fc$$

where,

f = infiltration capacity in inches per hour
a = infiltration capacity in inches per hour per inch of available storage
Sa = Available storage in surface layer
fc = constant rate of infiltration after prolonged wetting in inches per hour

Gardener (1962) found that water entering the soil under +ve heads through larger pores spreads to the smaller pores, and estimated this slow capillary movement as a constant (fc). The other term ($a\,Sa^{1.4}$) is an empirically derived expression of flow rates due to positive heads. It represents the sum of products of velocities and cross sections in flow tubes.

The infiltration process is quite complicated and varies both in space & time. It also varies with rain fall and intensity. The subroutines (flowcharts) dealing with evapotranspiration, evaporation, infiltration are shown in fig 17-19.

6.5 LEAVESLEY MODEL

Leavesley (1973) developed a mountain watershed model at Colorado State University for the prediction of water yield from forested watersheds of Rocky mountain region. Snowpack accumulation and melt runoff process have been the areas of major consideration in model formulation. Climatic physiography and vegetation factors affect these processes, and regional variation of these processes.

Model Structure

The model is a deterministic physical process hydrological model and uses daily climatic variables of temperatures, precipitation and solar radiation. A watershed needs to be subdivided into sub-units on the basis of measurable climatic physiographic, vegetative and soil features. Slope, aspect, vegetation type, soil type and snow distribution are the five primary features used in the sub-division process. The resulting subunits within the watershed are each considered homogeneous with respect to its hydrologic response, and thus termed as hydrologic response units or HRU's for short. A daily water balance is considered for each HRU and sum of response of all HRU's weighted on a contributing area basis, produce the overall response or water yield of the entire watershed.

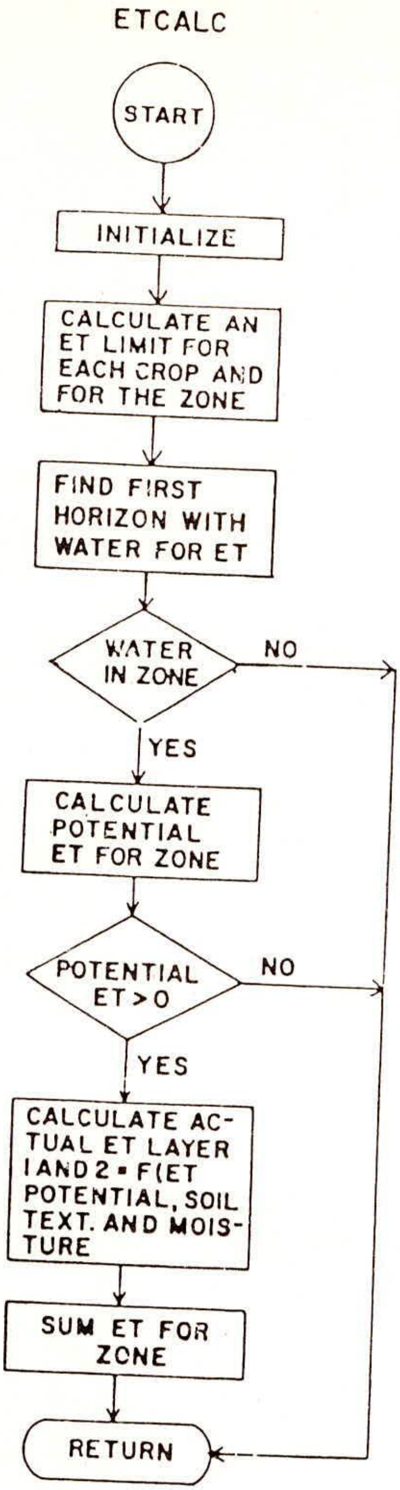


Fig.-17 Flow chart of USDA AHL-74 evapotranspiration.

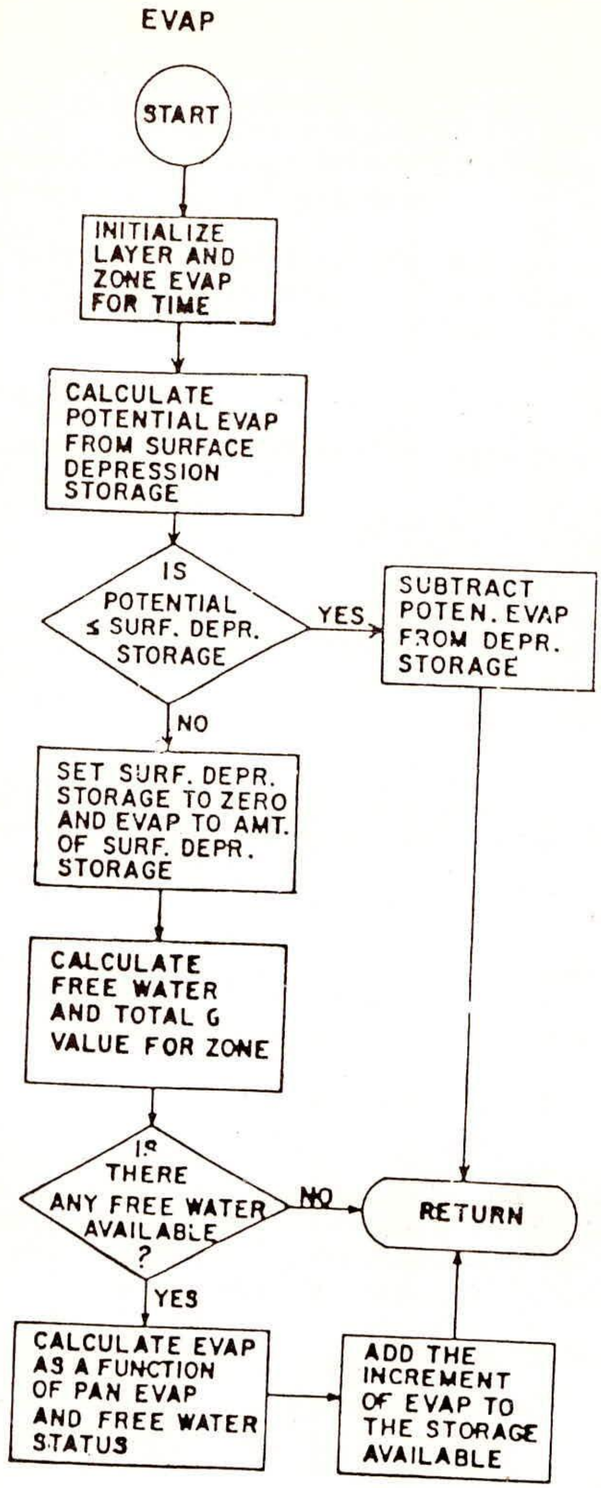


Fig.-18 Flow chart of USDAHL-74 evaporation.

