STUDIES ON SPACE - TIME VARIABILITIES OF HYDROMETEOROLOGICAL PARAMETERS OVER KERALA STATE

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CERTIFICATE

I hereby certify that this thesis entitled "Studies on Space-Time Variabilities of Hydrometeorological Parameters over Kerala State" is an authentic record of genuine and bonafide research work carried out by Shri. M.E. James during the period 1985 to 1991, under my supervision and guidance at the Physical Oceanography and Meteorology Division, School of Marine Sciences, Cochin University of Science and Technology, and that no part of this thesis has been previously submitted to any University or Institution for the award of any degree or diploma.

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CHAPTER I

INTRODUCTION

The State of Kerala lies in the southwestern part of the country, along the west coast. In spite of its small size, the State supports about 3.7% of the population of India and has the highest population density among the Indian States. The picturesque exuberant vegetation that clothes the land of Kerala for most part of the year is a distinct feature of the State. The diverse physiographic features of the State are very significant in influencing the climate, vegetation and land-use of the region.

Kerala is essentially an agricultural State: the main occupations of the people are associated with agricultural activities. High population density and the resultant increased necessity for food has increased the cultivation in the State, to nearly 64% of the total geographical area.

Within a short distance of 120 km from the coast to the Western Ghats, a variety of climates are observed due to the diversity of physical features. The most conspicuous feature of the climate of Kerala is the heavy rainfall due to the southwest monsoon. The vagaries of the monsoon - its onset and withdrawal, active and break conditions, space and time variations - are all very complex, and studies on the various aspects of these vagaries are going on in various institutions.

The State has a well-distributed drainage network consisting of 44 rivers. Due to effluent seepage, rivers of the State are perennial and they possess high potential for hydel-power generation, irrigation and transportation.

Floods and droughts are considered to be the two extreme conditions of variability of rainfall. But both these natural phenomena affect badly the agricultural production and hence the economy of the State. Landslides are yet another hazard which affect the State that are mainly associated with heavy and persistent rainfall.

There are large differences in the spatial and seasonal distributions of rainfall over the State. There are regions experiencing more than 500 cm of rainfall as also regions having less than 60 cm. Rainfall is also very unevenly distributed among the seasons; about 66% of the annual rainfall is contributed by the southwest monsoon season, but winter season contributes only 1% to the annual total.

A knowledge of what happens to the water that reaches the earth surface will assist the study of many surface and subsurface water problems, for efficient control and management of water resources. For a State such as Kerala, whose welfare depends very much on agriculture, a quantitative knowledge of water requirements of the region, availability of water for plant growth and supplemental irrigation, etc. on a monthly or seasonal basis is an essential requirement for agricultural development. Increasing population in recent decades and the resultant higher demands for food have led to many attempts aimed at optimal exploitation of water resources. Since the power generation of the State depends totally on hydel projects, a quantitative measure of the water surpluses of the region is a very useful parameter, since it provides a rough estimate of the utilisable water for the power projects.

In this context, a study of water balance of the State seems to be very relevant and necessary. The derived parameters of water balance, especially water surplus and water deficit, on a seasonal basis give very essential information useful for various agricultural activities, such as choosing the variety of crops, adjusting the farming operations, assessing the irrigation potential of the region, scheduling the irrigation operations etc.. A State such as Kerala, where agriculture is said to be a gamble with the weather, the water balance concepts have high utility. Study of water surplus is very important for the development of river basins for water supply, power generation, irrigation, flood control, drainage etc..

The spatial distribution together with seasonal variations of the water balance parameters help us to delineate the optimal regions for the development of agriculture and hydel-power generation and to assess the economic feasibility of different activities connected to water resources management.

Studies on large scale temporal changes in the hydrometeorological parameters, especially rainfall and temperature are pre-requisites for planning and development of a country's natural resources. There is a general opinion that rainfall of Kerala is decreasing and temperature is increasing.

In Kerala, whose economy is very much dependent on water availability, fluctuations in rainfall affect human welfare, through its effects on agriculture, power generation and industrial activities. Power cuts and load shedding have become a common feature in the State during the last decade due to the deficiency of power. This again affects agricultural and industrial production and thereby human welfare. Even though well-developed irrigation facilities reduce the risk in agricultural activities, prolonged drought conditions will affect the irrigation system itself. Salt water intrusion through the rivers is another problem in Kerala, especially during pre-monsoon months, which indirectly affect agriculture. Since the population density is very high, and is further increasing, the water requirement for domestic purposes too, would be increasing. In the present context, a detailed study of time series of rainfall and other water balance parameters such as actual evapotranspiration, water surplus and water deficit to detect the trends and periodicities in the series, seems to be very relevant.

The spatial and temporal variabilities of some hydrometeorological parameters over the State have been analysed in the present study. The thesis consists of six Chapters including the introduction. The first section of the Second Chapter explains the concepts of hydrologic cycle and water balance, various methods of estimation of potential evapotranspiration, book-keeping procedure of water balance of Thornthwaite (1948) and the various applications of water balance techniques. The second section of this Chapter is mainly concerned with the applications of time series analysis in climatology. Various techniques such as power spectrum analysis, Mann-Kendall statistic test, Student's t-test and filtering methods which are employed to reveal the temporal variations in time series have been discussed. An exhaustive and relevant review of various techniques of hydrometeorological studies are cited in this Chapter.

The third Chapter consists of a discussion of the important physico-climatic features of Kerala State. The location and extent, physiography, drainage, soil type, agricultural pattern and land-use systems over the State are explained in the first section, while details about rainfall, temperature, wind and humidity which form the climatological features are discussed in the second.

The seasonal and annual distributions of normal water balance parameters namely rainfall, potential evapotranspiration, actual evapotranspiration, water surplus, water deficit, surface flow, underground flow and total discharge over the State have been mapped and discussed to present a broad picture of hydro-climatic background of the region in the fourth Chapter. The spatial distribution of various indices derived from the water balance procedure, such as moisture adequacy index, aridity index, humidity index, and moisture index have also been presented. Classification of climates of Kerala based on Thornthwaite's scheme has also been depicted in this Chapter.

The fifth Chapter deals with the time series analysis of rainfall, actual evapotranspiration, water deficit and water surplus over the State as revealed by spectrum analysis and trend aspects as indicated by Mann-Kendall statistic, Student's t-test and low pass filtering techniques.

The sixth Chapter comprises the summary of the study and conclusions about the spatial and temporal variation of hydroclimatic parameters over the State.

CHAPTER II

LITERATURE REVIEW, MATERIALS AND METHODS

An exhaustive and relevant review of literature on various aspects such as importance of hydrologic cycle, concepts and applications of water balance approach and climatological time series has been presented in the first Section of this Chapter. The second Section deals with the methodology employed in this study and the data utilised.

2.1 Literature review:

2.1.1 The hydrologic cycle:

The hydrologic cycle, which constantly redistributes the water between the earth and the atmosphere is well known to meteorologists, hydrologists, agriculturists, geographers and all others concerned with problems of water utilisation and management. The full cycle of events through which the water passes in the earth-atmosphere system, comprising of evaporation from the land and water surfaces, condensation of water vapour to form clouds, precipitation to the earth surfaces in different forms under different conditions, movement and accumulation of water in the soil and water bodies and finally evaporation once again back into the atmosphere, describes the essence of the hydrologic cycle.

The significance of the hydrological balance of the earth is now well appreciated and many attempts are being made to investigate the moisture factor in the climate. About 97% of the earth's water is in the oceans which covers about 71% of the earth surface. It is an astonishing fact that at any instant, rivers and lakes hold only 0.33% of the total fresh water, which is only 3% of the total water in the earth-atmosphere system, and the atmosphere holds only 0.035% (Barry, 1969). According to Allaby (1977), about 875 km^3 of fresh water evaporates every day from the sea and about 160 km^3 of water is lost from the land through evapotranspiration. About 775 km^3 of rainwater falls on the seas and 100 km^3 of water is carried by the atmosphere from the sea to the land areas which receive about 260 km^3 of precipitation. The cycle is completed by the return of 100 km^3 of water to the sea through the rivers.

The knowledge of what happens to the water that reaches the earth surface will assist in the solution of many surface and groundwater problems, for efficient management and utilization of water resources. The water balance studies of any basin should indicate the exact amount of water resident in various phases of the hydrologic cycle and be able to identify the part of the resident water, that can safely and effectively be tapped for increasing the available water in the region, without causing serious imbalances to the water cycle. The study of water balance is the application of the principle of conservation of mass, often referred to as the continuity equation in hydrology. This states that for any arbitrary volume of water during any given period of time, the difference between the total input and output will be balanced by the change of water storage within the volume. At this point, it is worth mentioning that the word 'water balance' or 'water budget' has another connotation, as a long term balance of water over the whole world, synonymous to the hydrological cycle. But in the following sections, the term 'water balance' is used with reference to a particular area only.

In general, the inflow part of the water balance equation consists of precipitation (P), surface and subsurface water flow to the area (Q_{si} + Q_{ui}), while the outflow includes the evaporation (E), surface and subsurface flows from the basin (Q_{so} + Q_{uo}). When the inflow exceeds the outflow, the total water storage in the body increases, and when the inflow is less than outflow the storage decreases and these changes in the storage are represented by ΔS. Since all water balance components are subjected to errors of measurements or estimation, the water balance equation should include a discrepancy term (γ). So, the water balance may be represented by the general equation.

$$P + Q_{si} + Q_{ui} - E - Q_{so} - Q_{uo} - \Delta S - \gamma = 0$$

For application in a variety of water balance problems, the above equation may be simplified or made more complex depending upon the available initial data, purpose of computation, the type and dimension of the body, its hydrographic and hydraulic features etc.. For a large area and for a definite time, the budget equation may be approximated to

$$P = E + Q + \Delta S$$

where Q is the total runoff.

Thornthwaite (1948) introduced the concept of 'book-keeping' of water balance to solve many soil moisture problems and employed it as the basis of a new, improved and rational climatic classification. Since then, further studies based on this approach have led to many revisions and extensions of the procedure itself, and have resulted in numerous applications in various fields. The details of the water balance and its computation have been explained by Thornthwaite and Mather (1955, 1957) and Subrahmanyam (1982). Various applications of the water balance method have been elucidated by Subrahmanyam (1972, 1982).

Water balance or water budget is a monthly or daily comparison of water supply in the form of precipitation (P) with the water demand or potential evapotranspiration (P.E.), the soil moisture acting as a sort of reserve available for use to a limited extent for the purpose of evapotranspiration during periods of water shortage. In this context, details about studies of precipitation (rainfall) and evapotranspiration (actual and potential) in India are now discussed.

2.1.2 Rainfall studies - a review:

Precipitation is the only source of fresh water on the earth and it constitutes the entire water supply to the region from the hydrological point of view. Basically, it is the resultant product of a series of complex interactions taking place within the earth-atmosphere system. Precipitation is the most widely measured meteorological parameter and its records are the bases of most of the studies dealing with water resources. Even though our country enjoys a fairly good amount of rainfall, wide variability in its distribution with respect to space and time are responsible for the two extremes of floods and droughts. While there are regions which receive abundant precipitation, there are regions practically devoid of it. Knowledge about the amount, seasonal distribution, spatial variability, frequency of occurrences, rainfall intensity etc. are important in many applications. A very detailed review of hydrometeorological studies of Indian rainfall have been presented by Dhar and Rakhecha (1975).

Rainfall measurements have their own limitations. How large an area can be considered accurately represented by the catch in the raingauge is not fully clear. Even if we have a raingauge for every square kilometre, our knowledge of distribution of precipitation may be questionable, especially in hilly areas of tropical regions. In Kerala, there are more than eighty raingauge stations maintained by the India Meteorological Department and the State Government. Another important point to be projected at this stage is that most of the raingauges in the State are located in lowland and midland areas and network of raingauge stations, especially over undulating high lands where high variability is expected is very poor.

According to Pisharoty (1986), annual rainfall over the plains of India based on the data of 2800 stations is 117 cm and this is the highest value anywhere in the world for a country of the same size of India. The seasonal and annual distribution of rainfall and its coefficient of variation using the data of 3000 stations for the period 1901 to 1960 has been prepared by India Meteorological Department (1971).

The mean total volume of rainwater over India has been computed using the data of 306 raingauges for the period 1871 to 1978 by Mooley et al. (1981) and found to be 3143 km^3 with a standard deviation of 300 km^3.

Investigations of Rao and Mishra (1971), have shown that annual rainfall of India is quite stable in general, but, it is most uncertain in the north-western parts of the country. Variability of more than 100% at some stations in the interior tracts of these areas indicate the liability to very high rainfall in some years and very scanty rainfall in others. Studies on a subdivisional basis by Dhar and Kulkarni (1974), showed that monsoon rainfall was highest in coastal Karnataka (289 cm) where it is about 87% of the mean annual rainfall and lowest in Tamil Nadu (35 cm) where it is only 19%.

Various aspects of the rainfall of Kerala State has been studied by Ananthakrishnan et al. (1979b). They found that the actual duration of southwest monsoon rainfall is only 6% of the total duration of the monsoon season at Trivandrum, 12% at Cochin and 18% at Mangalore. But most of the monsoon rains is contributed by high intensity rainfall whose duration is only a small fraction of the total duration of the rainfall. About 50% of the monsoon rainfall is contributed by 10% of the total rain duration and 50% of the rain duration contributes only 10% of total rainfall. They revealed that 50% of the rain contributed by falls of high intensity occurs with an integrated duration of less than 1 day at Trivandrum and less than 2 days at Cochin.

Sinha (1958) inferred that average rainfall per rainy day was one inch or more in case of plain stations lying in the field of activity of southwest monsoon and northeast monsoon, but it is noticeably greater in the case of hill stations. According to Ram Mohan and Nair (1986a), the number of rainy days of Kerala generally increases towards the coast and towards south, with maximum values in the southwest monsoon season over the Western Ghats region.

Like other meteorological parameters, rainfall also exhibits diurnal variations. According to Ananthakrishnan et al. (1979a), rainfall of coastal Kerala has characteristic diurnal variation with maximum in the early morning and minimum in the afternoon, and least rainfall has been observed between 1000 to 1600 hours.

According to Mooley and Appa Rao (1971), the normal distribution gives a good fit to seasonal and annual rainfall of stations in some parts of India, but does not give a good fit over large parts of the country, where, instead, Gamma distribution is more suitable. Rao et al. (1972) have shown that by and large, the south-west monsoon rainfall is normally distributed. Employing the Chi-square test and measures of dispersion, Parthasarathy and Dhar (1975a) studied the seasonal and annual rainfall of contiguous India and opined that for all practical purposes, Indian rainfall for the period 1901 to 1960 can be considered as normally distributed and all statistical tests that require normality can be applied to these time series.

2.1.3 Actual and Potential Evapotranspiration:

Evapotranspiration, one of the major constituents of the hydrologic cycle, represents the total exchange of moisture from the earth surface to the atmosphere through evaporation and transpiration. Different factors affecting evapotranspiration are a) external supply of energy b) capacity of air to remove water vapour, which is dependent on wind speed, turbulent structure of the atmosphere and water vapour gradient c) nature of vegetation, its albedo and depth of root zone d) availability of water for evapotranspiration, which is determined by the soil moisture, depth of water table and texture of the soil. Evapotranspiration varies from place to place and time to time due to variations in the weather, land-use and management practices, plant growth etc.. Evaporation from an exposed soil is less than evapotranspiration from cropped land area (Kakde, 1985).

Lysimeters are generally used to measure evapotranspiration, but its measurement faces many difficulties. In order to get reliable measurements of actual evapotranspiration, a number of requirements are to be fulfilled - disturbances due to existence of evaporimeter should be minimum, area of the evaporimeter should be sufficiently large to give a representative vegetation cover, effect of radiation on the instrument should be normal in order to get natural thermal conditions, advection effects should be minimum, and the soil and vegetation in the tank should be exactly the same as that of the surroundings. But it is practically impossible to satisfy these ideal conditions: even then the evapotranspiration values obtained do not give actual demand or the need of the soil. To overcome these inherent problems, Thornthwaite (1948) introduced the concept of Potential Evapotranspiration (P.E.). He defined it as the total water loss from a large homogeneous vegetation covered area (albedo 0.22 to 0.25), which never suffers from lack of water. This is a function of climate only and does not depend on any biotic and edaphic controls as does Actual Evapotranspiration (A.E.). Attempts for the measurement of this parameter using modified lysimeters were also unsatisfactory due to the difficulties in maintaining the ideal conditions during installation and maintenance of the instrument.

A number of empirical methods have been developed to estimate P.E. and extensive literature has been generated on these methods, their utility and limitations. There are a number of assumptions in all these approaches: some are specific for some methods while others are universal.

Tanner and Lemon (1962) have emphasised the limitations of these assumptions and clearly stated that for non-temperate regions these limitations are more erroneous. Under different conditions, different approaches have proved better and there exists no unique method which can satisfactorily be used under all conditions.

Various theoretical approaches such as mass transfer method, water budget method, energy budget method, aero-dynamic profile method, eddy transfer method and a number of combination methods have been employed to arrive at satisfactory estimates. The method developed by Lowry and Johnson (1941) is based on the correlation between the day degrees and the measured consumptive use by plants on annual basis. Penman (1948) suggested a formula based on good physical reasoning by combining energy budget and Dalton's approach. Thornthwaite's (1948) formula is based on correlation between mean air temperature and evaporation rate. Blaney and Criddle's method (1950) requires mean monthly temperature and percent day-time sunshine hours to estimate consumptive use. Ramdas (1957) developed a semi-empirical formula to evaluate P.E.. Mcllroy's (1960) expression requires measurement of air temperature, humidity, wind speed at screen level along with measurements of net radiation and soil heat flux. Another method based on combinations of energy balance and aerodynamic approach was developed by Tanner (1960). Homan's (1961) formula uses data on latitude converted into day length and mean temperature converted into saturation vapour density. Relationship of solar radiation with mean weekly day temperature was used by Jensen and Haise (1963). Based on vapour pressure, Papadakis (1965) evolved a formula to determine P.E. and Christiansen (1968) estimated P.E. using climatic data.

Sellers (1965) carried out a comparative study and remarked that Penman's estimates are slightly low in summer (October to April) and high in winter (May to September), Mcllroy's estimates are high in all months except in January and the annual total of his estimates is about 8% higher than that observed. Blaney and Criddle's estimates are low in summer and high in winter. Values calculated by the Thornthwaite's method are low in all months especially in summer. Krishna Kumar et al. (1987) found that Penman's P.E. estimates are higher than Thornthwaite's, during winter and pre-monsoon months and lower during monsoon months, at most of the Indian Stations.

Since almost all physical parameters such as wind speed, humidity gradient, solar radiation etc. have been considered, the values derived using Penman's equation are widely acknowledged to be more reliable than estimates from other methods. All the empirical formulae except that of Thornthwaite require a number of parameters which are not easily available. On the other hand, Thornthwaite's formula requires only the mean monthly temperature of the station. Thornthwaite's original formula involved the mean temperature and relative humidity, but in refining it to utilise only the generally available climatic data, he dropped the humidity term. He assumed that the air temperature has a positive correlation with net radiation, which acts as the energy source for P.E..

Mather (1954) felt that Thornthwaite's P.E. values are underestimates in winter and overestimates in summer. Van Wijk and De Vries (1954) reported that Thornthwaite's formula gives good results in similar climates, where it was developed, but values obtained for semiarid climates are very low. Thornthwaite's formula is fairly good for humid regions or seasons, but not suitable for dry conditions. Chang (1968) enumerated five weaknesses of Thornthwaite's method a) temperature is not a good indicator of energy available for evaporation b) since air temperature lags behind the radiation, Thornthwaite's estimates also show a lag in relation to the measured values of P.E. c) according to Thornthwaite, evaporation will stop when mean temperature is below zero degree centigrade d) wind effects are not considered e) formula does not take into consideration the effect of warm and cold air advection.

Even though these limitations to Thornthwaite's equation exist, it is widely accepted among the researchers in various fields. According to Penman (1956), Thornthwaite's formula is quite acceptable, considering its simplicity and limitations. After evaluating Thornthwaite's method Pelton et al. (1960) pointed out that the high mutual correlation of both mean temperature and evapotranspiration to net radiation can be used advantageously for estimating monthly, seasonal and annual P.E. values, but not for short periods. Bailey and Johnson (1972) remarked that noticeable error in Thornthwaite's estimates occurs in tropics where annual march of temperature is controlled more by cloud variations than the insolation received, and in the midlatitudes, P.E. estimates are reasonable except near the glacial limits. The method is internally consistent over a wide range of annual heat indices, 17 to 146, rather than the range 25 to 140 suggested by Thornthwaite and Mather (1955). In the studies of Krishna Kumar and Rakhecha (1986) on the harmonic analysis of P.E. calculated using Penman's equation in comparison with Jagannathan's (1957) work on temperature, they inferred that monthly air temperature is highly correlated to P.E., which is the basic assumption of Thornthwaite's P.E. estimates.

There are many reviews about various approaches and their limitations to estimate P.E., such as Mather (1954), Deacon et al. (1958), Thornthwaite and Hare (1965), W.M.O. (1966a), Tanner (1967), Cowan (1968) and Kakde (1985). Various studies suggest that in spite of some limitations the values derived from the Thornthwaite's formula are not very much different from measured values and it is not improper to use the formula for estimating P.E. on a monthly basis, where actual measurements are lacking. The detailed instructions and tables to compute P.E. values using Thornthwaite's method are given by Thornthwaite and Mather (1957) and Subrahmanyam (1982).