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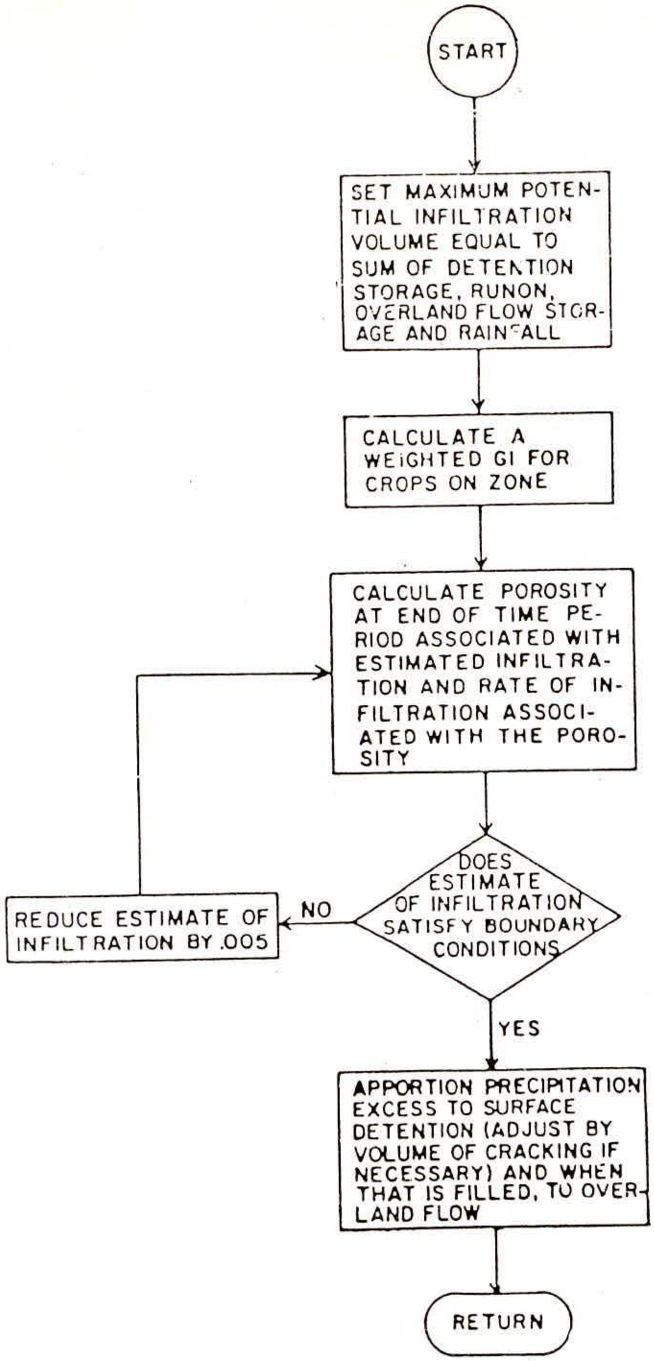


Fig.-19 Flow chart of USDAHL-74 infiltration.

The watershed system developed in this model can be visualized as a series of linear and nonlinear reservoir whose outputs combine to produce total system response in terms of mean daily stream flow. The upper soil zone reservoirs are linear ones. Each HRU has its own upper soil zone reservoir, however, the surface and ground water reservoir may be associated with one or several HRU's. The flow chart of the model operation is shown in fig.20.

Interception is computed using vegetation type, canopy density with precipitation type and form. For infiltration and surface runoff, contributing area concept is used to calculate the volume of surface runoff from rainfall events which occur on snow free HRUs. For snowmelt events, the assumption is made that infiltration is not limited and thus no surface runoff occurs when soil water stored in upper soil zone (SMAV) is loss than maximum available water storage capacity in upper soil zone (SMAX). When SMAV equal SMAX, all snowmelt in excess of SMAX and less than the maximum daily infiltration parameter (SRX) is added to the subsurface reservoir storage (RES) for routing as subsurface flow.

The time of the year in which transpiration occurs are specified as a period; months between ITST and ITND which are input variables specifying the starting and ending months respectively of the transpiration period. Leavesley (1973) used April and November as ITST and ITND values respectively. Transpiration begins on the first day of ITST for all snow free HRUs but may be delayed to some later date for snow covered HRUs, by using temperature index parameter (ITST).

The upper soil zone of each HRU is classified according to its texture as either a sand, loam or clay for the purpose of soil water accounting. Based on soil texture type (Sand, Loam or Clay) and ratio of SMAV and SMAX, ratio of actual ET (AET) and potential ET(PET) have been fixed which are used to calculate AET of various HRUs.

Interception

The factors like vegetation type, canopy density and precipitation type have been taken into consideiation to compute interception (XII) of each HRU (Hydrologic response unit) of watershed (with homogeneous hydrologic response) cover density (COVDN) expressed as a percent the HRU, surface covered by a horizontal projection of the vegetation canopy, a canopy storage for rain (RNST) in inches depth and a canopy storage for snow (SNST) in inches water equivalent depth are input for each HRU.

For the pricipitation events occurring as all rain or all snow and where

i. Precipitation depth PPT, RNST or SNST

$$XIN = (RNST \text{ or } SNST) \times COVDN \text{ (Inches)}$$

ii. Precipitation depth PPT < RNST or SNST

$$XIN = PPT \times COVDN \text{ (Inches)}$$

when the precipitation takes place as a mixture of rain and snow it is assumed that rain occurs first followed by snow.

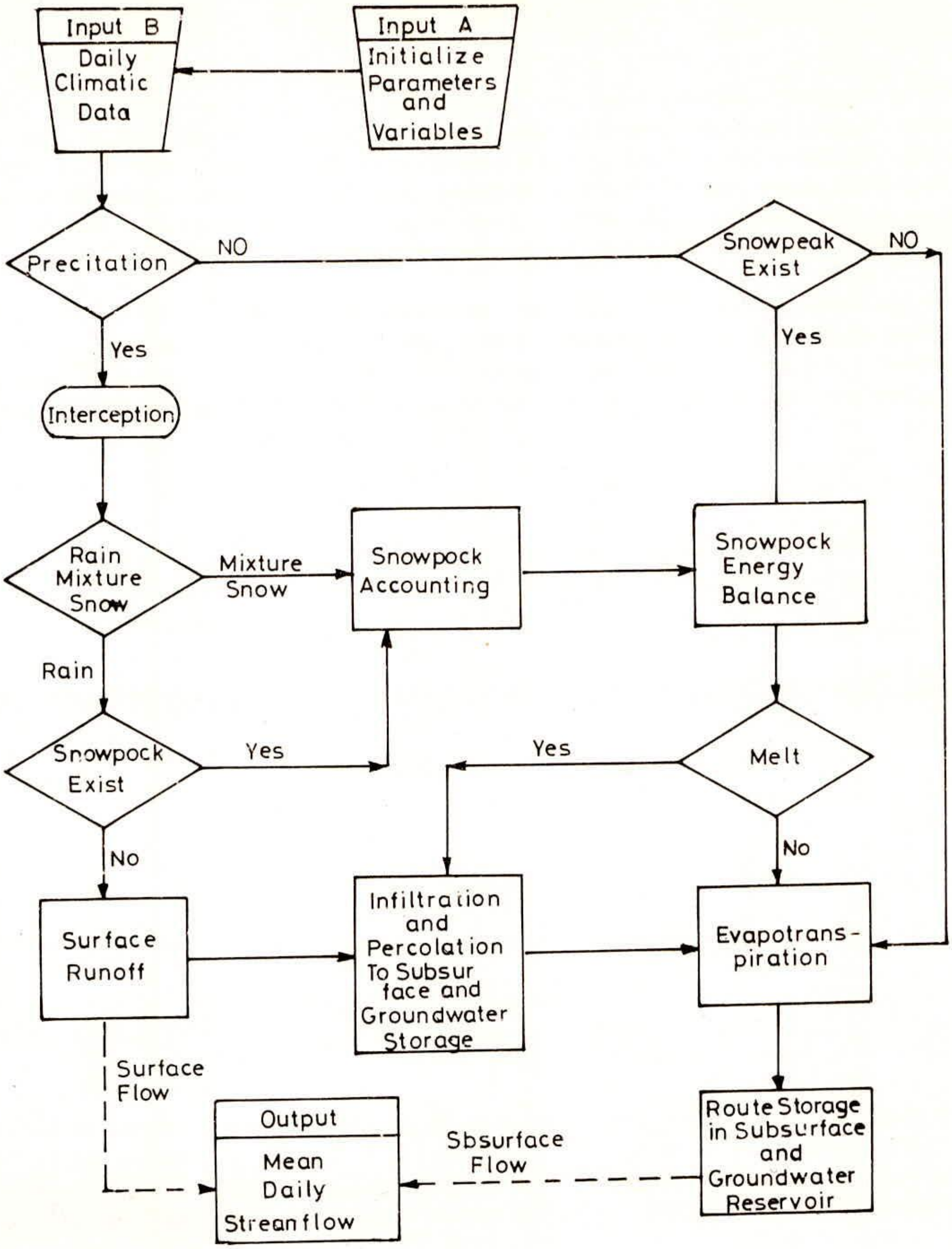


Fig.-20 Flowchart of the model operation. (Levesley Model)

Interception losses through evaporation and sub-limitation are assumed to vary with precipitation form. For intercepted rainfall, all interception loss, XIN is considered lost through evaporation.

Infiltration

The major factors affecting infiltration and subsequent surface runoff are soil texture, soil structure, antecedent soil water conditions and water input intensity. It is observed that infiltration on the major portions of most forested watersheds is not limiting and that surface runoff contributions come from source areas lying along the stream courses of the basins. This source area is a small percentage of total area of the watershed and varies in size with antecedent soil water conditions, storm amount, duration and intensity.

Dickenson and Whitley (1970) developed a relationship between minimum contributing area of a basin and a basin moisture index (which was function of soil water and storm amount) as shown in figure 21 contributing area remains small untill some moisture index threshold is reached after which contributing area increases rapidly to some upper limit imposed by the basin.

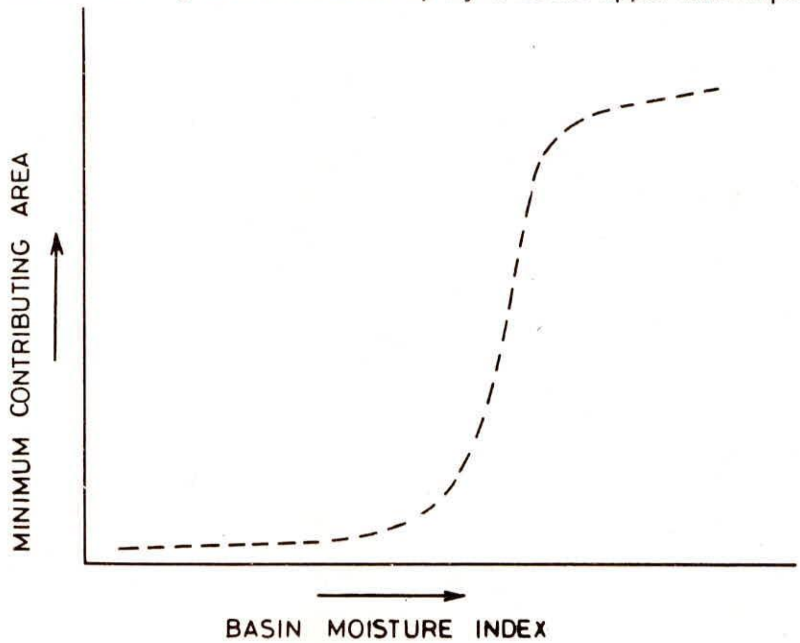


Fig.-21 Relationship Between Minimum Contributing Area of A Basin and Basin Moisture Index.

In this model the contributing area concept is used to calculate the volume of surface runoff from rainfall events which occur on snow free HRU. The % contributing area of an HRU is assumed to be a linear function of the amount available soil water stored in the upper soil zone (SMAV) at the time of rainfall and of a maximum percent contributing area factor which is defined by the HRU variable SCT. Value of SCT may vary from 3 to 85% depending on soil and vegetation conditions.

Surface runoff contributing area (CAP) expressed as a % of the total HRU area for a given storm is computed by

$$CAP = SCT \times (SMAV/SMAX)$$

Volume of surface runoff is then computed as

Vol. of surface runoff = rainfall x CAP x Area of HRU

where,

CAP	=	surface runoff contributing area
SCT	=	Max percent contributing area factor
SMAV	=	soil water stored in the upper soil zone
SMAX	=	max value of soil water in upper soil zone

Units are:
depth in inches
area in acres
volume in acre inches

The volume of surface runoff is removed from the effective rainfall reaching the soil surface and remaining rainfall is assumed to infiltrate the upper soil zone replenishing any existing soil water deficit upto SMAX.

6.6 COMPARISON OF MODELS

A comparative study of various watershed models discussed above for applying any particular model would largely depend upon the needs and suitability to site specific conditions and hence should be decided objectively. Sensitivity analysis also enables one in this process. However, selection of a particular method depends among other factors including:

i. Data availability
ii. Accuracy required
iii. Time available to get results.

Deterministic and distributed models such as SHE are particularly suitable for catchments where extensive data is available. The SWM-IV requires relatively less data being a lumped model. However this model is suitable for estimating daily evapotranspiration with simpler computations. For interception parameters calculation Leavesley model is suitable, where the precipitation is either snow or rainfall or a combination of both. The USDAHL model (also deterministic) gives fairly reliable results if the catchment is subdivided into small watersheds and the model is applied independently.