2.1.4 Concepts of Water Balance:

Water balance or water budget is a monthly or daily comparison of water supply in the form of precipitation with the water demand or P.E., where the soil moisture acts as a sort of reserve available for use to a limited extent for the purpose of evapotranspiration during periods of water shortage. The book-keeping procedure of water balance, based on such a comparison, provides comprehensive information on many parameters such as amount of water stored in the soil, actual evapotranspiration, water surplus, water deficit, surface flow and underground flow at a place in a quantitative manner. Since measurement of these parameters, especially A.E. and soil moisture, are not generally feasible due to technical and economical difficulties, the book-keeping procedure of water balance is extensively used in various fields.

Whenever Precipitation (P) exceeds Potential Evapotranspiration (P.E.), the soil moisture gets recharged and when the soil moisture storage exceeds the field capacity of the soil, water surplus occurs. This latter parameter is of interest to hydrologists who are concerned with careful conservation and efficient utilisation of available water resources. The water surplus either percolates downward and adds to the groundwater storage, produces subsurface flow and underground flow or produces surface runoff from that area, which adds to streams, rivers and finally, to the oceans. In such cases, when precipitation equals or exceeds P.E., evapotranspiration attains its potential rate, which implies that A.E. and P.E. are equal. However, when P.E. exceeds precipitation, evapotranspiration cannot be at the potential rate, the stored soil moisture gets depleted and there will be a deficiency of water, which is a parameter of vital importance to agriculturists. When the water deficiency becomes large with respect to the water need, the climate becomes progressively drier or more arid. On the other hand, the climate becomes more humid when large amounts of water surplus occurs. When precipitation equals P.E., the water is available for use just as needed: there is neither water deficiency nor water surplus.

In the earlier stages of development of the book keeping procedure of water balance, Thornthwaite (1948) assumed that soil can hold a maximum of 100 mm moisture as a storage in the root zone, and the moisture would be removed at a rate equal to potential water need as long as any storage remained. But Thornthwaite and Mather (1955) modified this concept with a more realistic approach in such a way that the general root zone of the normal soil can hold an average of 300 mm of water and the amount of water that can be drawn from the soil is proportional to the amount of water in the soil: when water retained in the soil gets depleted, the amount of water that can be drawn is also reduced.

Even before these water balance concepts were put forth, there were different attempts based on different techniques and empirical formulae to establish rainfall-runoff relationships, as that of Khosla (1949). Subba Rao and Subrahmanyam (1961) conducted a comparative study of runoff from river basins, estimated using Thornthwaite's modified approach and Khosla's formula with the measured values. They found agreement on annual basis between measured and computed values according to both the methods. But on a monthly basis, wide divergence was observed according to Khosla's method. They pointed out that this was due to the fact that Khosla had considered neither moisture holding capacity nor detention factor in his estimation.

Actually, the water holding capacity depends on various factors such as soil type and structure and the type of vegetation growing over the surface and so it is very difficult to get a clear information about this parameter. A sandy soil will hold less moisture than silt or clay of the same depth, but at the same time different species of vegetation will send roots down into soils to different depths. Soil with vegetation having deep roots will hold more amount of water in the root zone compared to soil with shallow root zone, but the same plants will send the roots to different depths in different types of soil. Thus, in a sandy soil, the plants tend to be more deeply rooted than in silt or clay soils. So, the depth of water available to the roots of the matured plants is not very much variable. Since the measurements of this quantity are not available in most places, they have to be estimated from the knowledge of soil and plant characteristics. Thornthwaite and Mather (1957) described the different provisional water holding capacities with different combinations of soil and vegetation types.

Thornthwaite and Mather (1955), in the book keeping procedure of water balance, evaluated monthly runoff from surplus values. In the absence of detailed field investigations, they assumed that half of the water surplus appears as runoff in the same month and other half is detained in the soil as detention water and contributes to the next month's surplus. But this is valid only when the surface is flat, semipervious and devoid of vegetation. Subba Rao (1958) changed this runoff coefficient to suit Indian conditions and suggested that two thirds of the surplus becomes surface runoff and the remaining part is detained. Subrahmanyam and Pardhasaradhi (1980) and Subrahmanyam and Ali (1982) developed new runoff coefficients based on slope of the surface, soil type and vegetation pattern of the region. The runoff coefficient of a station is the product of slope, soil and vegetation factors and the detention coefficient is the complement of the runoff coefficient. Nair (1987) adopted the coefficients of Ali (1982) for studying the water resources of Western Ghats.

Palmer (1965) had a different opinion about Thornthwaite's assumption of exponential depletion of soil moisture. He considered the effective soil as two layers, a surface layer and an underground layer. The surface layer is assumed to hold 25 mm of available moisture at field capacity and the underlying layer, a certain quantity depending upon type of soil. According to him, surface layer gets recharged or desiccated first and only then the underlying layer, and the moisture loss from the surface layer is at a potential rate while from the underlying layer, it is at an approximately exponential rate.

Thornthwaite (1948) and Thornthwaite and Mather (1955) had assumed that all the detention water is added to the next month's surplus without any provision for underground flow. But Subrahmanyam and Ali (1982) modified this approach by including the aspect of underground flow and extended this to determine groundwater flow and total discharge. Depending on runoff coefficients, a part of the monthly water surplus will produce surface runoff or surface flow, and the excess monthly water surplus over surface flow has been considered as recharge to previous month's groundwater storage. A portion of this total groundwater slowly flows out as underground flow depending upon the underground characteristics of the area, and the remaining part is available as ground water storage. Since underground flow is relatively small and slow, compared to surface flow, 40% of the runoff coefficient has been considered as coefficient of underground flow, as a uniform coefficient for the evaluation of the underground flow based on experimental evidences. The total discharge of every month is the sum of the surface flow and the underground flow corresponding to that month.

Theoretically, the amount of water recharged to the groundwater will emerge as total groundwater flow and the discharge will be equal to the total surplus on a climatic basis. Barry (1969) reported that groundwater contributes on an average 30% of the runoff, although within the geographical zone, this proportion varies considerably and for all continents, the average annual runoff is approximately 27 cm.

On a climatic basis,

Precipitation = A.E. + Water surplus 2.1

P.E. = A.E. + Water deficit 2.2

Groundwater recharge = Underground flow 2.3

Water surplus = Surface flow + Groundwater recharge 2.4

Water surplus = Total discharge 2.5

Total discharge = Surface flow + Underground flow 2.6

Equations 2.1, 2.3, 2.5 are strictly valid only on a climatic annual basis, but other equations are valid not only for climatic monthly values but also for year-wise monthly values. Due to the processes of soil moisture accretion and depletion, the first equation is not valid on a monthly basis, except when the soil is at field capacity. The depletion and recharging of groundwater compensates each other on a climatic basis, but it will not be true in individual years or for months on a climatic basis. Underground flow originates from the total groundwater storage and will be present, even if there is no surplus in any one of the months.

Water balance of more than 240 climatological stations of India and vicinity were worked out by Carter (1954). This concept of water balance was introduced in India by Subrahmanyam (1956a), and he used the derived parameters of water balance for climatic classification of India. Subrahmanyam (1956b) mapped the annual values of surplus and deficits over India using modified book-keeping procedure. A comparison of values derived from 1948 and 1955 methods have been worked out for the Indian region by Subrahmanyam et al. (1965). Kayane (1971) presented distribution of water balance components over monsoon Asia and observed that greater part of moist monsoon Asia suffers from water deficits in the dry season. Sarma and Narayana Swamy (1986b) conducted a comparative study of water balance parameters over Visakhapatnam derived using modified book-keeping procedure by using different potential evapotranspiration values, estimated from T hornthwaite (1948), Penman (1948), Khosla (1951) and Christansan (1968). They concluded that Thornthwaite's method presents high water deficits and low water surpluses for most of the years compared to other methods.

2.1.5 Applications of Water Balance:

The information thus provided by the water balance technique is of high utility in different fields. Subrahmanyam (1972, 1982) has described applicability of this approach in various aspects such as climatic classification, agriculture, hydrology etc..

a) Climatic classification:

The basic idea behind climatic classification is to provide a concise description of various climatic types in terms of effective factors, which are primarily related to heat and moisture. The validity of any climatic classification depends upon the accuracy with which climatic regions can be identified and demarcated and the rationality of numerical parameters employed to define these boundaries. Koeppen (1900) made a major advance in climatic classification by his novel idea, that plants can serve as meteorological instruments, capable of integrating the effects of various climatic elements and enabling the climatic region to be classified in terms of vegetation. But his classification lacked the rational basis for the limiting values of temperature and precipitation.

Thornthwaite (1948) in his rational classification used the efficiency of temperature and effectiveness of precipitation for the growth and development of natural vegetation. The dryness and wetness of a station can be evaluated by comparison of water deficit and water surplus with water need. By definition

Aridity Index I_a (%) = (water deficit/P.E.) * 100

Humidity Index I_h (%) = (water surplus/P.E.) * 100

Thornthwaite incorporated water surplus and water deficit in relation to water need on an annual basis in the definition of another parameter, the Moisture Index, which is given by

Moisture Index I_m (%) = ((water surplus-water need)/P.E.) * 100

He used this index for classifying the moisture regime of climate. Various limiting values have been assigned by him to the moisture index for different climatic types - negative values indicate dry climates and positive values indicate moist climates. Carter and Mather (1966) later modified these limiting values in the case of dry climates. In the thermal regime he has used the numerical value of P.E. as an index of thermal efficiency. The moisture regime of climates are again subclassified based on aridity and humidity indices and thermal regimes are subgrouped using summer concentration of thermal efficiency. The budgeting scheme which is the root of this classification has rational concepts and criteria from the thermal as well as the moisture regimes.

Subrahmanyam (1956a) used the 1948 scheme of Thornthwaite for studying the climate of India. Subrahmanyam (1956b) discussed the water balance of India and vicinity according to the 1955 scheme. Subrahmanyam (1958) concluded that in most parts of India, Thornthwaite's scheme of classification holds good in the case of the general pattern of vegetation as reported by Champion (1936). Monsoon climates of the world, in general, and of India in particular, were delineated from the point of view of agriculture and vegetation by Subrahmanyam and Ram Mohan (1980) using the Index of Moisture Availability (I_{MA}) defined as the ratio of A.E. for any individual month of an year to the average monthly value. Subrahmanyam and Ram Mohan (1984) presented the climatic map of India and surroundings. Ram Mohan and Maria Juliet (1986) modified the criteria in classifying the monsoon climates of the world and found that there is general agreement with the categorisations suggested by others.

All these studies on the water balance of India point to the fact the country has a wide spectrum of climates, some regions having water surpluses and others having large deficiencies.

b) Agriculture and Irrigation:

Increasing population in recent decades and the resulting demands on food production have led to vigorous attempts at optimal exploitation of water resources at all possible areas. Scientific and rational approaches to improve agricultural production require a sound knowledge of climatological techniques. In agricultural planning, detailed information on soil moisture status such as absolute moisture content, its seasonal variation, duration and magnitudes of moisture deficiency and surplus etc.

are very essential and can be evaluated from the water balance procedure. Since routine measurements of these parameters have many technical and economic difficulties, the water balance approach, especially for short periods such as a week or a day, is a very powerful tool for practicing scientific irrigation.

The irrigation need of a region can be assessed from the water deficit parameter of water balance, while the water surplus indicates the irrigation potential. This procedure not only indicates when the moisture is needed but also recommends how much water is essential, so that the time and the amount of irrigation scheduling can be adjusted. It also makes clear whether the surplus in other seasons permits sufficient water accumulation to provide essential irrigation during the following dry periods. The values of A.E. or P.E., separately do not give adequate idea about the suitability of the region for agricultural development. Subrahmanyam et al. (1963) introduced the Moisture Adequacy Index (I_{ma}) defined as the ratio of A.E. to P.E. to provide objective indication of the moisture status of the region in relation to the water need and mapped the distribution of this index over the country in relation to distribution of a few agricultural crops. Moisture Availability Index (MAI) introduced by Hargreaves (1975) defined as the ratio of dependable precipitation at 75% probability level to P.E. is helpful in planning for agricultural development.

Plant phenology is another field, that has direct application of water balance concepts. Krishnan (1971) classified the moisture availability periods into two categories as growth period with little water stress when A.E. > P.E./2 and growth period with moderate water stress when P.E./4 < A.E. < P.E./2. He suggested that the first moderate water stress period is suitable for sowing and later one is for ripening and harvesting. So, by knowing the stress periods irrigation can be adjusted or a suitable type of vegetation can be selected. Such a study on the basis of weekly moisture availability has been carried out by Subramaniam and Rao (1986). Rao and Nair (1986) investigated the correlation of monthly water surplus with various phenological phases of rice crop and found that a negative correlation exists between water surplus with seedling and flowering phases.

c) Drought Climatology :

Droughts are one of the most severe natural hazards to man and even today with advanced science and technology, they remain an example of man's helplessness against nature. In a country such as India, whose economy depends mainly on agriculture, frequent occurrences of droughts can cause widespread famine and distress.

The term 'drought' has different connotations in different contexts. Thornthwaite (1947) suggested that drought can never be defined in terms of rainfall shortage alone, since this does not take into account either the water need of the region or the important role of soil moisture. According to the water balance concepts, drought is a situation when water need of a region exceeds the amount obtainable from the precipitation and soil moisture storage. So the water balance approach can be considered to be realistic and rational in drought analysis. Subrahmanyam and Subramaniam (1964), Subrahmanyam (1967) and Subrahmanyam and Sastri

(1968) realised that the aridity index (I_a) is a powerful parameter in drought studies. According to them, the years of drought and their intensity can be assessed from the study of departure of I_a from the mean or median value for the station. Subrahmanyam and Sastri (1969, 1971), Ram Mohan (1978) and many others adopted this technique for drought classification.

Successive charts of water deficiency anomalies at close intervals depict movements of drought zones, which have been termed as "spread of drought", and such studies give indication of occurrences, intensification and dissipation of droughts. Incidence and spread of continental droughts have been analysed by Subrahmanyam (1967), the origin, spread and dissipation of droughts in N.W. India by Sastry and Malekar (1979) and droughts in Tamil Nadu by Ram Mohan (1978). The technique of cumulative deviation of water deficit gives the duration and intensity aspects of drought. The cumulative deviation technique has been employed to delineate and categorise the intensity and duration of drought spells on a small time scale for individual stations by Ram Mohan et al. (1983). Ram Mohan (1984) utilised the percentage departure of index of moisture adequacy from climatic normals to categorize droughts from the agricultural and ecological point of view. Climatic shifts due to change in the moisture regime of climate can be studied by the variation of the moisture index; such a study has practical value in the assessment of the climatic stability of the region. Such shifts of climates, though temporary are of great interest to the ecologist in assessing the impact on vegetation. Trend analysis of aridity and humidity can give more insight about the change in climatic regimes (Subrahmanyam and Subramaniam (1964), Sarma and

Ravindranath (1986) and Sarma and Narayana Swamy (1986)).

Various aspects of droughts in Andhra Predesh have been studied by Subrahmanyam and Sastry (1970), George (1970), Subba Rao (1973), Rakhecha (1973) and Subrahmanyam and Hemamalini (1979a, b). Drought climatology of N. India, Assam and vicinity, Tamil Nadu and vicinity and Karnataka were analysed in detail by Rama Sastri (1973), Bora (1976), Ram Mohan (1978) and Barai and Naganna (1979) respectively. The aridity and droughts, in different climatic zones of India, using different techniques have been studied by Subrahmanyam et al. (1974).

d) Appraisal of Water Resources:

Information on the water surplus is fundamental to many hydrological studies, which deals with runoff to streams and rivers, recharge of ground water etc., which could only otherwise be obtained from extensive stream gauge installations and detailed well records. These parameters are important for development of river basin for the purpose of water supply, power generation, irrigation, flood control, drainage etc.. Subba Rao and Subrahmanyam (1961) estimated the yields from river basins in peninsular India. Yields from Godavari river basin have been assessed by Subrahmanyam et al. (1970). Subrahmanyam and Pardhasaradhi (1979) examined the ground water potential over dry climates of India and Subrahmanyam and Pardhasaradhi (1980), later evaluated the water potential of peninsular India. Rational assessment of water resources of the Godavari river basin and Tamil Nadu region were carried out by Subrahmanyam and Ali (1982), Ram Mohan (1984) respectively. Water potential of Western Ghats and South India were investigated by Ram Mohan and Nair (1986a) and Ram Mohan et al.

(1986) respectively. Water resource development with respect to Kavery river basin was studied by Venkatesh (1986) using water balance models.

e) Soil Tractionability Studies:

During the periods of water surplus, problems arise with respect to movement of animals and vehicles over unpaved surfaces. An increase in soil moisture content above field capacity in clay soils will result in a loss of bearing capacity and shearing stress, which results in decrease of tractionability. On the other hand, the reverse is true in sandy conditions: there the tractionability improves with soil moisture content till quicksand condition is reached. So the soil moisture content is the most important factor in determining tractionability. A knowledge of the variation of this factor through time at a place can determine the temporal variation of tractionability. The water balance method does provide a means by which soil moisture can be determined easily from readily available climatic data, but for a precise evaluation of this parameter, other aspects such as slope of the surface, surface cover, structure and texture of the soil, etc. are to be measured.

f) Oceanographic Studies:

In oceanographic study, the water surplus, a derived parameter of book-keeping procedure of water balance, is important in determining the amount of fresh water flow from the land to the oceans. This is particularly significant in case of bays, estuaries and seas which are almost entirely landlocked. The volume of freshwater runoff to the water bodies is important in determining the salinity, density and other characteristics of the sea water.

g) Continentality Studies:

Continentality is a climatic feature of a station located in the interior or strongly influenced by vast continental territory. The summer concentration of thermal efficiency (SCTE) introduced by Thornthwaite in connection with climatic classification can be used for continentality studies. Subrahmanyam (1957, 1963) conducted such studies of thermal continentalities with special reference to India. A derived parameter of moisture adequacy index known as Index of seasonal moisture effectivity (ISME) was used for continentality studies by Subrahmanyam et al. (1980). Continentality aspect of Indian subcontinent and the anomalies of thermal Continentality in wet and dry years for south Indian region have been investigated by Sachi Devi (1982).

2.1.6 Climatological Time series:

Weather and climate over the earth are not constant with time: they change on different time scales ranging from the geological to the diurnal through annual, seasonal and intra-seasonal time scales. Such a variability is an inherent characteristic of the climate.

Like other aspects of atmospheric behavior, the fluctuations in climate are also of great complexity. The study of climatic fluctuations involves description and investigation of causes and effects of these fluctuations and their statistical interpretation. Much of the work done in the past is about variability of the two important meteorological parameters, the rainfall and temperature.

It is observed that many of the fluctuations are not randomly distributed around a constant normal. In fact, there are variations in the normal itself, may be in the form of a trend or periodicity. The periodic phenomena reproduce themselves regularly and hence have predetermined period and phase. Quasi-periods are less regular and non-periodic phenomena are random fluctuations.

Large day-to-day changes may cause little trouble, but abnormalities of larger periods disrupt orderly planning. Such abnormalities sometimes prolong themselves for years, even decades as the Dust Devil period of 1930s in N. America and Sahelian drought of 1968-1973 in Africa. This type of prolonged fluctuations, even with minor amplitudes, can impose cumulative influences on water resources, agriculture, forestry, fisheries and probably on a number of other aspects of world economy.

In order to study long term climatic variability, continuous reliable data is required. Since detailed weather records obtained from direct measurements are available for may be a little of more than a century only, we have to rely on proxy evidences, that is on the records of weather-related effects that have been preserved, such as tree rings, ocean sediments, pollen sequences in bogs and lakes etc. which can give information about climates of the past. Such studies reveal the existence of various epochs such as Medieval warm phase of 800-1200 A.D., Little Ice Age of 1500-1850 etc..

Availability of observed data for the last one or two centuries helped us to understand more details about climatic fluctuations. More details about inter-annual variability is given in latter sections. Seasons are very much part of the climate and the seasonal variations are periodic, being controlled by the orbital movement of the earth around the sun and the tilt of the earth's axis. Similarly, diurnal variations of many meteorological parameters are periodic, controlled by rotation of the earth on its axis. Since the seasonal and diurnal variations account for a dominant proportion of overall variability within the cycle, these effects should be removed before investigating variabilities arising from other causes.

It is observed that there are oscillations of climatic parameters on an intra-seasonal basis during the monsoon period. A quasi-periodicity of 4-6 days has been observed by Misra (1973) in pressure values, and by Bhalme and Parasnis (1975) in pressure gradients. Krishnamurti and Bhalme (1976) studied the various elements of monsoon system such as pressure of the monsoon trough, pressure of Mascarene high, cross equatorial low level jet, Tibetan high, tropical easterly jet, monsoon cloud cover, monsoon rainfall, dry and moist static stability and found the existence of a quasi bi-weekly oscillation (14 $\pm$ 2 days) in almost all elements, and they also observed spectral concentration of 4-5 days. Murakami (1976, 1978) observed 5 day and 15-day oscillations in the pressure and motion fields of summer monsoon over India.

During the last decade there have been many studies on the 30-50 day mode of the monsoon. The zonal components of wind, cloud and rainfall exhibit this mode of oscillation. Madden and Julian (1971) observed a 30-50 day oscillation in zonal wind over equatorial region. Using satellite pictures, Yasunari (1979, 1980) and Sikka and Gadgil (1980) found a 30-50 day northward propagation in cloudiness; Krishnamurti and Subrahmanyam (1982) also observed this mode in the zonal component of wind over India.

Kasture and Keshavamurty (1987) observed a concentration of spectral density of about 30- 50 day period for all stations in the u-component of wind at all standard levels in the troposphere in almost all years. An inter-annual variability for this oscillation is observed by them, and the period of this oscillation is somewhat longer in drought years, than in the normal years.

Active and break cycles of monsoon activity on the intra-seasonal time scale have been well experienced in the Indian summer monsoon. These breaks appear to be in two cycles, either of 10-12 days or of 40-50 days duration (Feins and Stephens, 1987). Joseph and Pillai (1988) observed an intra-seasonal variability with the 30-50 day mode in the cyclogenesis in the equatorial trough and in the monsoon rainfall. Keshavamurty et al. (1988) concluded that northward movement of this 30-50 day oscillation in the Indian monsoon region appears to be controlled by the basic zonal wind profile and convective activities.