6.7 CASE STUDIES AND MODEL APPLICATIONS

6.7.1 Rainfall interception evergreen forest Nelson Newzealand

Hydrological investigations were made at Big bush forest at Nelson, Newzealand to assess the impact of various forest manipulation regimes on the hydrologic behaviour of four small catchments. Four models such as storm linear regression, monthly linear regression, Gash (1979) analytical model were applied to test the comparison of predicted and observed interception.

The following table 13 summarises annual throughfall and rainfall. Monthly throughfall indicates a seasonal pattern with a greater proportion of rainfall reaching the ground in winter (Apr.-Sept.) than in summer (Oct.-Mar) fig.22. In fig.23 (A) monthly throughfall has been plotted against corresponding monthly rainfall. Linear regression analysis carried out

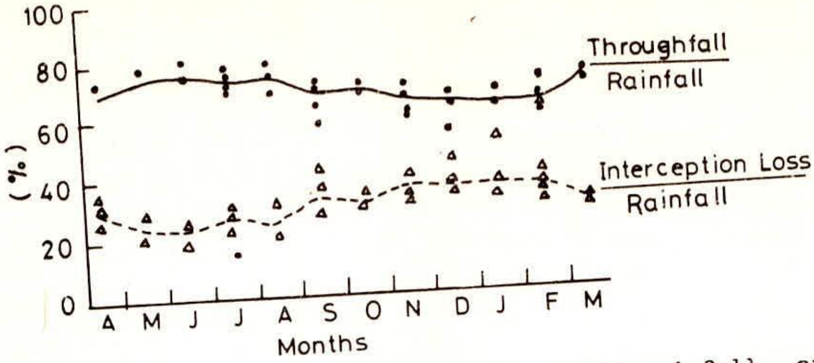


Fig.-22 Percentage monthly throughfall/rainfall and intercception loss/rainfall for a beech forest stand, Nelson, 1977-1981.

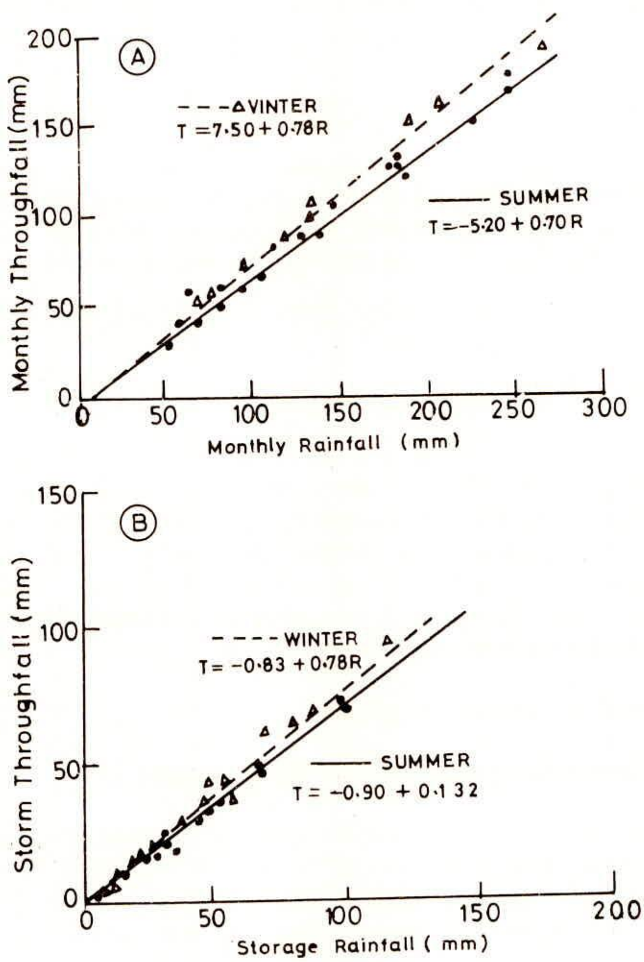


Fig.-23 Throughfall-rainfall relationships for a beech forest stand, Nelson, 1977-1981: (A) monthly data; and (B) storm data. Above R = 50 mm all points have been plotted; below R = 50 mm, a representative selection of the 312 data points have been plotted to show the range of values obtained.

in each data set indicated highly significant correlation between throughfall (T) and rainfall (R) with 98 and 99% of the variances being explained for winter and summer respectively. Overseas literature summarised by Helvey and Palric (1965) has many instances of significantly different summer and winter relationships for hardwood forests however, they are deciduous forests.

Table-13

Annual throughfall, stemflow, interception loss and rainfall Donald Creek, Nelson Apr. 77 - Mar 81

Year (mm)	Throughfall (mm)	Stemflow* (mm)	Interception (mm)	Rainfall
1977-78	925	25	390	1,345
1978-79	1,080	30	435	1,540
1979-80	1,215	35	535	1,780
1980-81	910	25	370	1,305
Mean	1,035	30	430	1,490

Stem flow estimated at 2% of rainfall

Interception loss is here treated as complement of throughfall, less an estimate of stem flow calculated as 2% of gross rainfall. The average yearly interception loss for the study period are as already given in Table-13. Newzealand studies have reported annual interception loss to be 26% for mixed beach forest (Rowe, 1975) averaged 38.6% compared to the equivalent for this study of 32%. Studies in hardwood forests elsewhere have reported interception losses in the range of 5% of gross rainfall to 38% (Dabral and Subba Rao, 1969) with most results above 20 percent. Fig.24 shows the data for monthly interception loss as function of monthly rainfall.

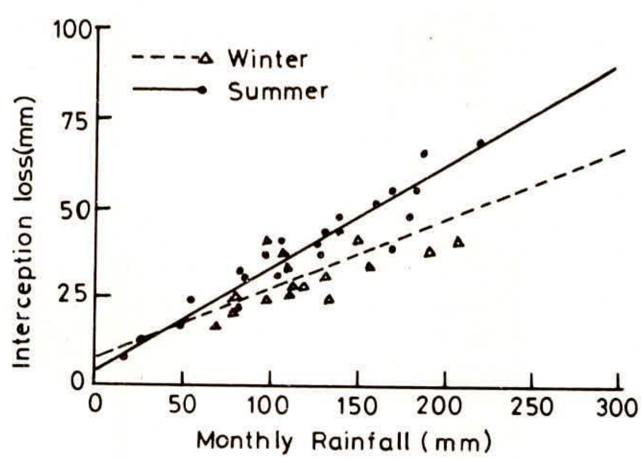


Fig.-24 Monthly interception loss-rainfall relationships for a beech forest stand, Nelson, 1977-1981.
Source: Halladin et al. (1984).

Since the regression models are simplistic and empirical, a physically based model, that the Gash (1979), itself a simplification of the model of Rutter (1978) gave satisfactory results. Gash's model has been reportedly to be nearly realistic (cited from L.K. Rowe, 1974).

Further grasslands meteorological data was applied to a forest stand in Newzealand by Gash, Pearce and Steward (1974) to predict interception loss for scotpine stand in Thetford forest and satisfactory results were obtained in close comparison with observed values.

6.7.2 Rainfall interception phenomena of Bracken plant (UK)

John Ian Pitman published a paper on the interception phenomena of Bracken vegetation, a cosmopolitan invasive plant currently covering some 6720 square km (2.8% of land area) of UK with the most extensive areas of Bracken being in wales and Scotland.

A rainfall simulator was used to investigate how the free throughfall coefficient P, Canopy storage C, and drainage rate Ds of bracken varies with projected leaf area index (LAI) over a range of .4 to 5.88. The field canopies was found to be a simple exponential function of LAI. Measured maximum storage Cmax was related by LAI by Cmax = 0.46 (+ or - 0.004) LAI. However attempts to relate the measured storage and drainage rate using the modified Rutter drainage function and the more recent Calder drainage model were unsuccessful primarily because both assume zero drainage at zero C. The experimental data shows that C always has some positive value. Cmin was related to LAI. Further two drainage functions were derived using optimisation and excellent results were obtained where Cmin, K & A were simple function of LAI and storage and hence generalised over a complete range of LAI. If remote sensing techniques such as developed and tested by Curren (1983, 1986) are used to determine the given LAI then the throughfall co-efficient P can be determined easily for bracken communities where interception and throughfall measurements are non existent.

6.7.3 Evapotranspiration

Forest evaporation consists of two components, the losses derived from interception and transpiration process occurring under wet and dry canopy conditions respectively. The interception process has received considerably more attention and a very good physical understanding of it has been acquired. However transpiration from forests is difficult to measure adequately by using sampling techniques within tree crowns. Transpiration from European forests micrometeorological techniques revealed very little variability between studies and the losses were much less than suggested by calculations of potential transpiration using traditional formula such as Penman (1963). John Roberts (1982) in his paper on forest transpiration referred it as conservative hydrological process.

The most significant advance towards understanding and estimating evapotranspiration was achieved by the formulation of the Rutter model (Rutter et al 1971). The model is a detailed description of the rate and magnitude of inputs stores, interchanges and losses from a forest canopy during and after a rainstorm. The predictive performance of the model or derivation from it and has been shown to be successful in several studies and in temperate region, at least the structure of the forest plays only a minor role in determining interception loss which compared to the important factors which are frequency and duration storms (Rutter and Morton 1977, Gash and Morton 1978) with physical insight provided by the Rutter model it has been possible to simplify rainfall interception models drastically (e.g. Gash, 1979).

The transpiration components of evaporation is influenced by many factors such as climate, forest age, species structure and soil moisture condition. The following table 14 presents information derived from several studies in Europe.

The influence of forests under storeys, negative feed back effects of surface resistance with climate demand and in insensitivity to changes in available soil moisture are considered important explaining the observed results. However selection by nature or forestry enterprise, of species known to show good growth and survival as a given rate may limit the variability of transpiration.

A case study of Swedish pine forest is discussed in the later part of this chapter.

Table 14

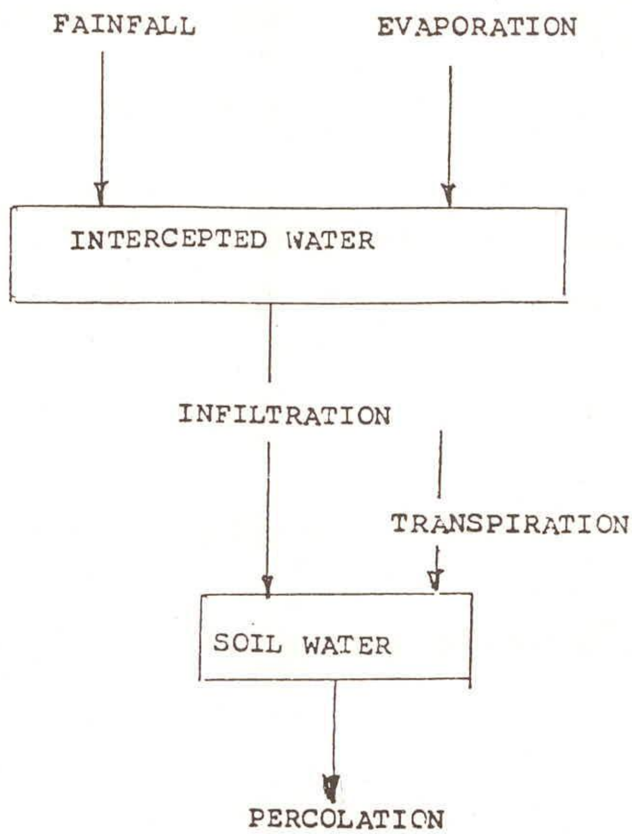
Annual transpiration of tree species in British Forests

Species	Author	Location	Transpiration mm/yr.
Sitka spruce	Low (1956)	Yorkshire (UK)	340
Norway spruce	Tejchman (1971)	F.R. of Germany	362
-do-	Bruchtel (1976)	-do-	279
-do-	Calder (1977)	Wales (UK)	290
Scot Pine	Brucheel (1976)	F.R.Germany	324
-do-	Gash & Stewart (1977)	Thetford (UK)	353
-do-	Rutter	Crowthrone U.K.	427
Oak	Bruchtel (1976)	F.R.Germany	327

Source : John Roberts, published paper in J.Hydrology, 66 (1983)

6.7.3.1 Evaporation by simulation using routine meteorological data

This model was originally conceived for a Swedish pine stand (Halldin and Grip, 1979) Subsequently changed to a mature Oak forest in France. The study site was set up for basic research in the water balance of deciduous forests with the specific aim to estimate the duration and severity of water stress and its influence on production (Saugier at al, 1985). The validity of the model was tested using measurements of throughfall and soil water content in a well confined profile for the climatically different years of 1981 and 1982.



MODEL STRUCTURE

Fig: 25

Source: Halladin et al. (1984).

Model description

The model is based upon two fundamental principles:

1. That all its structural parameters must be possible to physically identify and can be measured independently of the final result and

2. That it should properly represent only the most fundamental physics of the system and that each additional process to be included had to show its marginal utility in a set of real situations.

The model structure indicated in fig.25 has nine structural parameters viz. surface resistance (a, Ko, Ro), aerodynamic resistance (PRA). Interception (Ss, Sw), soil water (VMIN, VSTRES and VMAX). In addition there are a number of conversion factors in the computer code that allows several types of data to be transformed into the set finally required by the model: leaf area index, corrected precipitation, vapour concentration deficit, wind speed psychrometric constant etc.