Annual rainfall shows high variability on an inter-annual basis. Monsoons have large inter-annual variability in the quantum of monsoon rainfall and in the dates of onset and withdrawal. Extremes of variation of rainfall result in floods and droughts, severe economic stresses of many countries have been known to be due to these abnormalities. But studies show that most of the severe droughts and floods are normal to the climate, in the sense that they have occurred before, and presumably will occur again. They are inevitable consequences of the year to year variability, and need not imply a climatic change. The fact is that such hazards are hitting a world of increasing population, where the demands for food and settlement have been rising severalfold and hence adverse impacts are becoming severe.

The existence of periodicity in annual rainfall implies that wet and dry years may recur with a certain regularity and long term periodicity implies that wet and dry years tend to persist for a few years. A general review of investigations about cyclic behaviour in the atmosphere is given by Lamb (1972). Stringer (1972) reported that atleast 35 quasi-periods with more than one year in length have been discovered in records of pressure, temperature, precipitation, and extreme weather conditions over many parts of the earth surface, even though the physical aspects behind this tendency is not fully explored. A very common quasi-periodic oscillation is the quasi-biennial oscillation (QBO), in which the climatic events recur every 2 to 2.5 years. This phenomenon was first observed in stratospheric winds in low latitudes, but later Landsberg (1962) and Landsberg et al. (1963) established the existence of QBO as a worldwide phenomenon in surface meteorological parameters also. This QBO in Indian rainfall has been first reported by Koteswaram and Alvi (1969), latter many others also reported this phenomena in Indian rainfall (Bhargava and Bansal, 1969, Jagannathan and Bhalme, 1973, Parthasarathy and Dhar, 1974). Existence of QBO in other climatological time series such as annual frequencies of cyclonic disturbances in Bay of Bangal (Bhalme, 1972), mean annual temperature (Jagannathan and Parthasarathy, 1973), drought indices (Parthasarathy and Rakhecha, 1972) are also reported.

The solar cycle, the oscillation of 8 to 15 year period, is generally observed in many meteorological parameters. Sen Gupta (1957) showed a negative correlation between sunspot activity and rainfall amounts in Tamil Nadu. Reddy et al. (1979) found that there is a correlation between sunspot activity and rainfall amount during south-west monsoon season, but not during north-east monsoon. Jagannathan and Bhalme (1973) showed a positive relationship with sunspot and south-west rainfall at a number of subdivisions, especially along foothills of Himalayas. Bhalme (1975) found that breaks in monsoon are more during sunspot maxima while storms and depressions are less. Studies of Bhargava and Bansal (1970a, b) on the correlation of sunspot cycle with temperature and of Mukherjee and Singh (1978) with rainfall show that correlations have been found to have spatial and temporal modulations. Koteswaram and Alvi (1970) observed a negative relationship between rainfall and sunspot in west coast stations, particularly Cochin and Trivandrum. Ananthakrishnan and Parthasarathy (1984) observed a negative relationship between sunspot and rainfall in south eastern parts of Indian Peninsula and a positive relationship in other parts of Peninsula. According to Hare (1979), increased sunspot activity does not significantly alter the total energy received from the sun, and does not lead to changes in ultraviolet and particle emissions.He pointed out that many correlations have been established between short climatic series and sunspot numbers, but these often disappear when longer records are inspected; the phase difference in many cases shows that many are only chance correlations. Koteswaram and Alvi (1969), Parthasarathy and Dhar (1974) reported the influence of solar cycle in Indian rainfall.

Time series of rainfall of various parts of the world such as West African Sahel (Bunting et al., 1976), East Africa (Rodhe and Virji, 1976), South Korea (Cho, 1978), Malayasia and Singapore (Hu and Lim, 1978), N.E.

Brazil (Kowsky and Chu, 1978), Mauritious (Pathack, 1982), Sri Lanka (Suppiah, 1986) have been studied for trend and periodicity aspects. This fluctuations aspects of rainfall of various parts of our country such as Maharashtra, Madhya Pradesh, Narmada catchment have been analysed by Ragavandra (1974), Parthasarathy and Dhar (1976b), Ramana Murthy et al. (1987) respectively.

2.1.6.1 **Causes of variability:**

The variability of the climate may be due to external forces, such as passage of solar system through the galaxy, varying orbit and wobble of earth in relation to the sun, action of geologic processes such as continental drift, mountain building, volcanic activity etc., changes in solar radiation by solar activities or due to the internal dynamics of atmosphere, ocean and biosphere. In general, the external factors cause long term effects, while the internal mechanisms are more important in year-to-year fluctuations.

There are two categories of mechanisms responsible for interannual variability: a) changes in the internal dynamics, that is changes in the intensity of mean circulation of the atmosphere or ocean or due to shifts in location or timing of these circulation systems and b) changes in the boundary conditions, which includes changes in sea surface temperature, soil moisture, snow cover etc.. Charney and Shukla (1981) suggested that the Asiatic monsoon system is a dynamically stable one but its inter-annual variability is largely determined by slowly varying boundary conditions.

The environment is getting modified since several thousand years and some of these modifications affect the climate. There is ample evidence that local and regional climates can be modified by man. There is, however, no experimental evidence to demonstrate that global climate has been affected by human activities, but there may be modifications, which remains undetected because of the greater natural variability of the climate. There are three ways by which man can affect the climate:-

a) By changing the composition of the atmosphere: Man modifies the atmosphere by emitting gases and particles in the processes of power generation, industrial activities, transportation, agricultural activities etc.. The particles and gases may affect the climate by changing the radiation balance, modifying the thermal structure, upsetting stratospheric photochemical ozone budget, disturbing cloud condensation nuclei population etc.. The atmospheric gas that has been most widely suggested as cause of climatic changes is CO_2, but other gases such as water vapour, chloroflurocarbons, methane, NO_2, etc. contribute to the green house effect. Many of the current estimates show that there is a potential problem of warming of the lower atmosphere due to the increasing concentration of greenhouse gases. Munn and Machta (1979) stated that the various environmental effects of global warming are 1) altered evaporation and precipitation regimes, although the location cannot be predicted, it is very likely that there will be regional differences and some areas may show a decrease while some others increase in rainfall, 2) recession of snow lines and recession and disappearance of mid-latitude glaciers. 3) warming of polar regions which could disturb the oceanic circulation with consequent reduction in the upwelling processes, which are very important to fisheries. However Plass (1972) has pointed out that, 1% increase in cloudiness in the troposphere could compensate for any temperature rise that might result from CO_2 increase upto the year 2000.

b) By releasing heat into the atmosphere: This is mainly from power plants, industrial activities, moving vehicles, domestic activities, etc.

c) By changing the physical and biological properties of the underlying surface : Deforestation, urbanization and construction of hydroelectric, irrigation and drainage projects are the major human activities in this group. According to Baumgartner (1966), the net radiation over forests is relatively high in comparison with other vegetation covered areas or bare soil surfaces. Due to the radiation intercepted by forest, the vertical temperature gradient will be less over the forest area, which results in less outgoing radiation and also reduced evapotranspiration. The albedo of the forest cover is low which means high absorptivity. Forest cover has a significant role in energy transfer (Lettau, 1969) - the sensible heat transfer will be small and latent heat transfer will be high in a forest area. Moltschanov (1966) has shown that the runoff precipitation ratio (runoff/precipitation) in forest areas is comparatively low and that in the southern USSR the runoff ratio is 18% in the forest area, against 42% in open area. Baumgartner (1979) has demonstrated that the forest cover is one of the roughest earth-atmospheric interfaces: it is observed that the roughness parameter is 300 cm. in the forest against 0.2 cm over sand. So deforestation disrupts the energy balance.

The radiation interception decrease causes a high vertical temperature gradient and increased outgoing radiation. Increases in the albedo of the earth surface mean reduction in absorptivity, reduction in net radiation over the earth surface, evaporation decrease, increase in the sensible heat transfer, and decrease in the latent heat transfer. As a net result, the Bowen's ratio (sensible heat/latent heat) increases. In the hydrologic cycle, an increase in the runoff ratio results in less retention and infiltration, the increased runoff causes high soil erosion, less concentration time, and more chances of flash floods. Decrease of roughness parameter results in reduced surface drag, energy dissipation, and turbulent exchange which may cause reduction in distribution of pollutants over the surface. The CO_2 balance will get disturbed and result in increased CO_2 over the earth surface.

Ravindran (1982) reported that there was a reduction in the forest cover in Kerala from 1940 which continued upto 1970; from then onwards there was development of forest due to the plantation crops and social forestry activities. According to him, the percentage areas of the forest cover in 1940, 1950, 1960, 1970 and 1980 were 33.6, 30.6, 26.2, 24, and 27% respectively.

Development of urban areas causes changes in different meteorological parameters such as albedo, roughness parameter and elements in hydrological parameters etc.. Heat released from industrial areas, vehicular transport, residential areas etc. change the temperature structure of the area. It is observed that the mean temperature over urban areas is more than the surroundings: such a formation is now popularly known as 'heat island'. The emission of heat and particulate matter from urban areas has been shown to affect the precipitation characteristic of the area. Callendar (1961) analysed temperature trends of urban areas in comparison with a few other stations to study the effect of urbanisation. Callendar found that the difference of mean temperature for the periods 1921-1950 and 1891-1920 for the 9 largest cities in western Europe was 0.42°C whereas this change for 14 rural areas covering almost same area was only 0.36°C. Landsberg (1970) noted that average changes in climatic elements of an urban region are more than in surrounding rural environments.

The ocean which covers about three foruths of the earth surface smooths out many man-made variations on the land. For example, the effect would have been very high by deforestation, in reducing evaporation, if we consider only the land areas on a global scale.

2.1.6.2 Impact of climatic variability:

We are very well aware about the year-to-year changes of the climatic parameters, especially the extreme conditions. The long term climatic change and resultant changes in the environment may have impacts on social, political and economical activities. According to Flohn (1978), if man's interference with climatic system continues like this, together with uncontrolled growth of energy use, sooner or later during the next century, the warming will overcome natural factors which usually produce cooling, resulting in the melting of polar ice. This could diminish the pole to equator gradient of temperature, and result in changes in circulation. Fukai (1979) studied the impacts of climatic variability on agriculture.

Knowledge of climatic variability is important for the design and operation of water resource systems. At the same time reservoirs are essential tools in controlling the effects of variability. Climatic variability has direct impacts on natural vegetation, land-use pattern, dairy production etc. The human comfort and adaption to climate will be disrupted by the climatic variability.

Succession of great extremes in temperature and precipitation during 1970's has created an impression that climate is becoming more variable, (Hare, 1979). There are suggestions that temperature variability is likely to be increased during periods of global cooling. The argument depends on the observed fact that when cooling occurs it tends to be greatest near the poles. This increases the pole to tropic temperature gradient and hence the atmospheric and oceanic circulations and results in long lasting disturbances; this creates the anomalies of temperature and precipitation.

Analysis of time trends of spatial and temporal standard deviation of air temperature in three latitude belts since 1959 by Angell and Korshover (1977) supported the view that the spatial and temporal variabilities of temperature have recently increased, as has the poleward temperature gradient. This argument is not fully validated still. Hare (1979) reported that there is no evidence that heavy rainfall frequency has increased in recent times.

2.1.6.3 Statistical Interpretation:

Since we are unable to explain fully the physical reasoning of the fluctuations, statistical analysis of climatological time series have been employed to get more insight about the problems of climatic variability.

A climatological time series may consist of wholly random variations, of wholly non-random variations, or of a sum of both random and non-random components. But from experience, we know that a major fraction of the variance of real climatological time series behaves as a random variable. But in some time series, the successive values of the series are not statistically independent of one another, owing to the presence of persistence; trends, cycles or some other non-random components. If we could detect some form of non-randomness in the series, we can look into further details to determine whether there is a trend in the time series, and, if so, whether the trend is linear, quadratic or more complicated.

There is no single statistical tool, that is uniformly efficient, identifying all possible alternatives to randomness in the time series. The power spectrum analysis is, however, very effective and sufficiently flexible to distinguish between different types of non-randomness and also amenable for direct tests of their statistical significances.

The power spectrum analysis otherwise known as generalised harmonic analysis is developed based on the premise that time series are not necessarily composed of finite number of oscillations, each with discrete wavelengths. But they consist of virtually infinite number of small oscillations spanning a continuous distribution of wavelengths. The spectrum, therefore yields a measure of distribution of variance in time series over a continuous domain of all possible wavelength, ranging from an infinite wavelength (linear trend) to the shortest wavelength that can be resolved by any scheme of harmonic analysis. This shortest wavelength is equal to twice the interval between successive observation in the time series. The main limitation of the power spectrum analysis is the absence of information about the phase characteristic of the fluctuations. But the application of suitably designed filters enables one to investigate the phase behavior of any suspected periodicity. Another disadvantage is that if exact periodicities are present in the time series, the spectrum does not necessarily represent them as clearly as classical harmonic analysis can. The third drawback of this technique is that if the series is dominated by a strong periodic variation as in the case of annual march of temperature, the spectrum can be significantly influenced at other wavelengths. But this can be overcome by pre-whitening the series.

WMO (1966b) suggested various powerful statistical techniques such as Mann-Kendall statistic, Student's t-test, low-pass filtering etc. to detect the presence and nature of trend in a climatic time series. The most likely alternative to randomness in the climatic time series is some form of trend which may be linear or nonlinear. So the test of randomness is a good method to check the presence of trend. The Mann-Kendall statistic test is a very robust test in the sense that the distribution need not be of Gaussian normal type.

The low-pass filtering suppresses the irregularities and the high frequency oscillations of the time series and is a simple but useful technique to understand the nature of the trend.

Some of these techniques have been employed to analyse fluctuation features in time series of various climatological parameters such as moisture index (Sarma and Narayana Swamy, 1986), annual rainwater over India (Mooley et al. (1981), Precipitation Concentration Index (Singh et al., 1988), onset of southwest monsoon (Reddy, 1977, Ananthakrishnan and Soman, 1988), cyclonic disturbances over Indian region (Bhalme, 1972), drought indices (Parthasarathy and Rakhecha, 1972), Palmer drought index (Rao et al., 1973), indices of flood and drought intensity (Bhalme and Moole, 1980), index of dryness over India (Mooley and Parthasarathy, 1983), monsoon deficiency index (Mooley and Parthasarathy, 1982).

The instrumentally observed temperature data of various parts of the world have been analysed. There is a general opinion that temperature is increasing. Mitchell (1963) and Lamb (1966) observed cold winter in the late nineteenth century, culminating in warmth in 1920-1930 and cooling in many areas by 1950 in the Northern Hemisphere. Damon and Kunean (1976) observed a general rise between 1943-1975 in the mean air temperature over Southern Hemisphere chiefly with respect to land.

Over the Indian region Pramanik and Jagannathan (1954) studied the secular trends in the annual mean maximum and minimum temperature and concluded that there is no general tendency for a systematic increase or decrease in the time series. Jagannathan (1963) and Jagannathan and Parthasarathy (1972) analysed the time series of mean annual temperature over Indian stations. Jagannathan and Parthasarathy (1972) observed a general increasing trend in many stations but a slight decreasing trend at Fort Cochin, and they observed quasi biennial oscillations in both annual and seasonal temperature in different parts of the country. Jagannathan (1963) observed a slight negative correlation with solar activity.

The fluctuations in rainfall is much more complicated than the temperature fluctuations on a global or even on a regional scale. In many parts of the tropics, there were decreases of annual rainfall of the order of 30% by 1900 (Kraus 1954, 1955a, 1955b, 1958). Seasonal precipitation totals may show quite different trends according to the systems responsible for producing rain (Kraus 1954). The variations in rainfall amounts in Africa and India had been of great concern during last two decades. Winstanley (1973a, b) reported that monsoon rains from Africa to India decreased by more than 50% from 1957 to 1970 and he predicted that the future monsoon seasonal rainfall, averaged over 5 to 10 years is likely to decrease to a minimum around 2030 A.D. and he arrived at a hypothesis that there is a southward movement of Sahelian and Rajasthan deserts. Tyson et al. (1975) concluded that the view that S. Africa is undergoing dessication is questionable. Recurrent droughts and wet periods are characteristic of the tropical areas.

There are large number of studies on trend and periodicity analysis of annual and seasonal rainfall of contiguous India, various sub-divisions and of various individual stations for differend periods (Jagannathan and Parthasarathy, 1971, 1973, Jagannathan and Bhalme, 1973, Parthasarathy and Dhar, 1974, 1975a, b, 1976a, Parthasarathy and Mooley, 1978, Saha and Mooley, 1978, Mukherjee and Singh, 1978, Parthasarathy, 1984, 1985).

2.2 Materials and Methods:

2.2.1 Precipitation studies:

The studies are based on the data recorded at 42 raingauge stations distributed randomly over the State. These stations include all Observatories of India Meteorological Department and 35 State Government raingauge stations (Fig. 2.1). Monthly rainfall data for the period 1931 to 1984 for all the stations have been collected from the records of the India

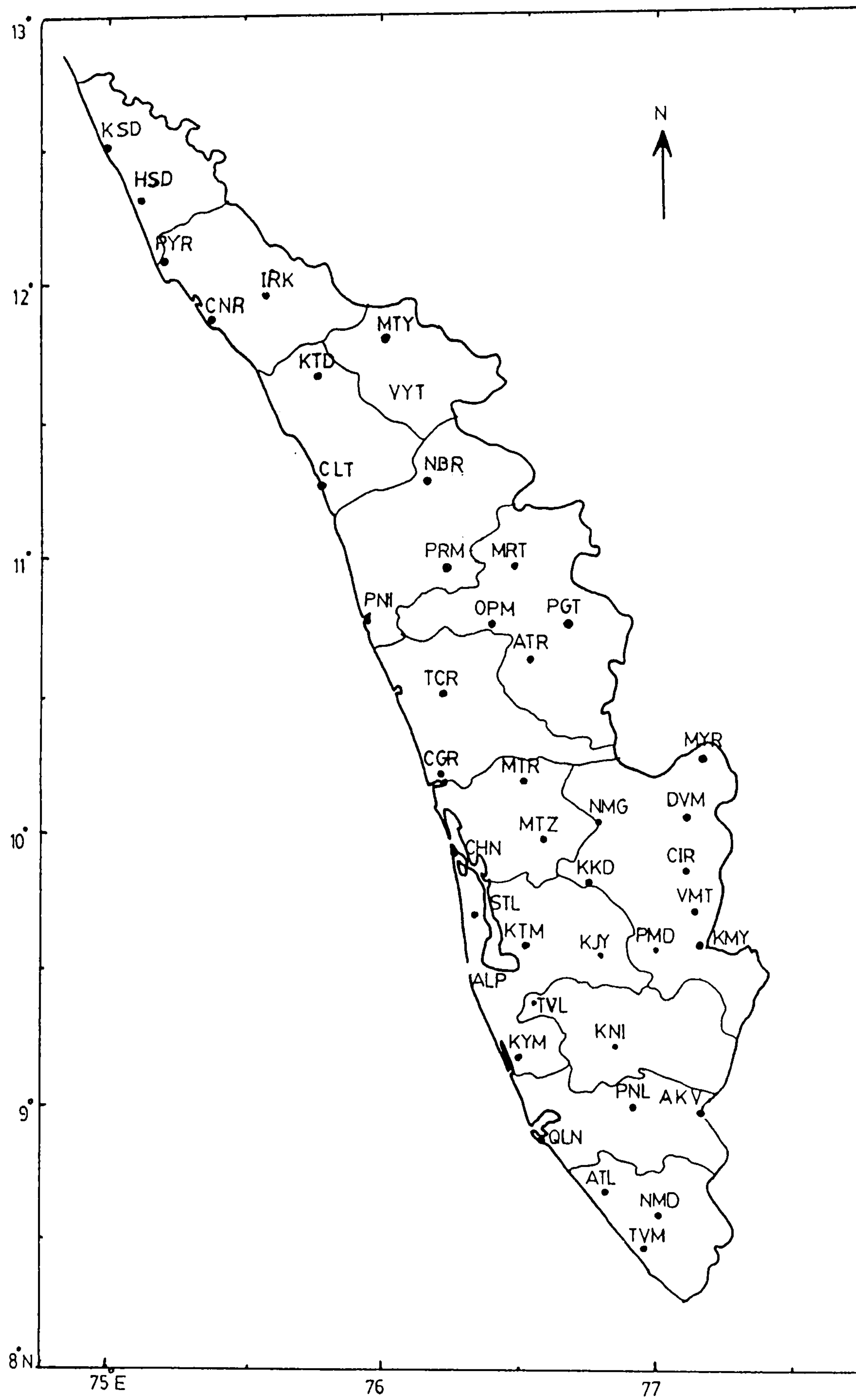


Fig. 2.1 Location of selected stations

Meteorological Department (IMD) office,Trivandrum and also from the records of the Board of Revenue, Government of Kerala, Trivandrum. The details of these stations and their periods of record are given in Table 2.1.

The missing values in these monthly rainfall records have been interpolated using the normal ratio method. Accordingly, any monthly rainfall PA of a particular station A, having corresponding normal monthly rainfall NA has been computed using the equation

$$PA = ((PB/NB) + (PC/NC) + (PD/ND)) \times NA/3 \qquad 2.7$$

where PB, PC and PD are the corresponding monthly rainfall values for three nearby stations and NA, NB and NC are the corresponding normal monthly rainfall values for the respective stations.

Seasonal and annual rainfall values have been calculated for each year for all the stations. Average rainfall, range, standard deviation, and coefficient of variation have been calculated on annual, seasonal and monthly bases for all stations using the data for a period of 50 years from 1931 to 1980. These average values have been taken as climatic normals and have been analysed.

The average climatic (normal) rainfall for the State as a whole has been computed using the climatic values of the 42 selected stations. In order to quantify the spatial variability of rainfall over the State, the coefficients of variation using the climatic normals of the selected stations have been evaluated, and denoted as 'spatial coefficients of variation', on an annual and a seasonal basis. The pockets of heavy rainfall and very heavy rainfall have been distinguished using the criteria $M + \sigma$ and $M + 1.5\sigma$ respectively, where M is the the mean

	Station	Abbreviation	Latitude ° N	Longitude ° E	Data period
1	Kasargode	KSD	12° 31'	74° 59'	1931 - 1986
2	Hosdurg	HSD	12 18	76 06	1931 - 1986
3	Payyannur	PYR	12 06	75 12	1931 - 1986
4	Irikkur	IRK	11 58	75 33	1932 - 1975
5	Cannanore	CNR	11 52	75 22	1931 - 1986
6	Manantoddy	MTY	11 48	76 01	1931 - 1986
7	Kuttiyadi	KTD	11 40	75 45	1931 - 1980
8	Vythiri	VYT	11 33	76 02	1931 - 1986
9	Nilambur	NBR	11 17	76 14	1931 - 1986
10	Calicut	CLT	11 15	75 47	1931 - 1986
11	Mannarghat	MRT	10 59	76 28	1931 - 1986
12	Perintalmanna	PRM	10 58	76 14	1932 - 1979
13	Ottapalam	OPM	10 47	76 23	1931 - 1980
14	Palghat	PGT	10 47	76 39	1931 - 1986
15	Ponnani	PNI	10 47	75 55	1931 - 1980
16	Alathur	ATR	10 38	76 33	1931 - 1986
17	Trichur	TCR	10 31	76 13	1931 - 1986
18	Marayur	MYR	10 16	77 09	1931 - 1980
19	Cranganore	CGR	10 13	76 12	1931 - 1986
20	Malyattur	MTR	10 12	76 31	1931 - 1976
21	Devikulam	DVM	10 04	77 06	1931 - 1980
22	Neriamangalam	NMG	10 03	76 47	1936 - 1973
23	Muvattupuzha	MTZ	09 58	76 35	1931 - 1972
24	Cochin	CHN	09 58	76 14	1931 - 1986
25	Chinnar	CIR	09 52	77 06	1931 - 1970
26	Karikode	KKD	09 50	76 40	1931 - 1986
27	Vandanmettu	VMT	09 43	77 08	1931 - 1980
28	Sherthala	STL	09 42	76 20	1931 - 1986
29	Kottayam	KTM	09 35	76 32	1931 - 1986
30	Kumily	KMY	09 35	77 10	1931 - 1970
31	Peermede	PMD	09 34	76 59	1931 - 1986
32	Kanjirapally	KJY	09 34	76 47	1931 - 1967
33	Alleppey	ALP	09 33	76 20	1931 - 1986
34	Thiruvalla	TVL	09 23	76 33	1931 - 1986
35	Konni	KNI	09 13	76 51	1931 - 1986
36	Kayamkulam	KYM	09 11	76 30	1931 - 1986
37	Punelur	PNL	09 00	76 55	1931 - 1986
38	Aryankavu	AKV	08 59	77 10	1931 - 1986
39	Quilon	QLN	08 53	76 36	1931 - 1986
40	Attingal	ATL	08 42	76 49	1931 - 1986
41	Nedumangad	NMD	08 36	77 00	1931 - 1986
42	Trivandrum	TVM	08 29	76 57	1931 - 1986

Table 2.1 - Details of rainfall stations and their record periods

and σ is the spatial standard deviation for that particular season or for annual values. The climatic normals for all the stations have been plotted on a seasonal and an annual basis and isolines drawn to get spatial distributions.

Normal weekly rainfall for the 26 IMD reporting stations has been analysed and variations of a few selected stations have been plotted.

2.2.2 Temperature and Evapotranspiration:

The monthly temperature data for all the seven IMD stations have been collected from Meteorological Office, Trivandrum, and their data periods are given in Table 2.2.

Station	Data period	Station	Data period
Trivandrum	1931 - 1980	Cochin	1931 - 1980
Calicut	1931 - 1980	Palghat	1943 - 1980
Alleppey	1944 - 1980	Punelur	1961 - 1986
Kottayam	1973 - 1986		

Table 2.2 - Details of temperature records

Average monthly temperature values for all these stations for the given periods have been calculated, and these values have been taken as the monthly normals for the analysis.

Potential Evapotranspiration (P.E.) for the above stations have been calculated on a monthly basis (climatic) using the formula of Thornthwaite (1948). According to this method, Unadjusted Potential Evapotranspiration (in cm),

$$UPE = 1.6\ [(10 * t)/\ I]^{a} \qquad 2.8$$

Where, t = mean monthly temperature in°C

$$I = \text{annual heat index} = \sum_{n=1}^{12} i_n \qquad 2.9$$

$$i_n = \text{mean heat index of } n^{th} \text{ month} = (t_n/5)^{1.514}$$

$$a = 0.49239 + 0.01792\ I - 0.0000771\ I^2 + 0.000000675\ I^3 \qquad 2.10$$

But when the monthly temperature is more than 26.5°C, another equation has been applied

$$UPE = -41.586 + 3.2233\ t - 0.043254\ t^2 \qquad 2.11$$

These unadjusted P.E. values have been corrected for day length and also for the number of days in a month using the tables given by Subrahmanyam (1982).

In order to work out the water balance for all the 42 stations, it is essential to compute P.E. values for all the stations. However, for stations where temperature data were not available, an interpolation technique has been applied to estimate monthly P.E.values (Ram Mohan and James, 1989). For this, mean monthly temperature data for 11 stations in and around Kerala State has been used. Correlation between heights of the stations and monthly P.E. values were examined and since these correlation coefficients were found to be statistically significant for all months, regression lines have been fitted. However, from the regression lines it was observed that the scatter was very large for high altitude stations, situated 1,500 m amsl., and hence such stations were omitted. From the fitted regression lines, rates of decrease of P.E. with height (lapse rate of P.E.) have been found out for all months. Since a uniformity was observed in lapse rates of P.E. of different months of the same season, regression lines have been fitted for different seasons (Fig. 2.2) and

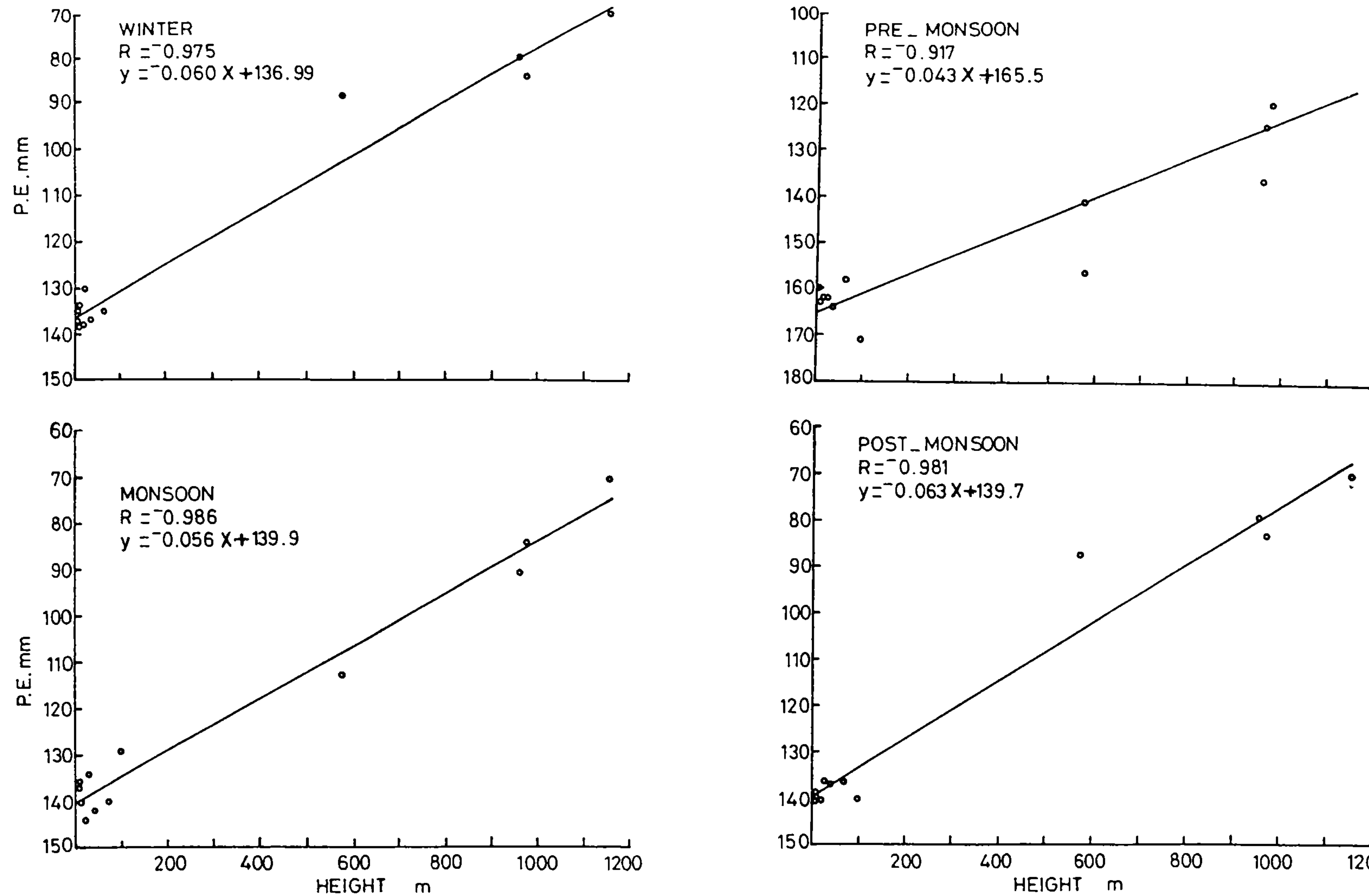


Fig. 2.2 Regression lines of average monthly P.E. with height for different seasons

average lapse rates of P.E. for the seasons have been evaluated and these values are given in Table 2.3.

Season	Correlation coefficients (r)	Lapse rates of P.E. $\gamma_{P.E}$ mm/100 m
Winter	-0.984	5.90
Pre-monsoon	-0.950	4.62
Monsoon	-0.991	5.72
Post-monsoon	-0.992	6.40

Table 2.3 - Correlation coefficients and lapse rates of P.E. for different seasons

The stations for which computed values of P.E. are available are taken as base stations. Using the calculated values of seasonal lapse rates, P.E. values for all 42 raingauge stations have been estimated from P.E. values of suitable nearby base stations. The base station is so chosen, that the height difference between it and the raingauge station is the least. If a base station has a height H_1 m and Potential Evapotranspiration $P.E._1$ mm, the Potential Evapotranspiration $P.E._2$ mm of another station having a height of H_2 m, which is nearby to the base station and has almost the same type of climate is given by the equation

$$PE_2 = PE_1 - (H_2 - H_1)\,\gamma_{P.E} \qquad 2.12$$

where $\gamma_{P.E}$ is the lapse rate of P.E..

When the estimates of P.E. values derived from the fitted lines were compared with the actual values (computed from temperature data), the differences were found to be less than 5% in 82% of cases and less than 8% in 92% of cases, while the maximum error was about 10%.

Using this procedure, P.E. values for all the stations which do not have the measured temperature data, have been interpolated on a monthly climatic basis. The seasonal and annual values of P.E. for all stations have been calculated and plotted separately for spatial distribution studies.

2.2.3 Water balance Studies:

The climatic water balances for all stations on a monthly basis have been worked out using the modified book-keeping procedure of Thornthwaite and Mather (1955). The third input for the water balance procedure apart from precipitation and P.E. is the field capacity (FC) of the station. Since there were no measured values of field capacities for all stations, their values have been estimated, based on provisional water holding capacities given by Thornthwaite and Mather (1957), using the soil type and vegetation characteristics. The soil type and vegetation characteristics of the stations have been identified using standard references (Department of Agriculture, 1978, Centre for Earth Science Studies, 1984, Public Works Department, 1974).

The monthly water need (P.E.) of each station has been compared with the water supply (P.). Whenever the water supply was not sufficient to meet the water need, the difference has been considered as the water loss, and if there were water losses in successive months, the accumulated potential water loss (APWL) has been calculated for each month. Using the accumulated potential water loss and the field capacity values, the soil moisture status has been computed on a monthly basis, using the formula

$$S = FC \times \exp\ (APWL/FC) \qquad 2.13$$

In such cases, the Actual Evapotranspiration (A.E.) is the sum of precipitation and the change of soil moisture content (ΔS) from the previous month. This change in soil moisture content is the soil moisture utilisation. In these months the A.E. will be less than the P.E., and this shortage is considered as water deficit for that month.

On the other hand, when precipitation is greater than P.E., the A.E. will be at its potential rate. The excess rainfall over water need recharges the soil; and when the soil moisture reaches its field capacity, the excess water is considered as the water surplus. In such months, there will not be any water deficit.

Using this procedure, A.E., water deficit and water surplus for all stations on a monthly basis have been computed. Water balance diagrams have been drawn to get qualitative as well as quantitative assessments of water surplus, water deficit, soil moisture utilisation and soil moisture recharge. From the monthly values, the seasonal and annual values of these parameters have been calculated and plotted for spatial distribution analysis.

The average values of these parameters for the whole State as a single unit and corresponding standard deviations and coefficients of variation on annual and a seasonal basis have been computed. These statistical parameters have been employed to delineate the regions of high and very high values or pockets over the State. Regions which have values more than the corresponding $M + \sigma$ have been termed as 'high' and those with more than $M + 1.5\sigma$ as 'very high', on both seasonal and annual bases. The percentage contributions of each season to the annual values for the State as a whole for all these parameters have been estimated. Monthly values of these parameters have been analysed for their extreme values.

The moisture adequacy index (I_{ma}) defined as

$$I_{ma}(\%) = (\text{annual A.E./annual P.E}) \; 100 \qquad 2.14$$

has been calculated for all stations and plotted for its spatial variation.

A comparison of water surplus and water deficit for all stations has been carried out by plotting the annual and seasonal water surpluses and water deficits together in a figure, on a latitudinal basis.

The dryness and wetness of the stations have been evaluated using the aridity and humidity indices, defined as

$$I_a \; (\%) = (\text{annual water deficit/annual P.E.}) \; 100 \qquad 2.15$$

$$I_h \; (\%) = (\text{annual water surplus/annual P.E.}) \; 100 \qquad 2.16$$

These values for all stations have been plotted together on the same figure for a comparative study.

The moisture index, which considers both water deficit and water surplus and defined as

$$I_m \; (\%) = ((\text{water surplus} - \text{water deficit})/\text{P.E.}) \; 100 \qquad 2.17$$

has been computed for all stations, and plotted for its spatial variation. The regions of negative values of moisture index have been considered as dry regions, and that of positive values as humid regions. These moisture index values have been employed to classify the climates of Kerala in the moisture regime of Thornthwaite's classification. The modified version of the limiting values of I_m for climatic types by Carter and Mather (1966) have been adopted here. The different climatic types and the corresponding limits of I_m have been given in Table 2.4.

Climatic Types		Moisture Index (%)
Humid Climates		
Perhumid	(A)	100 and above
Humid	(B_4)	80 - 100
	(B_3)	60 - 80
	(B_2)	40 - 60
	(B_1)	20 - 40
Moist sub-humid	(C_2)	0 - 20
Dry Climates		
Dry sub-humid	(C_1)	-33.3 - 0
Semi-arid	(D)	-66.6 - -33.3
Arid	(E)	below -66.6

Table 2.4 - Moisture Index limits and Climatic types (after Carter and Mather, 1966)

Climatic types		Thermal efficiency (cm)
Frost	E'	< or = 14.2
		14.2
Tundra	D'	
		28.5
Microthermal	C'_1	
		42.7
	C'_2	
		57.0
Mesothermal	B'_1	
		71.2
	B'_2	
		85.5
	B'_3	
		99.7
	B'_4	
		114.0
Megathermal	A'	> or = 114.0

Table 2.5 - Thermal efficiency and climatic types

The thermal regime of the climate of Kerala has been classified using P.E. values. The limiting values put forward by Thornthwaite (1948) have been employed here, and are given in the Table 2.5.

In order to segregate the monthly water surplus to surface and ground water components, the runoff coefficients developed by Subrahmanyam and Ali (1982) have been made use of. The surface flow or runoff coefficient of a station is the product of slope of the surface, soil type, and vegetation factors. The complement of this is the detention factor. Different runoff factors for different conditions of slope, soil and vegetation are given in the Table 2.6.

Standard references namely the toposheets (Survey of India), Soils of Kerala (Department of Agriculture, 1978), Resource Atlas of Kerala (Centre for Earth Science Studies, 1984), Water Resources of Kerala (Public Works Department, 1974) etc. have been utilised to identify the slope, soil types and vegetation patterns of all stations to derive the corresponding runoff factors, and then the runoff coefficient. Depending on these runoff coefficients, the surface flow for all months have been estimated.

Based on the principle put forward by Subrahmanyam and Ali (1982), the excess surplus over surface flow for each month has been considered as the groundwater recharge, and added to the groundwater storage of previous month to get the total groundwater storage for that particular month. A portion of the total storage has been considered as the underground flow. A value of 40% of the runoff coefficient has been taken as the uniform

Classification		runoff factors
Slope		
< 10 m/km	gentle	0.70
10 - 20 m/km	moderate	0.85
> 20 m/km	steep	1.00
Soil type		
Sandy	high permeability	0.70
Silt	medium permeability	0.85
Clay	low permeability	1.00
Vegetation		
Tropical rainforest	low flow	0.70
Monsoon forest	medium flow	0.85
Open jungle	high flow	1.00

Table 2.6 - Classification of runoff factors
(After Subrahmanyam and Ali (1982))

coefficient for underground flow. The sum of surface flow and underground flow for a particular month is the total discharge for that month. Based on these concepts, monthly values of surface flow, underground flow, and total discharge have been evaluated for all stations. To workout this procedure, varying number of iterations have been carried out for different stations. The annual as well as seasonal values have been analysed to study the spatial variabilities of these parameters.

For a comparative understanding, the monthly values of precipitation, P.E., A.E., water deficit, water surplus, surface flow, underground flow, and total discharge have been plotted. Steps of computations for the book-keeping procedure of water balance for a representative station Trivandrum is given in Table 2.7.

The estimation of the two input parameters - the field capacity and runoff coefficient - for use in the book-keeping procedure of water balance

Station: Trivandrum Latitude: 0829 N Longitude: 7657 E Height: 64 m
Field capacity: 250 mm Runoff factors: 0.70 1.0 0.85

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
T.	26.8	27.3	28.4	28.8	28.3	26.6	26.2	26.4	26.7	26.7	26.7	26.8	
P.E.	138.0	130.4	155.2	158.3	161.1	144.2	135.2	138.7	141.8	139.1	133.7	137.3	1713.1
P.	23.0	22.1	42.7	116.8	231.8	319.1	218.9	159.2	149.2	277.5	198.0	70.4	1828.7
P.-P.E.	-115.0	-108.3	-112.5	-41.5	70.0	174.9	83.7	20.5	7.4	138.4	64.3	-66.9	115.6
APWL.	-189.1	-290.2	-402.7	-444.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-66.9	
ST.	120.5	78.3	49.9	42.3	113.0	250.0	250.3	250.0	250.0	250.0	250.0	191.3	
DST.	-70.5	-42.4	-28.4	-7.6	70.7	137.0	0.0	0.0	0.0	0.0	0.0	-58.7	
A.E.	93.5	64.5	71.1	124.4	161.1	144.2	135.2	138.7	141.8	139.1	133.7	129.1	1476.6
W.D.	44.5	65.8	84.1	33.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.2	236.5
W.S.	0.0	0.0	0.0	0.0	0.0	37.8	83.7	20.5	7.4	138.4	64.3	0.0	352.1
S.F.	0.0	0.0	0.0	0.0	0.0	22.5	49.8	12.2	4.4	82.3	38.3	0.0	209.5
G.R.	0.0	0.0	0.0	0.0	0.0	15.3	33.9	8.3	3.0	56.0	26.0	0.0	142.6
T.G.	54.1	41.2	31.4	23.9	18.2	29.2	56.1	51.1	41.9	88.0	93.1	70.9	599.2
U.F.	12.9	9.8	7.5	5.7	4.3	7.0	13.4	12.2	10.0	20.9	22.2	16.9	142.6
G.S.	41.2	31.4	23.9	18.2	13.9	22.3	42.8	38.9	32.0	67.1	70.9	54.1	456.6
T.D.	12.9	9.8	7.5	5.7	4.3	29.5	63.1	24.4	14.4	103.3	60.4	16.9	352.1

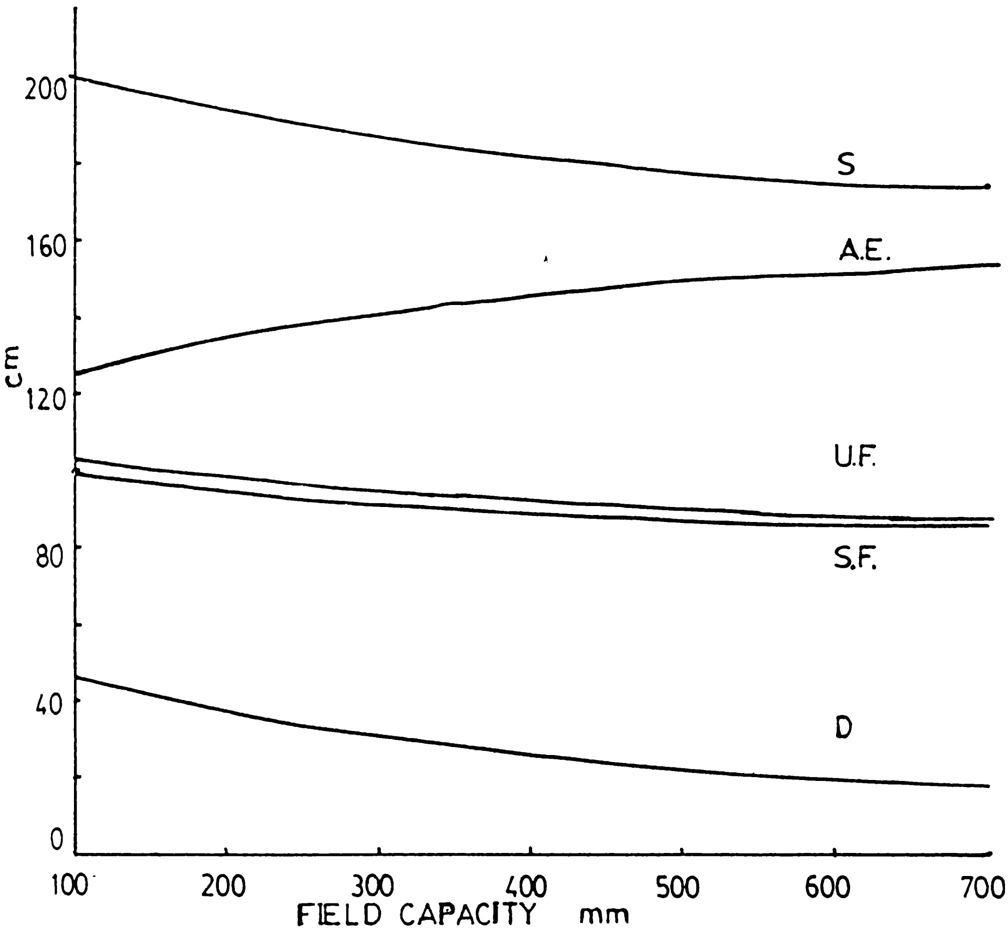
T. - Temperature
P.E. - Potential Evapotranspiration
P. - Precipitation
APWL. - Accumulated Potential Water Loss
ST. - Storage
DST. - Storage Change
A.E. - Actual Evapotranspiration
W.D. - Water Deficit
W.S. - Water Surplus
S.F. - Surface Flow
G.R. - Groundwater Recharge
T.G. - Total Groundwater
U.F. - Underground Flow
G.S. - Groundwater Storage
T.D. - Total Discharge

Table 2.7 - Climatic water balance computations for the station Trivandrum

may be questioned. An effort has been made to check the validity of these parameters by assigning some standard values for field capacity (units of 50 mm) and runoff factors, depending on the topography, vegetation and edaphic conditions of each station.