Evaporation is calculated using the following equations

$$LE = \frac{\Delta Rn + \varsigma Cp \ \delta e/ra}{\Delta + r(1 + rs/ra)}$$

L	=	latent heat of vaporization of water (j/kg)
Δ	=	slope of saturation vapour pressure Vs temp. curve (Pa/K)
Rn	=	Net radiation (w/m^{-2})
Cp	=	heat capacity of air at constant pressure ($J\ m^{-3}k^{-1}$)
δe	=	saturation pressure deficit of air (Pa)
ra	=	aerodynamic resistant ($S\ m^{-1}$)
r	=	psychrometric constant ($pa\ k^{-1}$)
rs	=	surface resistant (S/m)

Evaporation from a wet stand was given with rs taken as 0. When the canopy was dry, a potential transpiration is calculated with rs as a function of solar radiation, Rg. was vapour concentration deficit, c (kg/cubic meter) and single sided leaf area index (LAI)[1].

$$rs = ((Rg + Ro)/Rg)\ ((a+c)/Jo)\ (LAI)^{-1}$$

where Ro, a, Ko are constant for a particular forest.

In the original model the aerodynamical resistant was calculated using traditional formulae involving displacement height, roughness length, and stand height.

This has however been modified as ra = PRA/u where u is the wind speed. This modification allowed estimation of PRA from simple thumb rule to elaborate micrometeorological measurements without introducing much calculations in the model.

Model sensitivity can be assessed to the changes in the values of surface and aerodynamic resistance, the interception, the field capacity and soil water content at the onset of soil water stress. A comparison of different formulae to predict potential transpiration/

evaporation clearly demonstrated the necessity to include a surface resistance term in forest transpiration formulae. The aerodynamic resistance was less important and the simple threshold formulation for interception did not work well.

6.7.4 Remote sensing application to hydrological modelling

Remote sensing data from satellite can provide much useful information for hydrological modelling. These applications fall into different areas, satellite data can be used first, to improve the definition of soils and land covers over the watershed, which determines infiltration, evapotranspiration and runoff coefficient. Secondly because remotely sensed data measures spatial information rather than point data, it can help to correct errors on input parameter (like precipitation etc.) resulting from point measurement. But the most important information obtained from remote sensing techniques for hydrologists is the estimation of soil moisture and evapotranspiration that can be derived from satellite thermal infrared images and which can be assimilated by models to monitor was exchanges between soil layer and the atmosphere (Engman 1986).

These are now possible with infrared radiometric measurements and it has been shown (Carlson 1985, Taconet et al 1986) that surface soil moisture in the case of bare soils and soil water content in the root zone under dense vegetation can be obtained through the energy balance at the land atmosphere, interface, provided the atmospheric forces and the physical land biological behaviour of the surface are known. With modelling of hydrologic and energy budgets, surface temperature measured around its maximum daily value is sufficient to derive areal evapotranspiration and the global surface resistance to evaporation from the soil water content can be estimated.

A simple model to estimate evapotranspiration from satellite temperature and albedo images (Casselleles et al, 1987) is illustrated in the following discussion.

Model to estimate Evapotranspiration

This is based on the radiation model proposed by FAO, applicable to any area, for estimation of regional max evapotranspiration, ET, from temp. and albedo images obtained from satellite. The model is based on following relations (Doorenbos and Pruitt.., 1977)

$$ETm = Kc\ ETo$$

$$ETo = A + B\ Rg + C\ Rg\ Ta\ max$$

where,

ETo = Reference evapotranspiration
ETm = Evapotranspiration under actual conditions (presumed optimal)
Kc = Crop coefficient
Rg = Global radiation obtained from satellite albedo images
Ta max = max i temp.
A,b&C = empirical coefficients.

The empirical coefficients A, B & C are evaluated for each region as a function of air humidity and wind velocity levels given in that region and they can also be determined for different intervals of humidity and wind, consequently improving the model accuracy.

Model Description

The determination of max evapotranspiration by mean soft proposed procedure which requires use of data obtained from a satellite together with measurements taken on the ground itself is carried out through different steps schematically indicted in fig. 26.

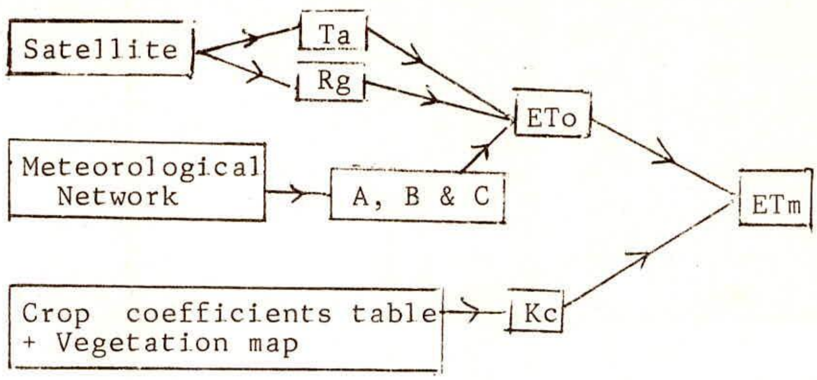


Fig.-26 MODEL NETWORK

To illustrate the model application it was applied (Caslleles et al., 1987) to Velentian region (Spain) using data obtained from HCMM satellite at 13.17 hrs GMT on 7 July, 1978. Encouraging results have been reportedly obtained.

The application of remote sensing enables in the obtention of Tx max, Rg, ETo nd ETm maps. The apparent temp. map obtained from satellite is transformed to air temp. through linear regression between the values obtained by the satellite and those registered under standard meteorological shelter in different points of the region.

The map of global solar radiation may be obtained from the measurements of albedo carried out from a satellite. The model uses following relation developed by Decian et al (1983).

$$Rg = Ro\ (1 - p)/(1 - s)$$

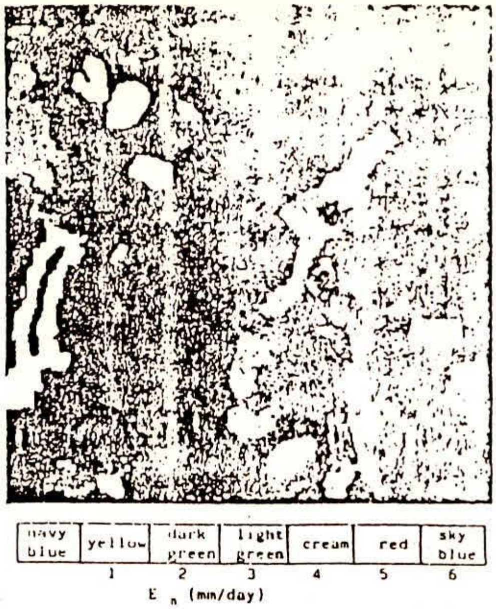
where,

Ro is the extra terrestrial radiation, p the planetary albedo obtained from satellite and s the surface albedo which is considered as the minimum of p obtained from a collection of images of clear days.