The water balance model has been run for different field capacities and for different runoff factors for two randomly selected stations Calicut and Punelur. Fig. 2.3 shows the variation of all hydrometeorological parameters with varying field capacities for Calicut. The field capacities have been varied from 100 mm to 700 mm. From the figure it is very clear that the annual A.E. increases with field capacity since more water is available for utilisation during deficit periods. Another interesting result is, that, as the field capacity increases, the surplus as well as deficits decrease. The decrease of surplus is due to the fact that, more water is needed for recharging the soil. On the other hand, because of the increased nature availability in dry periods the deficits were decreased. Since there was a decrease in water surplus, the surface flow, underground flow and resultant total discharge have been reduced with increasing field capacity. The change in parameters with change in field capacity are not linear.

For the station Calicut, the estimated field capacity is 200 mm, and that of Punelur 250 mm. The maximum variations in different hydrometeorological parameters, when there is a decrease or increase of 50 mm in estimated field capacities are given in Table 2.8. So, this table gives the variation of hydrometeorological parameters due to a change of 20% in the field capacity.



S. Surplus
A.E. Actual Evapotranspiration
U.F. Underground Flow
S.F. Surface Flow
D. Deficit

Fig. 2.3 Variations of hydrometeorolofical parameters for different field capacities

	Calicut		Punelur	
	Decrease	Increase	Decrease	Increase
	mm %	mm %	mm %	mm %
A.E.	-41 (-3.0)	+36 (+2.7)	-25 (-1.6)	+17 (+1.1)
W.D.	+42 (11.3)	-35 (-9.5)	+22 (+13)	-20 (-11.8)
W.S.	+42 (2.1)	-35 (-1.8)	+25 (+2.0)	-17 (-1.3)
S.F.	+21 (2.1)	-18 (-1.8)	+18 (+2.0)	-12 (-1.3)
U.F.	+21 (2.1)	-18 (-1.8)	+ 7 (+2.0)	-5 (-1.3)

A.E. Actual Evapotranspiration
W.D. Water Deficit
W.S. Water Surplus
S.F. Surface Flow
U.F. Underground flow

Table 2.8 - Variations in hydrometeorological parameters for a 50 mm change in field capacity.

It is very clear that the error in the derived parameters are comparatively higher if the estimated values are less than the actual value (for the same amount of increase). The percentage variation is maximum in case of water deficit; 11.3% for Calicut and 13% for Punelur. But, for all other parameters the probable error due the possible error in estimation of field capacity are less than 3%. This implies that even if the estimated field capacity is wrong by 50 mm, the variations in derived values are not that much significant.

We have already seen that three values were assigned for each runoff factor depending on different conditions. According to Subrahmanyam and Ali (1982), the runoff coefficients vary from 0.343 to 1.0. The possible combinations of the runoff factors and corresponding runoff coefficients are shown in Fig. 2.4. Various water balance parameters have been computed for a randomly selected station, Palghat, for various combinations of runoff factors, and have been plotted in the same figure. As expected, total discharge remained the same, independent of runoff factors; the

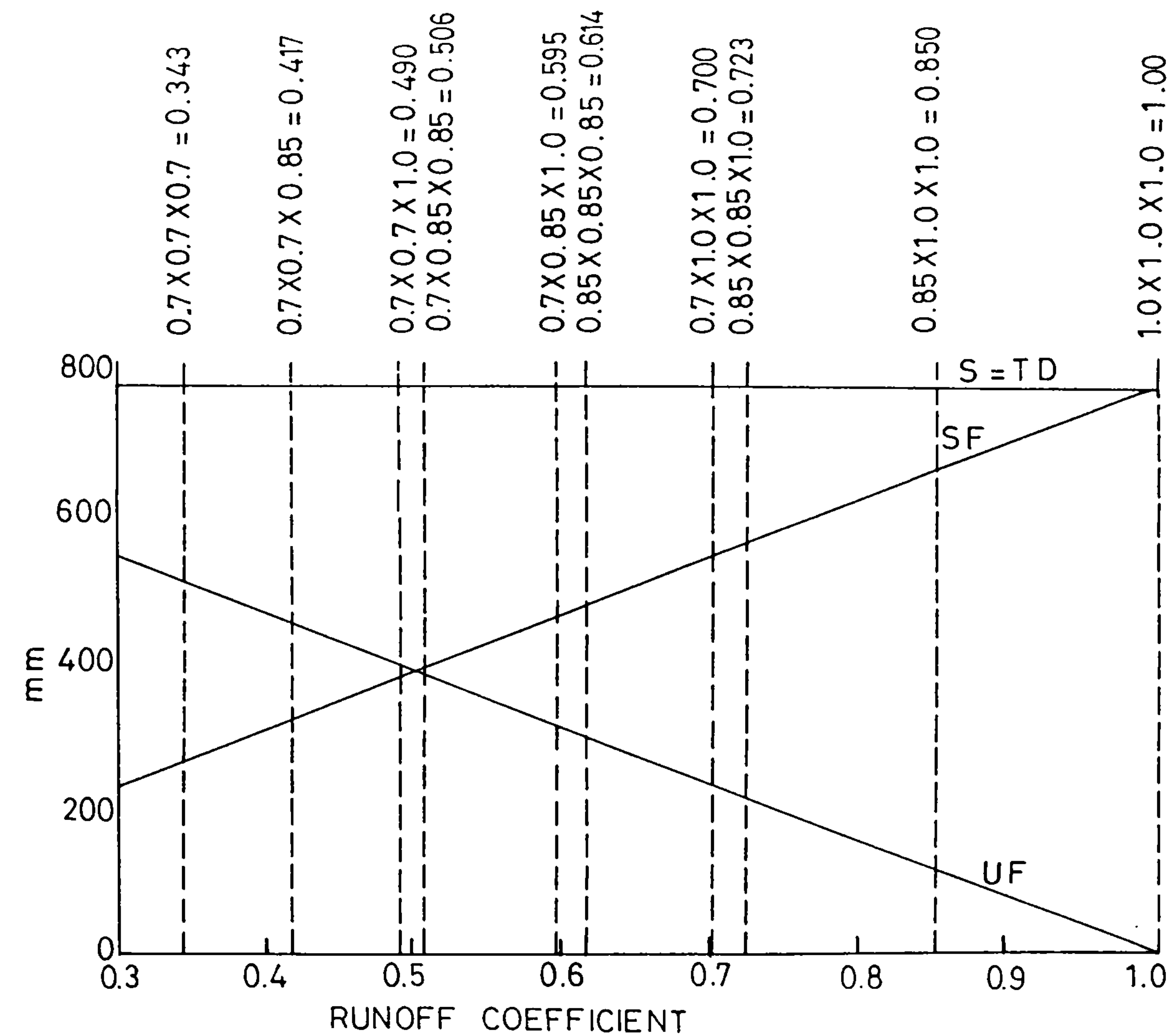


Fig. 2.4 Variations of water balance parameters at Palghat for different combinations of runoff factors

surface flow increased with the runoff coefficient and the underground flow decreased in a complementary fashion. As can be seen from the figure, the variation of runoff factors are not uniform and the variation of parameters cannot be standardised as that of field capacity. For the particular station Palghat, the runoff factors were 0.70, 0.85, 1.0 and corresponding runoff coefficient was 0.595. In this case, the possible variation of runoff coefficient by the unit change in any one of these factors was 0.490 to 0.723 and the corresponding variations in surface flow and underground flow were -18% to 21% and 21% to -31% respectively. In other words, the variations observed in flow parameters due to any errors in runoff factors could be high.

2.2.4 **Time Series Analysis:**

The various powerful statistical techniques suggested by WMO (1966b) namely Mann-Kendall statistic, Student's t-test, low-pass filtering technique and Power Spectrum analysis have been employed here to investigate various non-randomness in the time series of 56 years of rainfall, actual evapotranspiration (A.E.), water deficit and water surplus of 42 stations uniformly distributed over Kerala State.

The water balance model explained earlier, with some modifications, has been employed to evolve the water balance parameters on an yearly basis for all stations. The yearly water balance computations have been carried out, starting with the climatic values of accumulated potential water loss and groundwater storage; for the successive years, the corresponding values for the month of December of the previous year have been utilised. Homogeneity has been assumed for the time series of all parameters so derived.

2.2.4.1 Trend Analysis:

2.2.4.1.1 Mann-Kendall Rank Statistic:

Since the most likely alternative to randomness in the climatic series is some form of trend, which may be linear or nonlinear, the test of randomness has been employed to check the presence of trend. Mann-Kendall rank method suggested by Kendall and Stuert (1961) is a powerful test for trend analysis, and this is a very robust test in the sense that the distribution need not be a Gaussian normal type. Here, only the relative of the terms in the series has been analysed. The test statistic has been computed using the equation

$$T = \frac{4P}{N(N-1)} - 1 \qquad 2.30$$

where $P = \sum_{i=1}^{N-1} n_i$, where n is the number of values larger larger than the i^{th} value in the series subsequent to its position in the time series; and N is the total number of observations. This statistic is distributed very nearly as Guassian normal distribution for all N larger than 10 and has an expected value of zero mean and variance

$$V = \frac{4N+10}{9N(N-1)} \qquad 2.31$$

The significance of this statistic has been tested in comparison with

$$T = 0 \pm t_g \sqrt{\frac{(4N+10)}{(9N(N-1))}} \qquad 2.32$$

where t_g is the probability point of Gaussian distribution appropriate to two tail test. This significance has been tested first for 99% probability level but wherever it was not significant, it has been tested for 95% and then 90% probability levels.

2.2.4.1.2 Student's t-test:

In this case, the series has been broken into two equal halves and the trend has been analysed by comparing the mean for the two different equal periods. WMO (1966b) quoted that this test is also robust, if the length of the two periods chosen for comparison are equal. In this case the test statistic is computed using the equation

$$t_d = \frac{[\overline{X}_1 - \overline{X}_2 - (\mu_1 - \mu_2)]}{\left[\frac{[N_1 S_1^2 + N_2 S_2^2]}{[N_1 + N_2 - 2]}\left(\frac{1}{N_1} + \frac{1}{N_2}\right)\right]^{1/2}} \qquad 2.33$$

where, $\overline{X}_1$ and $\overline{X}_2$ are the mean of the first half and second half and $N_1 = N_2$ = total number of observations in both halves. $(\mu_1 - \mu_2)$ is the expected difference between X_1 and X_2. But according to the null hypothesis for randomness, this difference has been set equal to zero. The quantities S_1^2 and S_2^2 are the variances of X_i in both periods of record and $N_1 S_1^2$ has been computed as

$$N_1 S_1^2 = \sum_{i=1}^{N_1} X_i^2 - \frac{1}{N}\left(\sum_{i=1}^{N_1} X_i\right)^2 \qquad 2.34$$

similarly $N_2 S_2^2$ also has been calculated

The distribution of t_d given by the above equation follows the student's t-distribution for $(N_1 + N_2 - 2)$ degrees of freedom. Wherever the test statistic $|t_d|$ lies beyond the 99% points of the t-distribution appropriate to two tail form of test, the difference between the means has been accepted as an evidence of nonrandomness at 99% probability level. But, whereever this test statistic falls within the 99%

probability point of t-distribution, it has been tested for 95% and then 90% levels.

2.2.4.1.3 Low-Pass Filter:

The choice of the length of the averaging period is critical, since too much smoothening will destroy the significant features of the curve, but too little smoothening will not eliminate the irregularities that may mask any underlying pattern. The Gaussian filter is a widely accepted one, which is a nine point filter with the weights as 0.01, 0.05, 0.12, 0.02, 0.24, 0.20, 0.12, 0.05 and 0.01 have been employed here. This symmetrical moving average has a response function equal to unity at infinite wavelength, and tails of asymptotically to zero with decreasing wavelength; and is approximately given by

$$R(f) = \exp\left(-2\pi^2\sigma_g f^2\right) \qquad 2.35$$

where σ_g is the appropriate standard deviation.

2.2.4.2 Power Spectrum Analysis:

The methodology used for spectrum analysis here is that of Blackman and Tuky (1958), which is described in WMO (1966b), and is based on the autocorrelation technique.

The resolution of the spectrum is proportional to the maximum lag m, but, if m is very large compared to the maximum number of observations N, the estimates will be highly unstable in the statistical sense. So, the maximum lag m has been set in such a way to have an optimum compromise between the spectral resolution and the statistical stability. It has been so chosen that the maximum lag $m < N/3$. A maximum lag of 18 has been fixed for stations having the rainfall data for the period 1931 to 1986. In such cases the fundamental period has been 36 (2m) and the shortest wavelength resolvable in the spectrum has been 2 years.

Serial covariances for all lags T = 0 to m have been computed for the series of N equally spaced observations using equation 2.18

$$C_T = (1/(N-T)) \sum_{i=1}^{N-T} \left[(X_i-\overline{X})\ (X_{i+T}-\overline{X})\right] \qquad 2.18$$

where $\overline{X}$ is the mean of all X_i in the series and N is the total number of observations.

The next step has been to compute the serial correlation coefficients for each m+1 lags by dividing the each serial covariance with variance of the series. Then evaluated m+1 raw estimates of the power spectrum by the cosine transform of the m+1 lag correlation values. The i^{th} value [$0 < i < m$] of this raw estimate gives a rough measure of the total variance in the original series, that is contributed by the wavelength near the i^{th} harmonic of the fundamental wavelength. This raw spectral estimates S_k have been obtained directly from serial correlation coefficients by the equations

$$\hat{S}_o = (1/2m)\ [C_o + C_m] + (1/m) \sum_{T=1}^{m-1} C_T \qquad 2.19$$

$$\hat{S}_k = (C_o/m) + (2/m) \sum_{T=1}^{m-1} C_T \operatorname{Cos}(\pi kT/m) + (1/m)C_m (-1)^k \qquad 2.20$$

$$\hat{S}_m = (1/2m)\ [C_o + (-1)^m\ C_m] + (1/m) \sum_{T=1}^{m-1} (-1)^T\ C_T \qquad 2.21$$

Equation 2.19 has been used to compute 0^{th} spectral estimate corresponding to infinite wavelength (trend), and equation 2.21 has been used to compute the last spectral estimate, which corresponds to the shortest wavelength resolvable in the spectrum. All the intermediate m+1 spectral estimates have been computed using the equation 2.20 by setting 'k' in the cosine argument to successive integral values, ie., k = 1,2,3,... m-1.

Next, the final spectral estimates S have been computed by smoothing the raw spectral estimates with 3 term weighted average with weights equal to 1/4, 1/2, 1/4 respectively. In this hanning processes the smoothing formulae were

$$S_0 = (1/2)\ (\hat{S}_0 + \hat{S}_1) \qquad 2.22$$

$$S_k = (1/4)\ (\hat{S}_{k-1} + 2\hat{S}_k + \hat{S}_{k+1}) \qquad 2.23$$

$$S_m = (1/2)\ (\hat{S}_{m-1} + \hat{S}_m) \qquad 2.24$$

In the equation 2.23, the values of k have been set equal to 1,2,3,....m-1 successively.

For evaluating the results of the spectrum, a null hypothesis for the spectrum has been fitted. The null hypothesis for this purpose has been considered in accordance with, whether the series consists of persistence or not. In general, if the lag one serial correlation coefficient (r_1) of the series does not differ from zero by statistically significant amount, the series have been regarded as free from persistence. In such cases, the appropriate null continuum were that of a white noise, which is a straight line whose values are everywhere equal to the average of the values of all m+1 raw spectral estimates in the computed spectrum.

On the other hand, wherever r_1 differed from zero by a statistically significant amount, it has been checked whether the r_1 satisfies the following exponential relationship.

$$r_2 \doteq r_1^2, \quad r_3 \doteq r_1^3, \quad \text{etc.} \qquad 2.25$$

If it was true, the appropriate null continuum has been that of Markov red noise, whose shape depends upon the values of lag one correlation coefficient. The continuum has been constructed by the following procedure. The following equation for the various choice of harmonic number k, k = 0,1,....m have been evaluated.

$$S_k = \bar{S} \left[\frac{(1-r_1^2)}{1 + r_1^2 - 2r_1 \operatorname{Cos}(\pi k/m)} \right] \qquad 2.26$$

Where $\bar{S}$ is the average for all m+1 raw spectral estimates S_k in the computed spectrum. The resulting values of S_k have been plotted on the sample spectrum, and the smooth curve passing through the points has been the null continuum for the red noise.

Finally, wherever the lag one serial correlation coefficient r_1 differed statistically from zero, but the coefficients for higher lags did not bear the exponential relationship to r_1, then the spectral estimate has been tested with red noise continuum for the first half and with white noise for the remaining.

The confidence limits have been estimated, based on the fact that the ratio of the magnitude of the spectral estimate to the local magnitude of continuum has been found to be distributed as chi-square divided by degrees of freedom, which is given by the expression (2N-m/2)/m.

From the chi-square distribution, 99%, 95% and 90% points corresponding to the degrees of freedom have been found out. Products of these percentage points with the null continuum values over the spectral estimates have been plotted. The harmonic for which the null continuum is significant has been found out from the plot, and this implies that there is a periodicity corresponding to that harmonic. The wavelength corresponding to the harmonic is 2m/L.

The significance of r_1 has been tested using the statistic

$$(r_1)_t = \frac{[-1 \pm t_g\sqrt{(N-2)}\ ]}{(N-1)} \qquad 2.27$$

In which t_g is the standard deviate in the Gaussian distribution, corresponding to the desired significant point of r_1. This significance has been tested first for 99%, but whereever it was not significant at 99% level, it has been tested with 95% level and then 90% probability level. If the sample value of r_1 is greater than this test statistic, it has been concluded that the series is non-random at that level of significance.

In general, one tail significant test has been applied, but in case of negative values of r_1, two tail tests have been applied.

To reduce the chance of picking up high power, due to aliasing effect, the analysis has been repeated for three different maximum lags. For stations having data for the period 1931 to 1986, the analysis has been done for maximum lags of 18 and 16.

In this power spectrum analysis, if there is a trend in the series, the power is contained in one or a few very narrow bands; such bands can cause errors in the spectral estimates where there is less power (Jenkins and Watts, 1968). In such cases the series have been filtered digitally, in order to improve the spectral estimate at high frequencies. Parthasarathy and Dhar (1974, 1976b) employed the digital difference filter to remove the low frequency oscillations. The digital difference filter is defined by the equation

$$Y_t = X_t - X_{t-1} \qquad 2.28$$

where Y_t is the filtered series and X_t is the unfiltered series. The frequency response function is given by the equation

$$R(f) = 2j \exp(-j\pi f) \sin \pi f \qquad 2.29$$

where $j = \sqrt{(-1)}$, and f is the frequency. This will act as a high-pass filter.

CHAPTER III

PHYSICO-CLIMATIC FEATURES OF KERALA STATE

3.1 Kerala State - General

Various physical features of Kerala State such as its location and extent, physiography, drainage conditions, geological aspects, soil classification, land-use pattern, vegetation and agriculture are discussed in this Chapter. The latter part of this Chapter contains a review of the climatological features of the State.

3.1.1 Location and extent:

The State of Kerala lies at the southern tip of the Indian peninsula, between 8° 17' 30" N and 12° 47' 40" N latitudes and 74° 51' 57" E and 77° 24' 47" E longitudes. It is elongated in shape and bounded by the Western Ghats on the east and by the Arabian Sea on the west. The State extends over a length of 560 km along the west coast with the width varying from 15 km to 120 km; the maximum width is roughly along Anamudi in Idukki district narrowing towards both the northern and southern extremities. Kerala is one of the smaller States in India with an area of just 38,864 km^2, which is only 1.18% of the area of the country. The State is bounded by Tamil Nadu on the east, and by Karnataka in the north and north-east. Despite its small size, Kerala supports about 3.7% of the population of India and has the highest population density (655/km^2) among the Indian States, against the national average of 221/km^2 (1981 census report). Kerala, with a literacy of more than 90% stands in the forefront among the Indian States, against the national average of about 40%.

The State came into existence on 1^{st} November 1956 after the reorganisation of Indian States. The State Capital is located at Trivandrum, and for administrative purposes the State is divided into 14 districts.

3.1.2 Physiography and Geomorphology:

In the light of diversity of its physical features, the land mass of Kerala is distinguished into three natural zones namely lowland, midland and highland, and each of them runs almost parallel from north to south. From the lowlands of the adjoining westcoast, the landscape ascends gently towards the east to the midland and steeply ascends to the highlands, and later slopes downward from the Western Ghats. The population density is maximum in the lowlands and gradually decreases towards the highlands.

The highlands consist of mountain ranges in the eastern parts of the State, which form a natural wall with an average height of 1 km, separating Kerala from the adjoining States. The contour map of the State is given in Fig. 3.1. The highest of the peaks in these ranges is Anamudi (2695 m) in Idukki district, which acts as a nodal point for the three ranges: the Anamalai in the north, Palani hills in the north-east on which the famous Kodaikanal is situated and the Cardamom hills (Elamalai) in the south, where the hill station Peermedu is situated. To the north of Anamalai are the Nilgiris or the Blue Mountains, the meeting ground of the Western Ghats and Eastern Ghats. The highest peak in this mountain is the Dodda Betta (2637 m) over the Ootacamund area. The Anamalai and Nilgiris are the tallest mountains in the Western Ghats and are separated by 30 km wide Palghat Gap where the elevation drops below 300 m. This Palghat Gap is

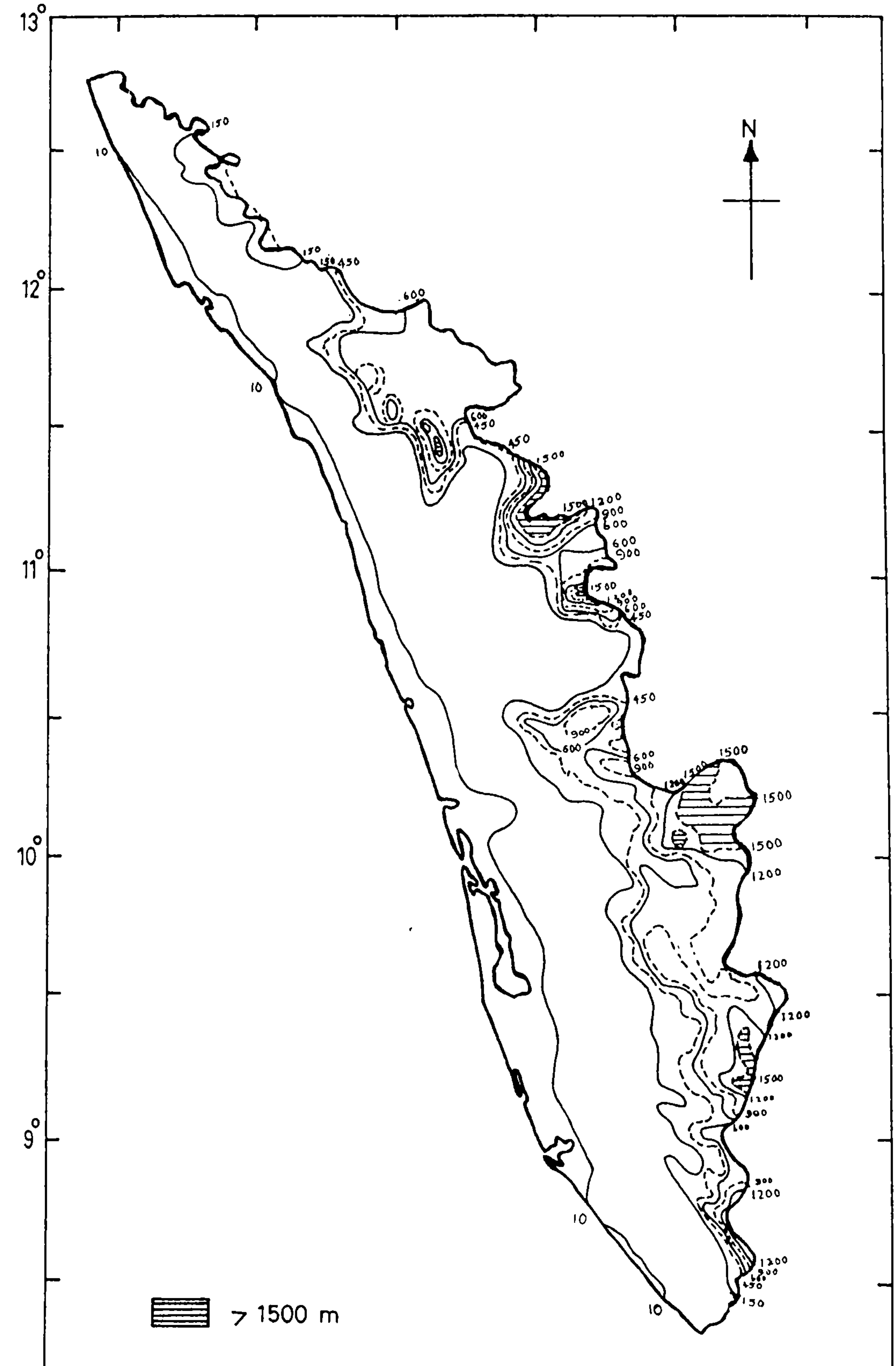


Fig. 3.1 Contour map of Kerala State (m)

considered to have been formed by tectonic and erosional processes and has a significant role in the meteorology of Kerala. The Western Ghats are pierced at a few places by passes of which Aryankavu pass is an important one. The hill ranges in the extreme north and south lie near the shore line at a distance of less than 40 km. The highland regions are ideally suitable for plantation crops such as tea, coffee, cardamom etc. and the main occupation of the people are activities associated with the cultivation of such crops.

The lowland region is a strip of area running along the coast with a maximum width of about 25 km from the shore near Alleppey. This area has level topography and is characterised by marine landforms, beach ridges, and beaches with swamps and lagoons. This lowland area has a number of lakes among which Vembanad lake is the largest, followed by Ashtamudi kayal. Kuttanad region in the lowlands is a unique agricultural area covering about 875 km^2 in the districts of Alleppey and Kottayam. A greater portion of this area lies below sea level and remains submerged during major periods of the year. The formation and behaviour of mudbanks are peculiar phenomena of the Kerala coast: these are the regions of calm waters of monsoon season and are abundant in fish yield. In several places, the lowlands are liable to be flooded during heavy rainfall.

Sandwiched between the lowlands and highlands is the midland region, characterised by undulating terrain. The soil in this zone is lateritic or its varieties. This area is rich in agricultural products and a variety of crops including paddy, tapioca, banana, pepper, ginger, arecanut are grown here.

3.1.3 Drainage:

The gift of copious rainfall during the monsoon months over the highlands has helped in the formation of watersheds of large number of rivers, which together with their numerous tributaries flow towards west and join the Arabian Sea or backwaters. The drainage network of Kerala consists of 44 rivers with a length of more than 15 km, of which 41 flow westward and only 3 to the east, and these rivers contribute 32 river basins. A few of the west flowing rivers originate in the neighbouring States and cross over to Kerala. Periyar is the longest river in the State having a length of about 244 km and has the highest catchment area (5,398 km^2) within the State. River Bharathapuzha has a larger catchment area (6,186 km^2), but about 40% of it is in Tamil Nadu. The four major rivers Periyar, Bharathapuzha, Pamba and Chaliyar together drain about 35% of the total runoff. The three eastflowing rivers are Kabbani, Bhavani and Pambar. Because of the undulating topography most of the areas enjoy a good drainage system except in the low lying areas. The drainage patterns observed are dendritic and parallel. During the monsoon season, the rivers in Kerala swell, and submerge the banks and flow with turbulent and impetuous force; but they gradually subside in the drier months and expose their sandy beds at many places.

In the State, most of the rivers flow through deep valleys and have enough groundwater seepage as subsurface runoff from the hillsides. Due to this effluent seepage, the rivers in Kerala are mostly perennial. The State possesses high water potential for hydel power generation and irrigation. The runoff of all rivers of the State amounts to 78,041 million m^3 of which 70,323 million m^3 is the contribution from Kerala's catchment. All the waters that flow down cannot be utilised due to several practical reasons. The total surface water resource of the State is computed as 42,772 million m^3 (Public Works Department, 1974).

3.1.4 Hydrogeology:

The occurrence and movement of groundwater are controlled by the prevailing topography, geological formations and rainfall. The physical features and nature of subsurface strata are not very favourable for holding large quantities of groundwater. The geophysical surveys by Bose and Kartha (1980) have revealed that large thickness of sediments containing fresh water exist around Ambalapuzha in Alleppey district and the area between Sherthalai in Alleppey district and Anjengo in Trivandrum district is the most promising for the development of groundwater. Revindran (1980) estimated the groundwater storage capacity of the confined aquifers over the State as 9,741 million m^3 and for the unconfined aquifers 7,200 million m^3.

3.1.5 Soils:

Soil is an important earth resource and precise scientific information is necessary for the proper use and management of the soil. The physical properties of the soil particularly its structure, texture, changes in the soil moisture content etc. have to be considered for land-use planning. Based on physicochemical properties and morphological features, soils of Kerala are classified into the following ten broad groups (Department of agriculture, 1978). 1) Laterite soils which are the most extensive soil group, occurring over 60% of the State. 2) Forest loam, occurs over 25% of the land area and is mainly confined to the eastern parts of the State. 3)

Coastal alluvium, distributed all along the coast and have been developed from recent marine deposits. 4) River alluvium, developed along the river valleys occurs throughout the State, cutting across the extensive laterite soils. 5) Brown hydromorphic, confined to valley bottom and low lying areas of the coastal strip. 6) Red loam, whose occurrence is very much localised and is found mostly in southern parts of Trivandrum district. 7) Greyish Onattukara occurring as marine deposits extending to the interior upto laterite belt. 8) Hydromorphic saline soils are seen in the coastal areas of the districts of Cannanore, Trichur, Ernakulam and Alleppey where inundation of sea water occurs. 9) Acid saline found mainly in Kuttanad regions. 10) Black soils, whose occurrence is restricted to Palghat district only.

3.1.6 Land-use:

Land-use is the result of human interaction with nature in which physiography and climate are major controls. A comprehensive knowledge of existing land-use pattern is an essential pre-requisite for developmental planning of any region. High population density and the resultant intensive necessity for food products have increased the cultivation in the State. Nearly 64% of the total geographical area is under cultivation, 27% is covered by forest and the remaining is waste or barren land (Kerala Land Use Board and ISRO, 1980).

The arable land forms a continuous stretch along the entire State, spreading from the coast to the inland and along the river valleys. The percentage of the net area sown of the State is significantly higher than the national average and within the State, Kottayam district has the highest percentage, while Idukki district the lowest. Generally, the 300 m. contour has been taken as the western limit of forest and it covers the entire eastern part of the State, except in the vicinity of the Palghat gap. The area under forest land does not represent the actual vegetation cover, but only indicates the area legally coming under the forest department. Idukki district ranks first in this category and Alleppey, the last. Many plantation crops such as tea, coffee and cardamom have been developed within the forest land. The land part put to non-agricultural use includes the area under the settlement, water bodies, roads, etc. in which Alleppey and Idukki districts come first and last respectively. The area under barren and uncultivable land covers the rocky area totally unsuitable for cultivation. Cultivable wasteland also exists in the State due to lack of irrigation facilities. Isolated patches of grass lands have also been observed throughout the State.

3.1.7 **Vegetation:**

The luxurious vegetation that clothes the land of Kerala for most part of the year is a distinct feature of the State. The State enjoys a diversified floristic composition due to its physical environment. Major types of vegetation and their areal extents are as follows

Wet evergreen and semi-evergreen	50.5 %
Moist deciduous	33.4 %
Dry deciduous	1.8 %
Montane subtropical and temperate	1.7 %
Plantation and others	12.6 %

Isolated patches of evergreen forest are observed in the slopes of Western Ghats and are characterised by large and very tall trees in the first storey and many ferns and herbs comprise a dense second storey.

Moist deciduous types are less diverse compared to the evergreen forests, but its major feature is that it remains more or less leafless during the hot summer period. The evergreen and moist deciduous forest types are located in the 200 to 300 cm rainfall zones with temperature more than 20° C; these are generally seen above an elevation of 300 m. The dry deciduous forests is confined to Pambar valley, a rain-shadow region, where annual rainfall is about 100 cm. and temperature in winter is considerably low. The montane subtropical and temperate forests commonly known as temperate shola, occur in the valley of the high ranges.

In general, the flora consists of timber trees, trees yielding gums and resins, avenue trees, cedars, palms, bamboos, reeds, and medicinal plants.

3.1.8 Agriculture:

Kerala is essentially an agricultural State and the main occupations of the people are associated with this. Depending on the diversity of the agro-climatic environment, there is a variety of crops which range from tapioca, pepper, coconut and rubber of the high rainfall humid tropics to coffee and tea of the humid temperate climate. Even among the tropical crops, they vary from paddy (requiring water continuously for 3 to 4 months) to tapioca and ginger (requiring moist but well drained soils), from arecanut and coconut requiring moist conditions throughout the year to cashewnut which can tolerate extremely dry conditions of summer and from seasonal crops such as rice and annuals such as banana to perennials such as coconut and arecanut.

Cropping pattern in the State is controlled by physiographic characteristics. The high hill ranges along the eastern border of the State support tea, coffee and cardamom plantations. On the lower hills and slopes of the other highland region rubber, pepper, and other tree crops are common. Further west, in the midland region a variety of annual and seasonal crops thrive. The coastal belt with wide flatlands traditionally hosts paddy and coconut cultivation.

Because of the varied edaphic, climatic and physiographic conditions, agriculture in Kerala has certain distinguishing features in the system and practices of crop production. Different farming systems existing in the State are a) homestead systems of cultivation with combination of perennials and annual crops b) Coconut based farming system in which coconut is the pivotal crop with a number of inter- crops such as pepper, arecanut, cocoa, banana, tubers etc. c) Rice-based farming systems prevalent in lowlands in which vegetables, pulses, oil seeds etc. are grown as summer crops. Nair (1973), delineated 13 agro-climatic zones in the State based on altitude, rainfall, soil type, and topographic features.

Kerala is a deficit State in the matter of food production. The production of rice, which is the principal food of the Keralites, is only 55% of the requirement (Public Works Department, 1974). Various agricultural programmes such as multiple cropping, adoption of high yielding varieties, application of fertilisers, adoption of irrigation facilities, and plant protection measures are being implemented to augment the agricultural production.

3.2 Climate of Kerala:

The State of Kerala has a salubrious climate which is controlled to a large extent by its position in the south-west part of the large country and the high variation of relief from the coast in the west to the highlands of Western Ghats in the east. Within the short distance of 120 km from the coast to the Ghats, a diversity of climate is observed which is a reflection of the rich diversity in the physical features. Even though biting cold is experienced over the high ranges during the winter nights, the climate of midland and lowland areas is hot and humid. Most of the areas are under tropical wet and dry conditions, with high maritime influence, but certain areas in the eastern parts experience subtropical type of climate. The most conspicuous feature of Kerala's climatology is the existence of the monsoon activities in association with the reversal of temperature and pressure gradients over the country. The southwest monsoon enters the subcontinent through the State. The vagaries of monsoon - fluctuations in onset, space and time distributions - are very complex. Usually, July is the wettest month and January is the driest. In the rainy season, floods are common and causes substantial damage to crops.

Based on the climatic conditions over the State, the year is divided into four seasons;

Winter	January - February
Pre-monsoon	March - May
Monsoon	June - September
Post-monsoon	October - December

Winter is the coldest and the driest season over the State. The pre-monsoon season is characterised by increasing day-time temperatures and thunderstorm activities. The monsoon (southwest monsoon) season is the primary rainy season which contributes about 66% of the annual rainfall. This season is characterised by heavy rainfall, low clouds, high humidity and is the period when floods occur over some parts of the State. The post-monsoon season sometimes referred to as retreating monsoon, constitutes the secondary rainfall season, especially in South Kerala. Major part of the rainfall in this season depends on the development of cyclones in Bay of Bengal and easterly waves over peninsular India. The pre-monsoon season is uncomfortable due to high temperature and humidity. The State is comparatively pleasant from September to February.

3.2.1 **Temperature:**

Because of the tropical location and proximity to oceans, the annual and diurnal variation of temperature over the State is small compared to central and northern parts of the country. But there is a spatial variation in temperature in the east-west direction due to physiographic features. Due to the influence of the southwest monsoon, the highest temperatures are experienced in the pre-monsoon months rather than in the summer months. At coastal stations, maximum temperature (about 33°C) occurs in April and minimum temperature (about 22°C) in January. But interior stations have high maximum temperature of about 37°C and minimum temperatures a little lower than that at coastal stations. The range of mean monthly temperature for the year is less than 4°C in coastal stations and less than 6°C at interior stations, and that of maximum temperature is less than 5°C at coastal stations and less than 9°C at interior stations; the range of minimum temperature is less than 4°C at all stations. The lowest monthly mean temperature occurs in July or August and highest in the pre-monsoon months. The zone with highest mean temperature for the whole year (> 27.5°C) falls in the midland region; along the coast, temperature is modest, whereas in the east, it is very low (Centre for Earth Science Studies, 1984). The diurnal variation of temperature is less in monsoon months due to the high clouding, and it is greater in January and is very high, >15°C in the high ranges.

3.2.2 Relative Humidity:

Due to the proximity to the sea, the moisture content over the region is very high. The monsoon currents bring lot of moisture from the Arabian Sea and it is found that the precipitable water vapour over Kerala increases from 3 to 3.5 grams in the winter months to about 5 grams in the monsoon months (Ananthakrishnan et al., 1965). The moisture content decreases towards the east, away from the coast. It also decreases very rapidly with elevation in the winter months, but more gradually in monsoon months. According to Ananthakrishnan et al. (1979b), monthly mean relative humidity at the surface is of the order of 75% in winter mornings and increases to about 90% in the monsoon months at coastal stations. The average humidity for the planes of the State is 77% with a maximum of 88% in July and minimum of 66% in January. Both morning and evening relative humidity variation shows almost same pattern with the highest value in July and he lowest in January. The morning values vary from 91% to 72% and afternoon values vary from 85% to 60%.

3.2.3 Pressure:

The average annual range of pressure for the State is less than 5 hPa and is lower than over other parts of the country. In all seasons, the pressure gradient over the State is in the eastward direction. Average monthly variation shows a maximum during January or December and minimum in May. Pressure over Calicut, Cochin and Alleppey are almost the same in all months (approximately 1011 hPa in January and 1007 hPa in May).

It is a well known fact that the pressure exhibits a diurnal variation with maximum around 1000 LMT and 2200 LMT and minimum around 1600 LMT and 0400 LMT. This diurnal range of pressure increases from the coast to the inland regions and this range is also less than 5 hPa (IMD, 1986). The maximum diurnal pressure variation occurs in February when the cloudiness is least while the variation is minimum during June and July.

3.2.4 Winds:

The wind flow over most part of the State is thermally driven, which is governed by the differential heating of land and water bodies. These land and sea breezes have a westerly component during day time and easterly component during the night and early mornings throughout the year. In general, these winds are strong during afternoons and weak during night time. Ananthakrishnan at al. (1979b) reported that the depth of this sea breeze is less than 1 km over Trivandrum. Notable differences in the speed and direction have been observed between the coastal and inland stations. But the winds are seasonal over Palghat and its vicinity and have a pronounced easterly component from November to March and westerly during the rest of the year.

But during monsoon season, strong westerly winds dominate the diurnal variation of winds everywhere. One interesting feature of winds in this southwest monsoon season is that, it blows northwesterly instead of southwesterly, especially over the southern coastal areas. Another feature of this monsoon current is the existence of short period squally winds with speeds even upto 40 knots. This squally winds may occur many times in strong monsoon conditions. The lower tropospheric westerlies strengthen and their depth increases in association with the formation of low pressure systems in the west coast or Bay of Bengal or a southerly shift of seasonal monsoon trough.

3.2.5 Cloudiness:

During the monsoon season, skies are heavily clouded, especially in June and July where about 7 oktas of the sky remains covered with clouds. A secondary maximum of cloudiness is observed over the State in October - November, especially in southern parts in association with post-monsoon activities. The minimum cloudiness over the State is observed from January to March.

3.2.6 Fog:

The mountain terrain of Western Ghats experiences hill fog during the rainy months of June to September, when air is almost saturated. Valley fogs are also observed in the eastern parts of the State.