The obtention of ETo & ETm maps requires knowledge of solar radiation Rg, maximum value of air temperature the coefficients A,B,C and Kc of equations mentioned above. From the measurements of air humidity and wind velocity which is carried out in a systematic way in meteorological networks a set of map are obtained by means of Ta max, Rg, A,B,C & Kc and then maps ETo, ETm are obtained.

6.7.5 Geomorphic indices of hydrologic characteristics

Gardener and Park (1978) reviewed the early foundations of Geomorphic studies, the contributions of Horton, extensions and refinement of Stranhlers and others concerns over



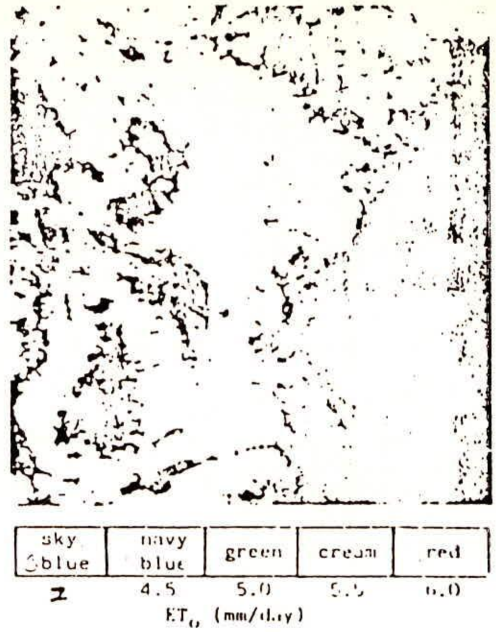


Fig.-27 Maximum evapotranspiration map for the area of study calculated by using proposed model. This map is optained to the HCMM Satellite image corresponding to the 13.17 hour GMT of 7 July 1978. The navy blue colour corresponds to non-agriculture areas.

Fig.-28 **Reference crop evapotransparation map corresponding to the area of study the sky blue colour corresponds to non-agricultural areas.**

Fig.-29 ed/crop map. Rice fields. red: vineyards, cream; cirus fields light green; orchards, dark green, dry land trees, sky blue; dry land grain, electric blue; forest, brush blue lake black data measurement and interpretations and applied uses of geomorphic analysis, including predictive modelling. martson (1978) developed statistically significant, physically sound correlations between geomorphic variables and hydrologic characteristics. James R Maxwell and Richard Martson (1980) together studied deeply and extended Martsons model and applied it to forested catchment at Oregon (USA). The methodology is briefly discussed below which involves basically five steps.

i. Establishing the hydrologic data base (mean annual flow, base flow, mean annual peak flow and mean annual sediment yield of selected catchments).

ii. Establishing geomorphic base map (this included delineation of stream network from toposheets).

iii. Selecting geomorphic variables (such as compactness coefficient, drainage density, stream frequency, bifurcation ratio, relief ratio, runoff factor, erosion factor etc. Table-15).

iv. Making geomorphic measurement (sonic digitizer was used for linear and areal measurements)

v. Performing statistical analysis (correlation analysis)

Table 15

Geomorphic variables and factors with derivation

Symbol	Variable	Derivation
B	Bifurcation ratio	Antilog of slope or regression of stream order Vs log of number of streams.
CC	Compactness coefficient	Perimeter divided by circumference of circle with same area
DD	Drain density	Total streamlength/area
RR	Relief ratio	Basin relief divided by basin length as measured along line dividing basin into two equal halves
SF	Stream frequency	Total number of streams divided by area
SRR	Stream relief ratio	Antilog of slope of regression
TR	Texture ratio	Total stream relief/perimeter
RF	Runoff factor	DD/CC
BR	Base flow factor	(B x SRR)/(RRxCC)
EF	Erosion factor	DD x TR x B x SRR

The results are briefly discussed below:

1. Base flow was correlated with base flow factor and the CD (Co-efficient of determination) was 0.841.

2. Mean annual peak flow was correlated with stream frequency and the CD was 0.914

3. Mean annual sediment yield was correlated with erosion factor and the CD was found to be 0.951.

These geomorphic factors may be used to estimate streamflow and sediment yield in research and experimental watersheds and may be applied over other homogeneous basins however, extrapolation may be difficult. The derived correlations demonstrate the importance of channel density and relief, basin and stream network steepness and basin shape to basin hydrology. Despite certain limitations the relationships constitute reliable tools for use in forest and basin planning. The base flow and sediment yield correlations have additional value for forest hydrology.

7.0 SUMMARY AND CONCLUSION

7.1 SUMMARY

The studies in India on hydrologic influences of forests have been on a modest scale and largely limited to small experimental watersheds. There are nearly 16 hydrological research stations working in India at present on some aspects of forest hydrology.

The technology of forest hydrology is relatively much advanced in developed countries. The problem has been identified in its proper perspective and the conventional methods of estimating the hydrological parameters are being replaced by mathematical models to computer simulated models for a realistic approach. Continuous monitoring of soil water pressure and rainfall runoff has been made possible for remotely located forested catchments thereby enabling scientists to study soil hydrologic characteristics. Remotely sensed data from satellites has provided the required break through in hydrological modelling.

7.2 CONCLUDING REMARKS

The following conclusions may be drawn on the basis of the review of studies carried out in India and abroad.

i. The interception is a function of forest type, density, composition structure and rainfall/ intensity. It may be inferred the average total interception by a dense forest cover (including canopy interception 20%, undergrowth 10% and litter 5%) appears to be around 35%. The interception in forested catchment does not have significant effect during heavy storm (100 mm or so).

ii. In general infiltration rates are relatively more in forested soils as compared to agricultural and grass lands. The infiltrated amounts are about 40-50% of precipitation (Mal Chanov, 1963).

iii. Soil moisture retention capacity of forested catchments are relatively higher compared to agricultural lands.

iv. Evapotranspiration from forested catchment are higher compared to other land uses. However there is abundant scope in this area for studies to be taken up as the process of transpiration has not been completely understood and as such all estimates are on conservative side.

v. The studies indicate that forests reduce the surface runoff both volumes and peak rates, sediment yield and regulate the stream flow by maintaining the flows during dry weather (i.e. lean flow period) due to slow release mechanism, of soil moisture storage from forested soils.

vi. The effect of forests on ground water have not been studied on large scale. However the direct influence of forests may be reflected through evapotranspiration. There are conflicting reports of the effect of deforestation on ground water.

vii. Based on limited studies it was reported that soil loss is less in well managed forests in comparison to ill managed (denuded) forests.

viii. A systematic and scientific study may be taken up in a large upper catchments of flood prone areas to examine the effects of forest on rainfall and floods. A systematic inventory of the forest cover complex and hydrologic grouping of the forest land may also be attempted in upland watersheds of flood prone areas.