3.2.7 Weather Phenomena:

a) Monsoons:

Monsoons are large scale seasonal wind systems which are basically thermally driven. During the summer monsoon period, the differential heating causes the winds to blow from oceans to land and replaces the hot dry air by equatorial moist air. But, in the post-monsoon periods, the thermal gradients get reversed and the wind blows from continents to ocean. On an average, 66% of the rainfall of Kerala is produced by south-west monsoon and about 18% by north east monsoon. Climatologically, 1st June is the date of onset of south west monsoon and its withdrawal from the extreme south is completed by December. The major synoptic systems or components which causes the rainfall during the monsoon period are the monsoon trough, monsoon depressions, offshore vortices, mid-tropospheric cyclones, orographic influences etc.. The orographic component has high influence in rainfall distribution over the State. During break monsoon conditions, Kerala experiences a dry spell. The monsoon rainfall is of great economic importance for agriculture, irrigation, hydro-electric projects etc. and vagaries of monsoon have a very crucial impact on the economy of the State.

b) Storms and Depressions:

The State experiences the influence of storms and depressions mainly in the post-monsoon season and in the month of May. During the period 1891 to 1970 the State experienced 13, 4, 3 and 1 storms in the months November, December, May and October respectively (IMD, 1986). Almost all the storms in the post-monsoon period originate in the Bay of Bengal between 5°N and 13°N latitudes and they move in west-northwesterly direction and strike North Tamil Nadu or South Andhra coast. Most of these storms weaken and decay when they enter into the land area but a few of these may cross the peninsula and intensify. In the months of May, storms generally form between latitudes 7°N and 12°N and most of the storms in the Arabian Sea moves to the Arabian coast, but those forming close to the Indian coast may travel towards north-east and have a landfall somewhere along the coast. Only a few of the storms develop into their full strength, most of the systems remains as lows or depressions. These tropical storms cause intensive winds and heavy rainfall over the whole

State, especially in the South Kerala, depending upon the track of movement.

c) Thunderstorms:

Thunderstorms occur in the pre-monsoon and post-monsoon periods, especially in the South Kerala. Thunderstorms in the north east monsoon season occur mostly at night or early morning hours. During the pre-monsoon season, intense heating of the ground results in high convection, formation of cumulonimbus clouds and thereby thunderstorm activities. Maximum thunderstorm activity occurs in month of April and a secondary maximum in the month of October. According to Pisharoty (1986), each station in South Kerala experiences 60-100 thunderstorms during an year.

3.2.8 Weather Related Hazards:

a) Floods and Droughts:

These are meteorological in origin, and are considered to be two extreme conditions of the variability of rainfall. Both these natural phenomena affect very badly the economy of the State through the damage caused to agricultural production. The continuous heavy rainfall over the steep and undulating terrain of the highland region, particularly when the soil and surface storage are already fully charged with water, results in the swell-up of rivers and submerges the low lying areas. Siltation and encroachments of the river banks aggravate the flood problems in the State. The year 1924 witnessed unprecedented floods in almost all rivers of Kerala. Even though 1924 flood levels have not been surpassed in most of the rivers, 1961 too was an year of heavy floods. Seven to ten days of heavy precipitation during the monsoon caused the rivers to overturn the banks. It is reported that 115 people lost their lives, over 50,000 houses were completely or partially damaged and 115,000 acres of paddy were seriously affected (Pubic Works Department, 1974).

Aridity and drought refer to the lack of water; but aridity is a permanent feature of a region, while drought is a short period phenomena caused by variability of rainfall. Even though the State has comparatively high annual rainfall, variability in the monsoon activities causes the development of drought conditions.

b) Landslides:

Because of the great damage landslides cause to life, engineering construction, farmlands, communication systems, highways, dams and reservoir, forest, etc., they have become a serious economic and social problem. This phenomenon can occur with or without human intervention. In general, a slope exists because of the balance between the downslope components of the forces acting on the surface and the resisting force. So anything that decreases the resisting force or increases the driving force facilitates the landslide occurrence. Kerala State is highly affected by this hazard, particularly highlands of Idukki, Wynad, Malappuram and Calicut districts are highly vulnerable. Most of the slides in the State are associated with continuous heavy rainfall during the monsoon and post-monsoon periods. It is observed that in the last decade, the reported number of slide occurrences and the associated damages were high, probably because of irrational exploitation of natural resources and the resultant reduction in the stability of the slopes. Prevention of this natural hazard is nearly impossible, but it can be minimised by judicious utilization of the nature.

c) Soil and Coastal Erosion:

Soil and coastal erosion assume special significance in several parts of the State. Soil erosion in the State is due to the running waters in the monsoon periods. This erosion is a natural process, but the soil loss is balanced by the soil formation from the parent rocks. This balance has been upset as a result of indiscriminate utilization of natural resources, such as deforestation, overgrazing, unwisefull drainage pattern, forest fire etc.. Soil erosion results in the depletion of the rich nutrients from the top soil, silting of rivers and reservoirs etc..

Coastal erosion is a serious problem to the long shoreline of the State during the monsoon periods and has been intensified through the years. More than 300 km of the coast is subjected to erosion, resulting in continuous recession, loss of valuable property and affects many aspects of the economy.

d) Salt Water Intrusion:

This is a worldwide phenomenon and is felt in many areas of Kerala coast, too. The important factor that facilitates the intrusion of salinity in Kerala coast is the propagation of density currents upstream, when the summer freshwater discharge decreases. This contaminates the surface and subsurface water and affects agriculture, industry and domestic requirements. A widely accepted solution to this problem is to maintain the requisite quantity of freshwater discharge all through the year.

CHAPTER IV

SPATIAL DISTRIBUTION OF HYDROMETEOROLOGICAL PARAMETERS OVER KERALA STATE

The results of the studies pertaining to spatial distribution of annual as well as seasonal rainfall, potential evapotranspiration, actual evapotranspiration, water deficit, water surplus, surface flow, underground flow and total discharge are presented and discussed in the following sections.

4.1 Rainfall:

Analysis of data pertaining to the period 1931-1980 for 42 stations distributed uniformly over the State reveals that the average annual rainfall of Kerala is 294.3 cm; it is about 2.5 times the average rainfall of India and about thrice the world average rainfall. The annual rainfall of Kerala is the second highest among all the Indian States: it is also about three times that of Tamil Nadu and more than twice that of Karnataka, the two adjoining States. Fig. 4.1 shows the variation of mean annual rainfall for each station from north to south, along with its standard deviation and extreme values recorded during the period 1931-1980. The highest annual rainfall recorded during this period was 842.5 cm at Peermede in 1968, followed by Neriamangalam in 1950 (778.7 cm). The lowest annual rainfall recorded was at Chinnar (12.3 cm) in 1939.

The spatial distribution of annual rainfall (Fig. 4.2) shows two pockets of very heavy rainfall regions ($M + 1.5\sigma$): one in the south comprising Neriamangalam and Peermede regions of Ernakulam and Idukki

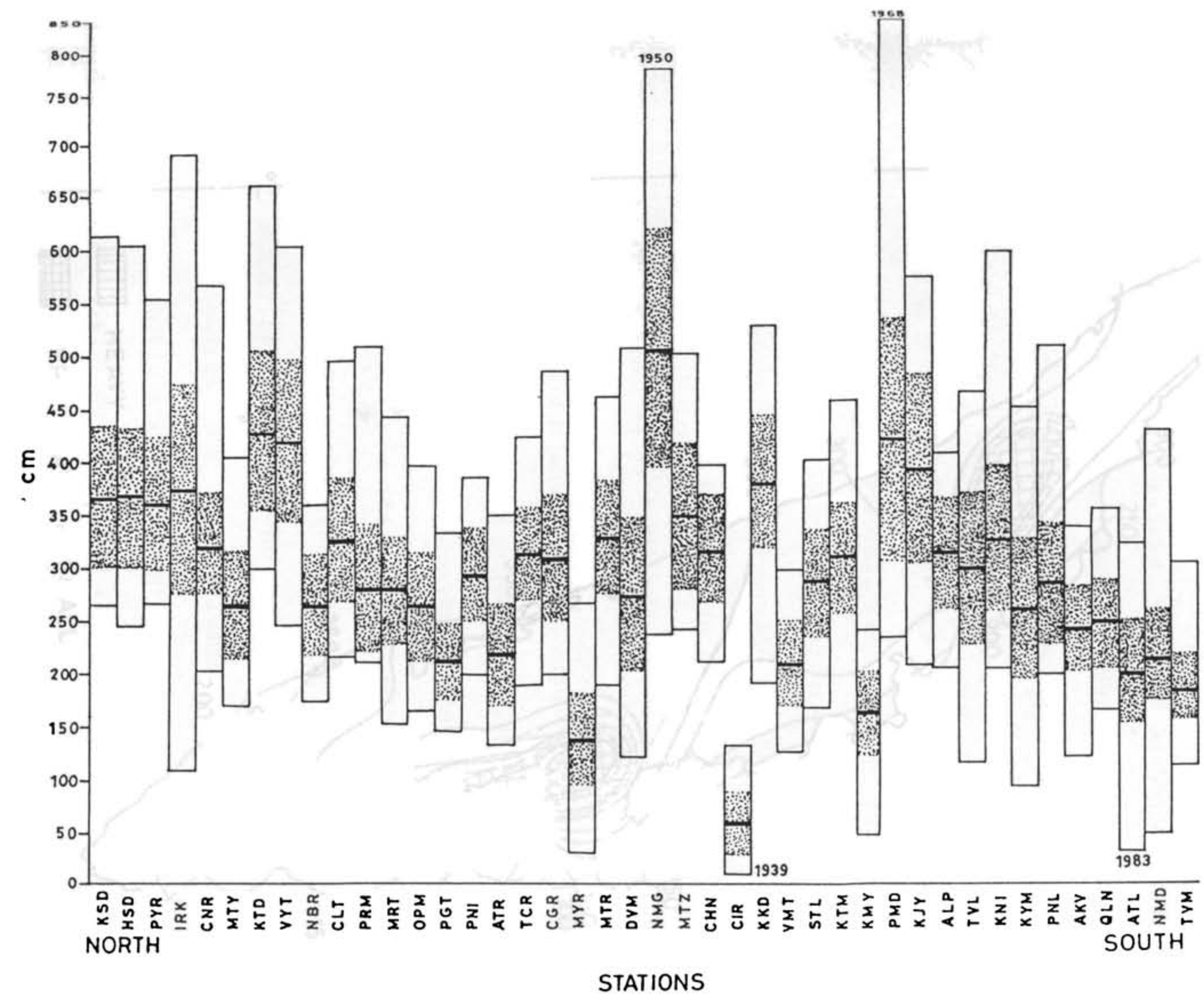


Fig. 4.1 North-South variation of mean annual rainfall over Kerala State

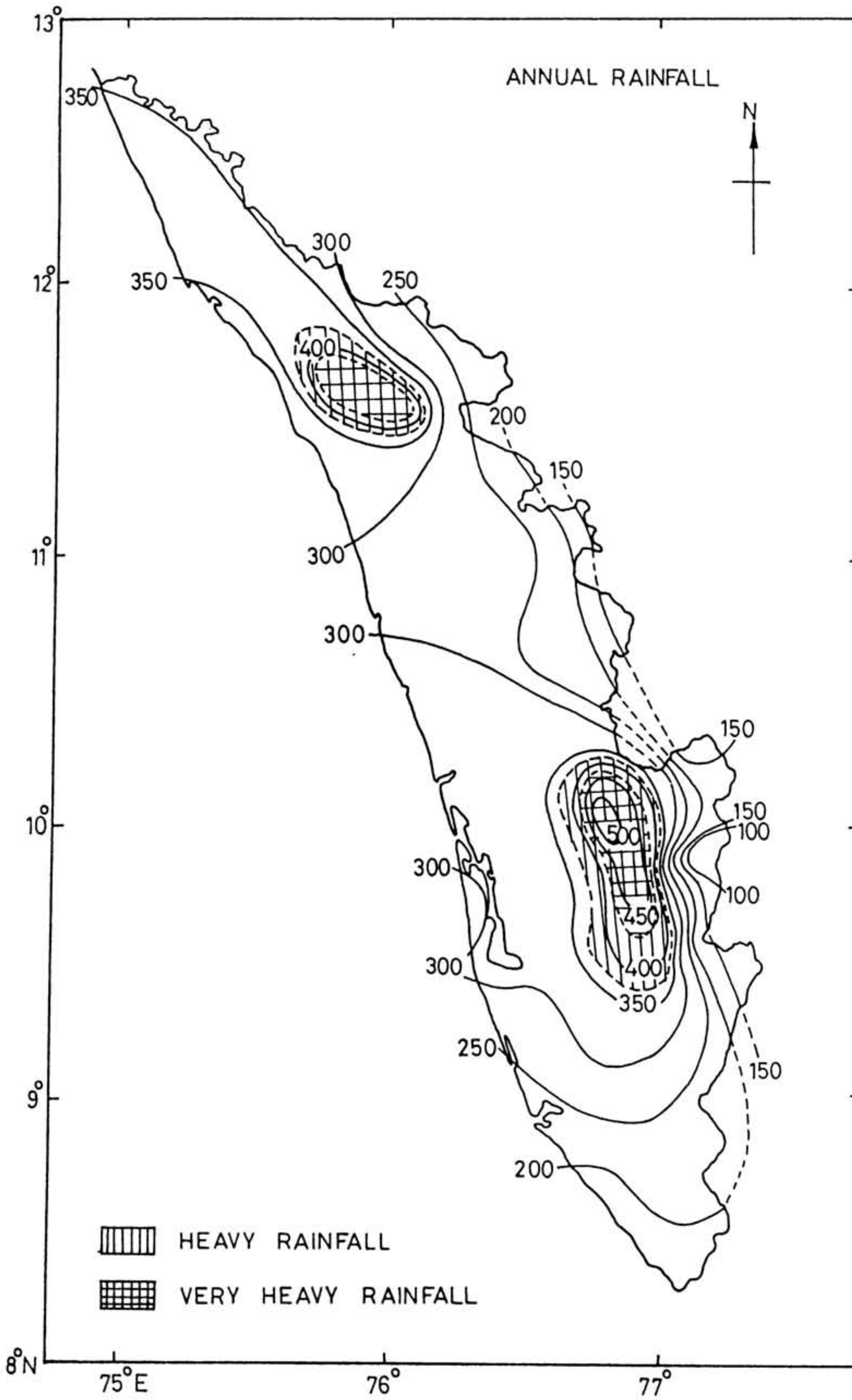


Fig. 4.2 Spatial distribution of annual rainfall over Kerala (cm)

districts, where the rainfall amounts exceed 500 cm and the other in north Kerala over Kuttiyadi and Vythiri regions of Calicut and Wynad districts. The lowest rainfall regions in the State are the extreme eastern parts of Idukki and Pathanamthitta districts, followed by the southernmost areas of the State. Among the 42 stations considered, the highest mean annual rainfall (507 cm) is observed at Neriamangalam which is in the southern heavy rainfall pocket and the lowest value is at Chinnar (60 cm), a station on the boundary of Idukki district. It is interesting to note that the highest and lowest rainfall stations are very close to each other, separated only by about 35 km. The difference between the highest and lowest mean annual rainfall is about 450 cm, which is more than 1.5 times the mean annual rainfall of Kerala. In the northern heavy rainfall pocket, highest value (442 cm) is at Kuttiyadi followed by Vythiri (420 cm).

In coastal and lowland stations, there is a sharp decrease of mean annual rainfall over the region south of Alleppey and a gradual increase is observed towards north of Cochin: it varies from 175 cm in the extreme south to about 350 cm in the extreme north. To a large extent, the isolines are parallel to the Western Ghats: there is generally an increase of mean annual rainfall from the coast to the foothills, while a decrease is observed towards the eastern flanks of the Ghats. This east-west gradient is especially pronounced over Idukki district. This general trend is partially disturbed in Palghat region due to the effect of the Palghat Gap. Ananthakrishnan et al. (1979b) found that district-wise annual rainfall increases from 181 cm at Trivandrum district to 376 cm at Calicut and drops at Cannanore district, with a steep reduction in Palghat district (236 cm). The major contribution to the annual rainfall of Kerala is by the south west monsoon, which is caused by orographic lifting of moisture-laden air from the Arabian Sea. It accounts for about 66% (195.4 cm) of the average annual rainfall of Kerala. For the whole State for the period 1901-1970, 1924 holds the record of the highest monsoonal rainfall of 339 cm against the seasonal normal of 207 cm, while the year 1918 recorded the least monsoonal rainfall of 109 cm (Ananthakrishnan et al., 1979b).

The onset of the southwest monsoon in Kerala is generally by the end of May or early June, the normal date of onset of monsoon over Kerala being 1^{st} June. In Kerala the southwest monsoon season is traditionally referred as to 'Kalavarsha', and the onset period is known as 'Edavappathi'. The onset of monsoon over Kerala has year to year variations. During the period 1901-1979, the earliest date of onset was 11^{th} May in 1955 and 1968 and the latest date was June 18^{th} in 1972. The south west monsoon rainfall exhibits wide variations in time and space due to irregular distribution, inconsistency in the dates of onset and withdrawal, breaks in the monsoon, changes in the frequency and tracks of monsoon depressions etc..

The spatial distribution of monsoon rainfall is given in Fig. 4.3. The rainfall increases progressively from 85 cm in the extreme south to about 300 cm in the extreme north. Seasonally too, there are two pockets of very heavy rainfall, as in the annual distribution. However, it is important to note that the maximum monsoonal rainfall is observed in the northern pocket; and the season's high rainfall regime in the north is spread over a large area. In the south, it is confined to a smaller area compared to that of the annual values. The season's maximum occurs at Vythiri (347 cm) which is about 80% of the annual total for the station and the minimum value at Chinnar, only 17 cm. Interestingly, Chinnar is the only station where the monsoon season's rainfall is the lowest among the four seasons; here, the rainfall in the post-monsoon months constitutes about 48% of the annual rainfall, compared to 28% in the monsoon months. The monsoon rainfall is more than 80% of the annual rainfall in the extreme northern parts of the State and gradually decreases to about 45% in the extreme south. The general pattern is disturbed over the low rainfall region around Chinnar and heavy rainfall pocket around Neriamangalam.

The next important season, which contributes significantly to the rainfall regime is the post-monsoon season, especially in south Kerala. The rainfall over the southern parts of the State during this season depends largely on the frequency and tracks of the tropical storms. In the absence of tropical disturbances, easterly waves over the south peninsula are mainly responsible for the rainfall in south Kerala. The distribution pattern is given in Fig. 4.3. About 18% of the average annual rainfall of the State is observed in this season, varying from 9% in the north to about 30% in the south. Another notable feature of the rainfall during this season is that, there is no seasonally high rainfall regime in the northern parts. The season's highest rainfall (95 cm) is observed at Neriamangalam, though its contribution to annual rainfall is only about 18%. As mentioned earlier, the percentage contribution of post-monsoon rainfall to the annual rainfall is highest at Chinnar (48%), the station which receives the lowest rainfall during the season. In this period, coastal stations south of Cochin have a uniform value of about 55 cm of rainfall.

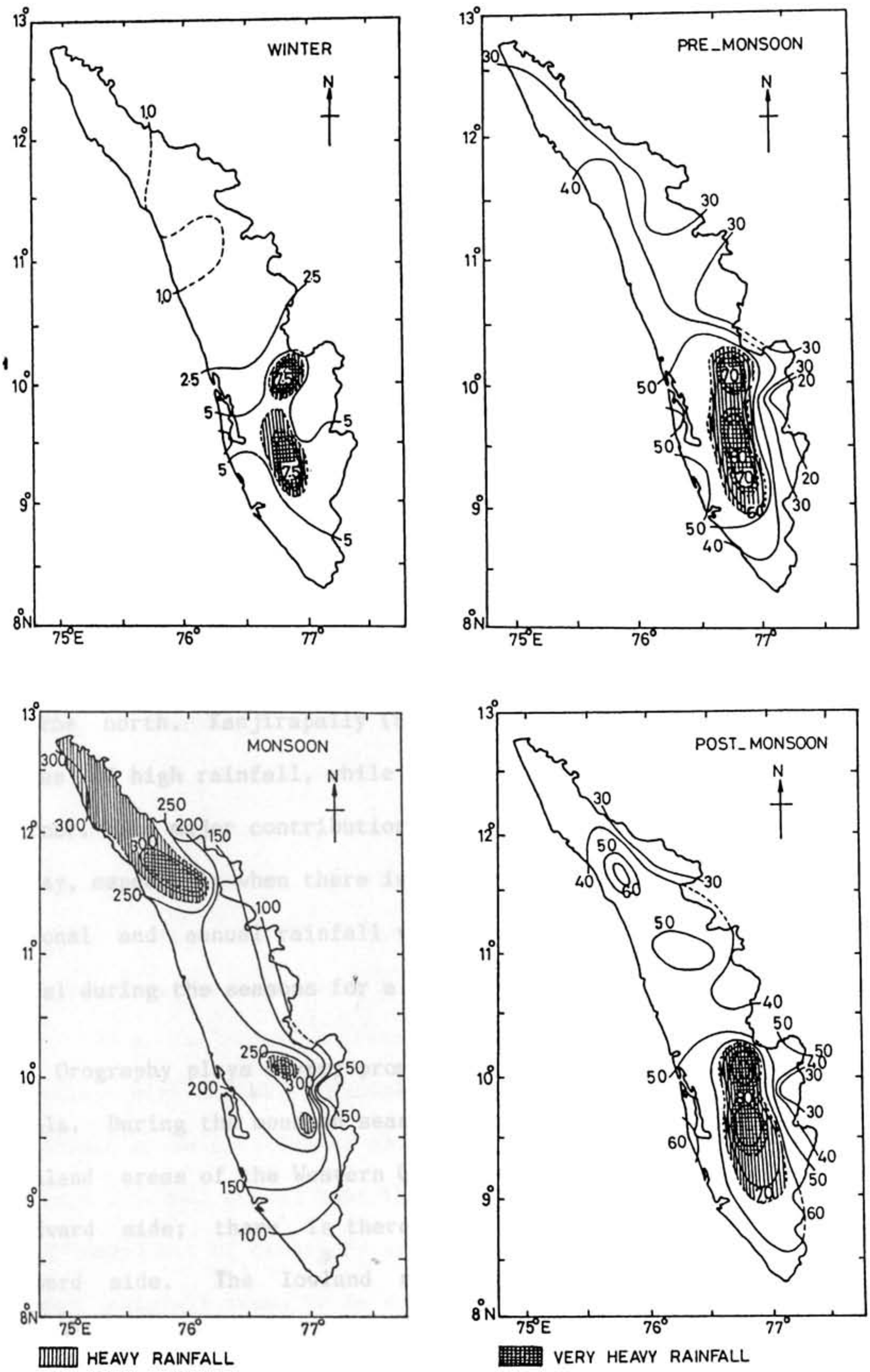


Fig. 4.3 Spatial distribution of seasonal rainfall over Kerala (cm)

The winter season contributes very little (1%) to the average annual rainfall of the State: varying from 0.2% in the north to about 3% in the extreme south (Fig. 4.3). The lowest values (0.5 cm) are observed in the extreme northern parts of the State, while the maximum is at Neriamangalam (9 cm).