Thus there is a need to gain better understanding of the various parameters representing hydrological processes within a catchment and to develop process based models using hydrological parameters such as vegetation cover and basin characteristics to make the model versatile. While regression based models have certain limitations and that extrapolation of which may be erroneous, other mathematical and simulation models such as SWM-IV, SHE, Rutters etc. have been found to be satisfactory and near realistic.

7.3 Proposed Studies

The influence of forests on their environment forms a part of complex relationship between environment and forest vegetation. A systematic and scientific study of forested catchments needs to be undertaken on priority basis. It is proposed to take up studies on following lines.

1. Contact, communicate and discuss with experts and consultants in the area of forest hydrology in Ind. identifying specific problems associated. Visit forested catchments along with experts.

2. Carry out studies for simulating forest influences on hydrological parameters.

3. Develop mathematical model or use available models with experts/consultants for application to catchments using available data for case studies. Instrumentation and studies for/in representative basins/large catchments studies would also be examined.

4. Develop manuals/technical report on

   i. modelling interception & evapotranspiration

   ii. rainfall-runoff relationship in forested water sheds and representative basins.

   iii. case studies on affect of deforestation on hydrological regime.

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APPENDIX

DETAILS OF EXPERIMENTAL FOREST WATERSHED IN INDIA

S.No.	Organisation	Regions(s)	No. of catch-ments under study	Location	Area and land use (ha)	Type of Studies	Period of study	Remarks
1.	CSWCRTI, Dehradun	Northern Himalayan Forest and part of upper Gangetic alluvial plain region	7	Selakui (Dehradun)	0.87-83.37 ha. Agri., Forest, Forest + Agril., Brush Wood etc.	To evaluate effect of various land uses, vegetative cover and land treatment measures on the hydrological behaviour of small watershed and to develop rainfall-runoff sediment relationship	Since 1960-61	Various treatments were imposed after pre-calibration of watersheds, Paired watershed techniques have been used.
	ORG Fakot (Tehri Garhwal)	Northern Himalayan region	2	Fakot (Bhaitan watershed)	240-270 ha mixed landuse (36% forest)	To study the effect of watershed management measures on watershed hydrology on relatively large watershed.	Since 1975	
			1	Bemunda (Tehri Garhwal)	1754 ha mainly under forest (i.e. 87%)	To study watershed hydrology of hilly forested watersheds	Since 1980	
2.	FRI,Dehradun	-do-	2	Rajpur (Dehradun)	6 ha each with Sal coppice forest	To study various aspects of forest hydrology	1965	Interception and run-off have been found under natural and thinned conditions
3.	CSWCRTI Chandigarh	Punjab,Haryana Alluvial Plains and Siwalik Hills	20	Mani Majra farm (low lying Shivaliks)	07-20 ha Natural hilly watersheds	To study forest influences and effectiveness of soil conservation measures on hydrological aspects and to develop rainfall runoff and sediment relationships for Siwalik hills.	Since 1963	Some studies are concluded and some are going on

		-do-	1	Sukhomajari	85 ha mixed landuse	Watershed management for sediment control	Since 1975	Part of watershed is being gauged for experimental studies
4.	Chandigarh Forest Department	-do-	3	Kansal, Ghareri & Nepli (Sukhna lake catchment)	1214 acres)mixed 574 acres)land 1485 acres)use mostly forest (84.5%)	To monitor effect of watershed treatment measures on sediment yield	Since 1979	
5.	ERS(FRI),* Simla	Northern Himalayan Snow Clad region	9	Simla	small forest catchment	Forest watershed management for municipal water supply	Since 1980	*Mathur (1980)
6.	CSWCRTI, Agra	Upper Gangetic Alluvial Plain Region with problem of Yamuna ravines	2 2	Challesar Agra -do-	0.206 ha (grass) 0.29 ha (sisham) 3.7-8.4 ha (Mixed land use)	To study hydrological behaviour of ravinous watersheds with trees and grass covers	Since 1965	Some results have been already reported
7.	CSWCRTI, Kota	N.E.Rajasthan region with Chambal ravines mixed yellow, red and black soil region	3	Kota	0.4-1.45 ha Agril,forest + grass and grass only	To study hydrology of small watersheds under different land uses	Since 1979	
8.	CSWCRTI, Vasad	Gujarat Alluvial Plain region,mixed soil region	2	Vasad	10 ha(60% forest + 40% Agril) 4.0 ha(56%Forest	To study effect of land uses on hydrological and determine runoff coefficient	Since 1961	
9.	CSWCRTI, Octacamund	Nilgiris hills (part of southern red soil region)	17 sub-watershed	In Nilgiris at various locations in Moyar & Bhawani basins	7.51-334.64 km. (mixed land use)	To study variations in water yield and develop regression models for ungauged watershed using physiographic characteristics	Since 1971	Study completed and relationships developed. These area not the expartental watesheds.
			Runoff Plots	Ootacamund	0.02 ha on 16% slope (shola Shrub and grass and trees)	To monitor effect of different vegetative covers on runoff & soil loss	Since 1958-63	
			-do- (4)	-do-	0.09 ha(Forest)	Small catchment studies on the effect of forest	Since 1958	

						covers both in natural degraded shola forest and man made forests		
			2	Glenmargan (Ootacamund	32 ha each natural forest & introduced plantation	To study hydrological behaviour of watershed with natural vegetation as well as introduced plantation	Since 1964	
10.	EMS(FRI)* Ootacamund	Nilgiri Hills (part of southern red, soil region)	4	Ootacamund	small forest watersheds	To study aspects of forest hydrology including ground water	Since 1981	*Mathur(1980)
11.	EMS(FRI)* Kursaong	Assam Valley region	2	i.Sonada ii.Rolling	i.experimental watershed ii.Bench mark watershed both under forest	To carry out investigations on various aspects of forest hydrology and develop rainfall-runoff models	Since 1981	*Mathur (1980)
12.	CWPRS, Pune	Western Ghats	1	Khandala Khopli forest range	80 ha(mainly forest & grassland)	To evaluate impact of soil conservation on runoff and soil loss and develop suitable rainfall runoff and sediment yield models	Since 1978-79	Only 20 ha is well instrumented and divided into microwatersheds
13.	LVC + Hazaribagh	Eastern red soil region	7	Upper catchment of Damodar-Barkar	35-450 km^2 (mixed landuse)	Hydrological monitoring to study the effectiveness of watershed measures on runoff and sediment yield	1964-78	The no.47 indicates the number of gauging sites
14.	Ramganga Project Authorities	U.P.Himalaya region	7	Upper catchments of Ramganga	Mixed land use	-do-	Since 1966-69	Number 7 indicates number of gauging sites

+part of River Valley Project Schemes.

Source : i. Annual Reports of CSWCRTI, Dehradun
ii. Anon. (1982)
iii. Das et al. (1984)