The pre-monsoon season or the hot weather period contributes about 15% of the average annual rainfall of Kerala State. The distribution pattern given in the Fig. 4.3 shows that north of Cochin, the isolines are very flat, values ranging around 30 to 40 cm. As in the post-monsoon season, in this season too, there is no high rainfall pocket in the northern parts: the highest rainfall in the southern pocket is more than twice the rainfall in the north. Kanjirapally (89 cm) and Neriamangalam (78 cm) are the places of high rainfall, while the lowest rainfall (11 cm) is observed at Chinnar. The major contribution to this season's rainfall is in the month of May, especially when there is an early onset of monsoon in south Kerala. Seasonal and annual rainfall values and percentage contribution to the annual during the seasons for a few stations are given in Table 4.1.

Orography plays a very prominent role in the rainfall distribution of Kerala. During the monsoon season, the moist southwesterly winds rise over highland areas of the Western Ghats and produce very good rainfall in the windward side; there is therefore a decrease from west to east on the leeward side. The lowland and midland areas of Kerala have copious rainfall due to this orographic lifting in the monsoon season. Raghavan (1964) reported that the distance of 150 m contour from the coast appears to bear a significant negative correlation with monsoon rainfall over the

Station	Winter		Pre-monsoon		Monsoon		Post-monsoon		Annual
	cm	%	cm	%	cm	%	cm	%	cm
KSD	1	0.3	30	8.2	302	82.5	33	9.0	366
CLT	1	0.3	42	12.8	239	73.1	45	13.8	327
CHN	4	1.3	52	16.5	204	64.8	55	17.4	315
TVM	5	2.7	39	21.2	85	46.2	55	29.9	184
NMG	9	1.8	78	15.4	325	64.1	95	18.7	507
VYT	1	0.2	37	8.7	343	80.5	45	10.6	426
PGT	1	0.5	28	13.1	146	68.9	37	17.5	212
CIR	3	5.0	11	18.3	17	28.3	29	48.4	60

Table 4.1 - Seasonal rainfall and its percentage contribution to annual

Western Ghats. Sarkar (1966) using the dynamical model of orographic rainfall found an increase in rainfall from the coast towards inland, reaching a maximum at about 10 to 12 km from the crest of the Ghats and then a decrease. Ramachandran (1972) concluded that the rainfall decreases gradually and continuously from the coast through Palghat region, but over the north and south of the Gap, rainfall increases with height. Muralidharan et al. (1985) observed that the southwest monsoon rainfall increases from the west coast to foothills and decreases up to a height of about 600 m and then increases upto 1.3 km and thereafter sharply decreases with height. Rainfall due to the northeast monsoon is found to be maximum at an altitude of about 1.8 km on the windward side. But Sinha Ray et al. (1982) argued that the rainfall along the west coast has a very small component of orography and the main factor which contributes to the coastal rainfall seems to be synoptic and sub-synoptic scale systems and convective instability.

In general, at all individual stations, the year-to-year annual rainfall variability is smaller than seasonal rainfall variability. The lowest annual variability is observed at the coastal station Ponnani (15%) and highest at Chinnar (47%). The coefficient of variation of annual rainfall for the State as a whole is 14% and the values for the districts ranges from a minimum of 13% at Ernakulam district to a maximum of 19% at Trivandrum district (Ananthakrishnan et al., 1979b). Figs. 4.4 and 4.5 show the annual and seasonal variability distributions. Of the four seasons, the monsoon season has the least coefficient of variation, while the winter season, with the least rainfall, has the highest coefficient of variation. In contrast to the general behaviour, for the station Marayur, the least variability is in the post-monsoon season. Peermede, a station in the southern heavy rainfall pocket has high annual variability (27%), but the stations in the northern heavy rainfall pocket have low variability. In the monsoon period, the coefficients of variation range from about 18% at coastal stations to about 78% at Chinnar. For all stations, the pre-monsoon variability is higher than that of post-monsoon season. The lowest variabilities for both pre-monsoon and post-monsoon are observed at Karikode, the values being 31% and 30% respectively. During the pre-monsoon season, Hosdurg has the highest variability (80%), even higher than that at Chinnar. For almost all stations, the winter variability is more than 100%: more than 300% variability is noticed in the extreme north-east and less than 100% in the extreme south.

According to Ananthakrishnan et al. (1979b) the average annual rainfall of Kerala as a single unit for the period 1901-1970 is 297.5 cm and the highest mean annual rainfall for the State has been recorded in

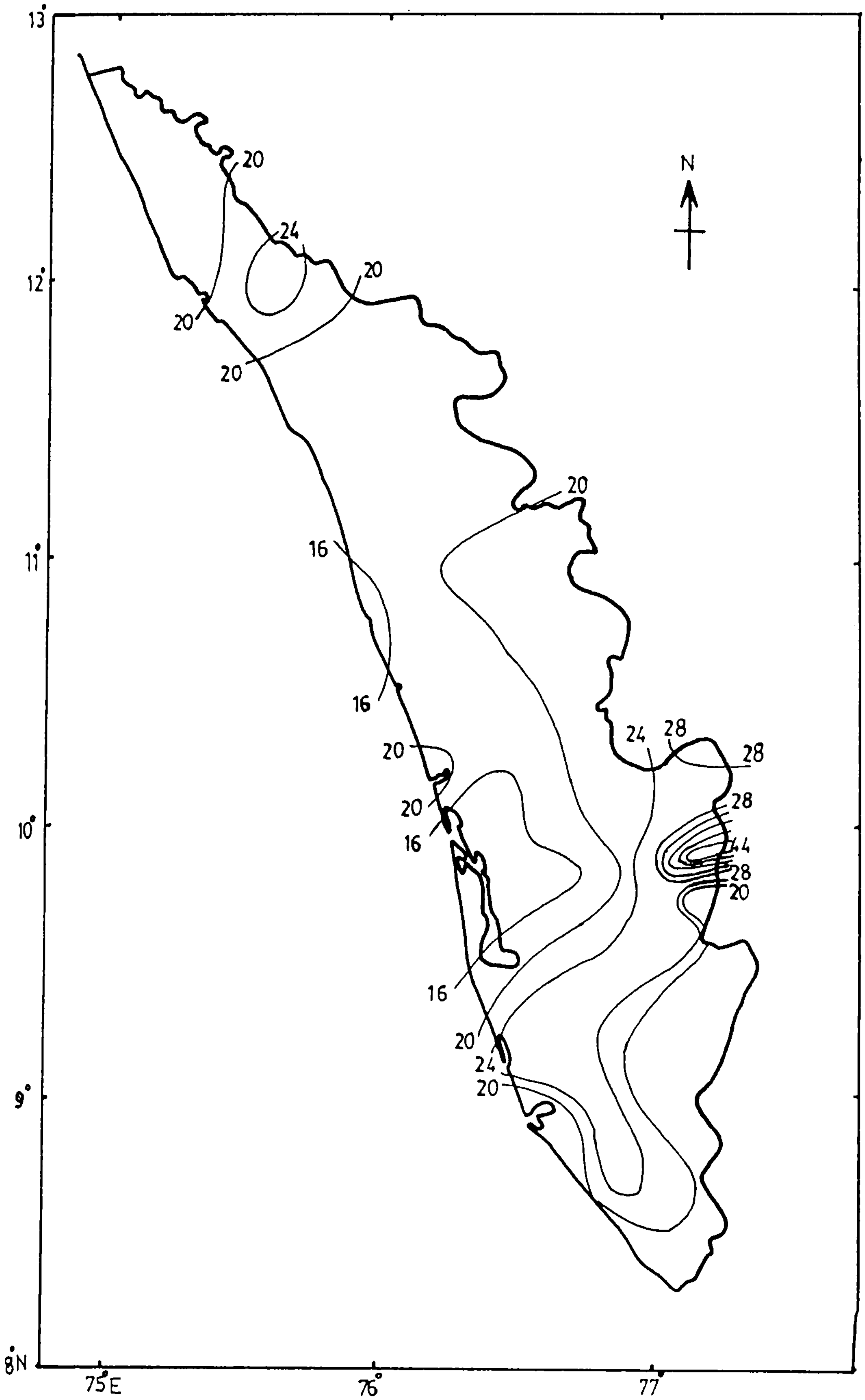


Fig. 4.4 Spatial distribution of variability of annual rainfall over Kerala (%)

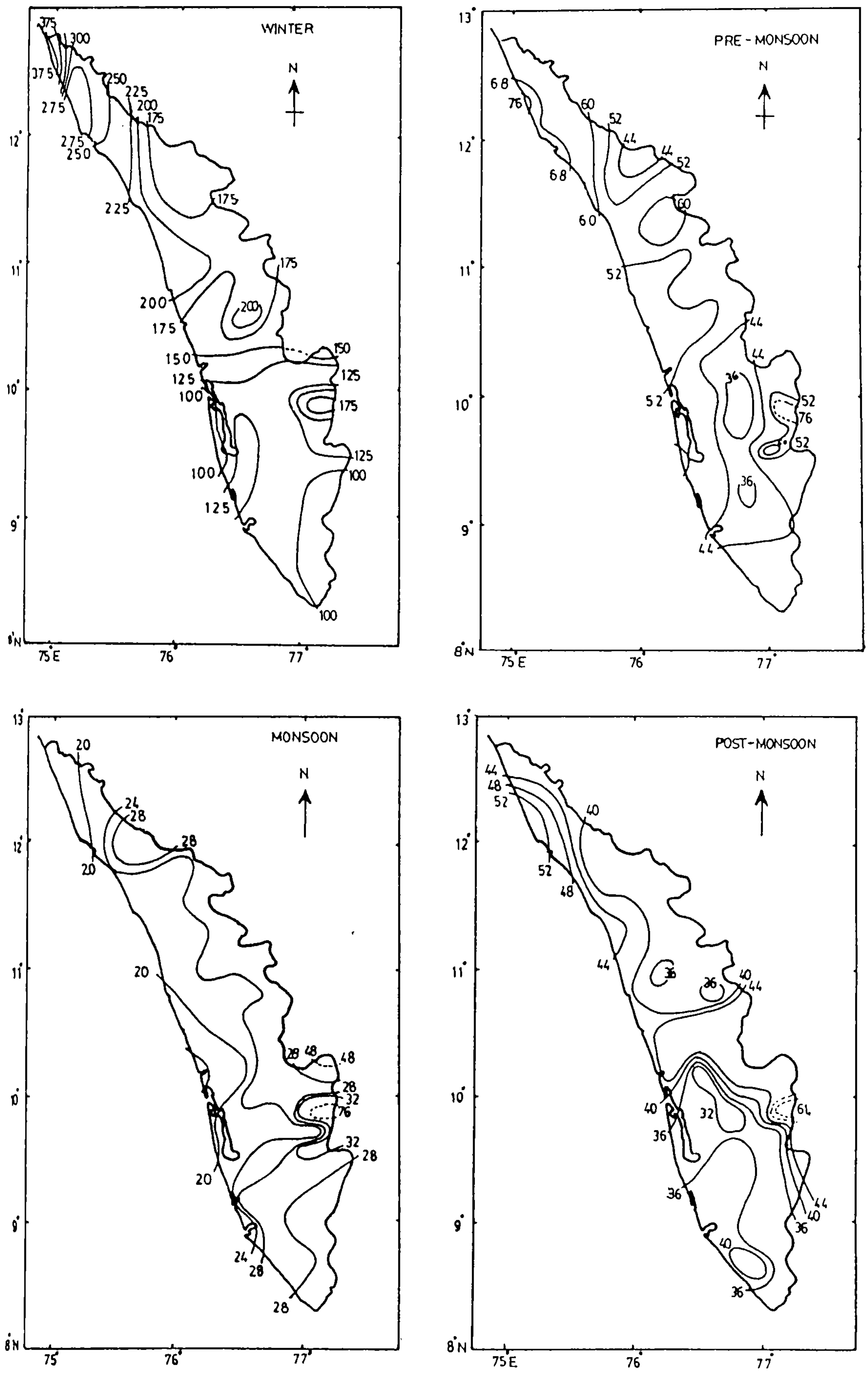


Fig. 4.5 Spatial distribution of variability of seasonal rainfall over Kerala (%)

1961 (419 cm) followed by 1924 (416 cm). The year of lowest rainfall was 1952 (231 cm) followed by 1931 (234 cm). Statistical details of the study are given in the Table 4.2

Parameters	Winter	Pre-monsoon	Monsoon	Post-monsoon	Annual
Mean	2.7	38.5	206.9	49.2	297.3
% of annual	0.9	13.0	69.6	16.0	100.0
Lowest value	0.1	16.0	108.9	24.1	230.9
Year	1940	1945	1918	1947	1952
Highest value	8.5	91.8	339.3	81.3	418.6
Year	1943	1933	1924	1932	1961
Std. deviation	2.0	15.9	39.3	12.5	41.7
Coeff. of vari. %	74	41	19	25	14

Wettest years			Driest years		
Year	Annual rainfall	% of normal rainfall	Year	Annual rainfall	% of normal rainfall
1961	418.6	140.7	1952	230.9	77.6
1924	415.8	139.8	1965	234.2	78.7
1933	406.3	136.6	1966	237.6	80.0

Table 4.2 - Statistical parameters of rainfall of Kerala State (After Ananthakrishnan et al., 1979b) (Rainfall in cm)

Similarly, Parthasarathy and Dhar (1975a) computed the mean annual rainfall of contiguous India for the period 1901 -1960, and found to be 118.8 cm. Table 4.3 gives the statistical details of their study.

A comparison of Tables 4.2 and 4.3 gives some interesting conclusions. The difference in the data period does not make much variation in the statistical terms. The mean rainfall for the State as a whole for pre-monsoon, monsoon, post-monsoon and annual are more than twice that of the country. But in the winter season, it is only approximately half of that of the country. This is due to the fact that the western disturbances which

Parameters	Winter	Pre-monsoon	Monsoon	Post-monsoon	Annual
Mean	4.2	12.7	89.7	12.2	118.8
% of annual	3.5	10.7	75.5	10.3	100.0
Lowest value	1.1	8.6	70.1	5.3	96.1
Year	1902	1922	1918	1908	1918
Highest value	7.2	16.9	106.6	20.9	144.6
Year	1906	1933	1917	1956	1917
Std.deviation	1.5	2.1	7.8	3.6	9.6
Coeff.of vari.%	35.6	16.8	8.6	29.4	8.0

Wettest years			Driest years		
Year	Annual rainfall	% of normal rainfall	Year	Annual rainfall	% of normal rainfall
1917	144.6	121.7	1918	96.1	80.9
1956	139.6	117.5	1920	100.4	84.4
1933	136.3	114.7	1905	102.8	86.5

Table 4.3 - Statistical parameters of Indian rainfall
(After Parthasarathy and Dhar, 1975a)
(Rainfall values in cm)

are the major rain producing systems during this season, do not affect Kerala State. The percentage contribution of monsoon rainfall to the annual total of the State is less than that for the whole country, due to comparatively high percentage of post-monsoon rainfall in the State. The coefficient of variation of rainfall over the State is higher (nearly double or more) than that of contiguous India except during post-monsoon season. It should also be noted that the excess rainfall over normal (40%) during the wettest year (1961) over Kerala was higher than that of contiguous India (22% in 1917). Similarly during the driest year in Kerala (1952), the deficit (22%) was more than that of contiguous India in its driest year (19% in 1918). The years of extremes of rainfall for the State and country do not coincide.

The statistical analysis of spatial distribution of annual and seasonal rainfall of the State is summarised in Table 4.4. The spatial coefficient of variation is the highest in winter and the lowest in post-monsoon season. A prominent feature observed in this analysis is that annual variability is less than seasonal variabilities. The north-south gradient in the monsoon season is in a direction opposite to that for all other seasons.

Parameters	Winter	Pre-monsoon	Monsoon	Post-monsoon	Annual
Mean (M)	3	43	195	53	294
Lowest value	.4	11	17	24	60
Station	HSD	CIR	CIR	MTY	CIR
Highest value	9	89	343	95	507
Station	NMG	KJY	VYT	NMG	NMG
Std. devi. (σ)	2	16	75	15	85
Coeff. of vari.%	72	36	38	28	29
M + σ	5	59	270	68	379
M + 1.5 σ	6	67	307	75	422
M - σ	1	27	120	38	209
M - 1.5 σ	-	19	83	30	167

Table 4.4 - Statistical parameters of spatial distribution of mean rainfall over Kerala State (rainfall in cm)

Figs. 4.6 and 4.7 show the mean monthly distribution of rainfall of a few stations. Stations in the southern parts have the highest monthly rainfall in June, but as one moves to the north, the maximum precipitation is in the month of July. Primary maximum occurs in June for the districts from Trivandrum to Trichur, except Kottayam and it is observed in July for other districts (Ananthakrishnan et al., 1979b). The heaviest mean monthly rainfall of 140 cm occurs at Vythiri, followed by 130 cm at Kuttiyadi: both are in the northern heavy rainfall region, and both the maxima occur in the month of July. The lowest rainfall values are observed in the months of

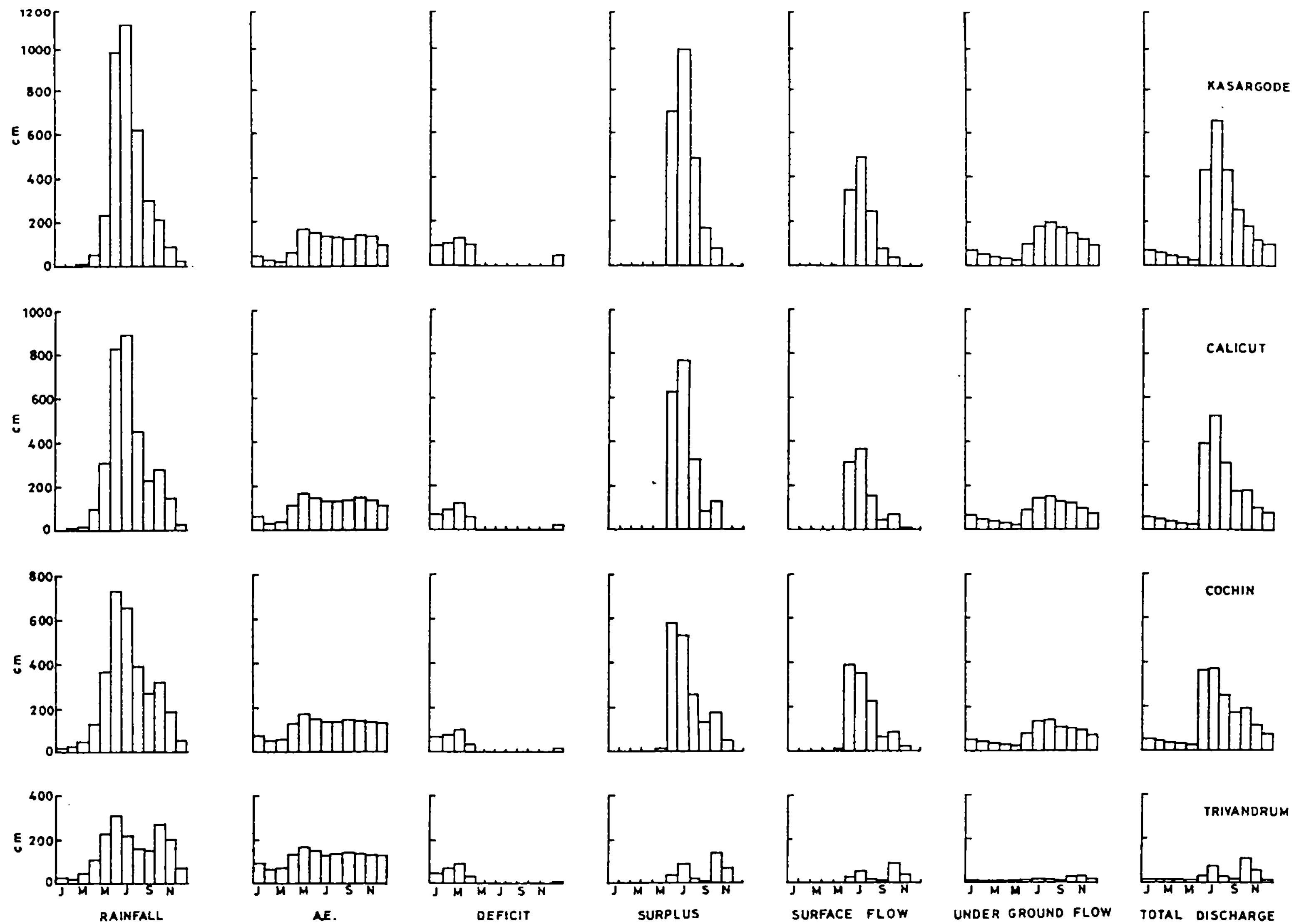


Fig. 4.6 Distribution of mean monthly values of hydrometeorological parameters at a few selected stations

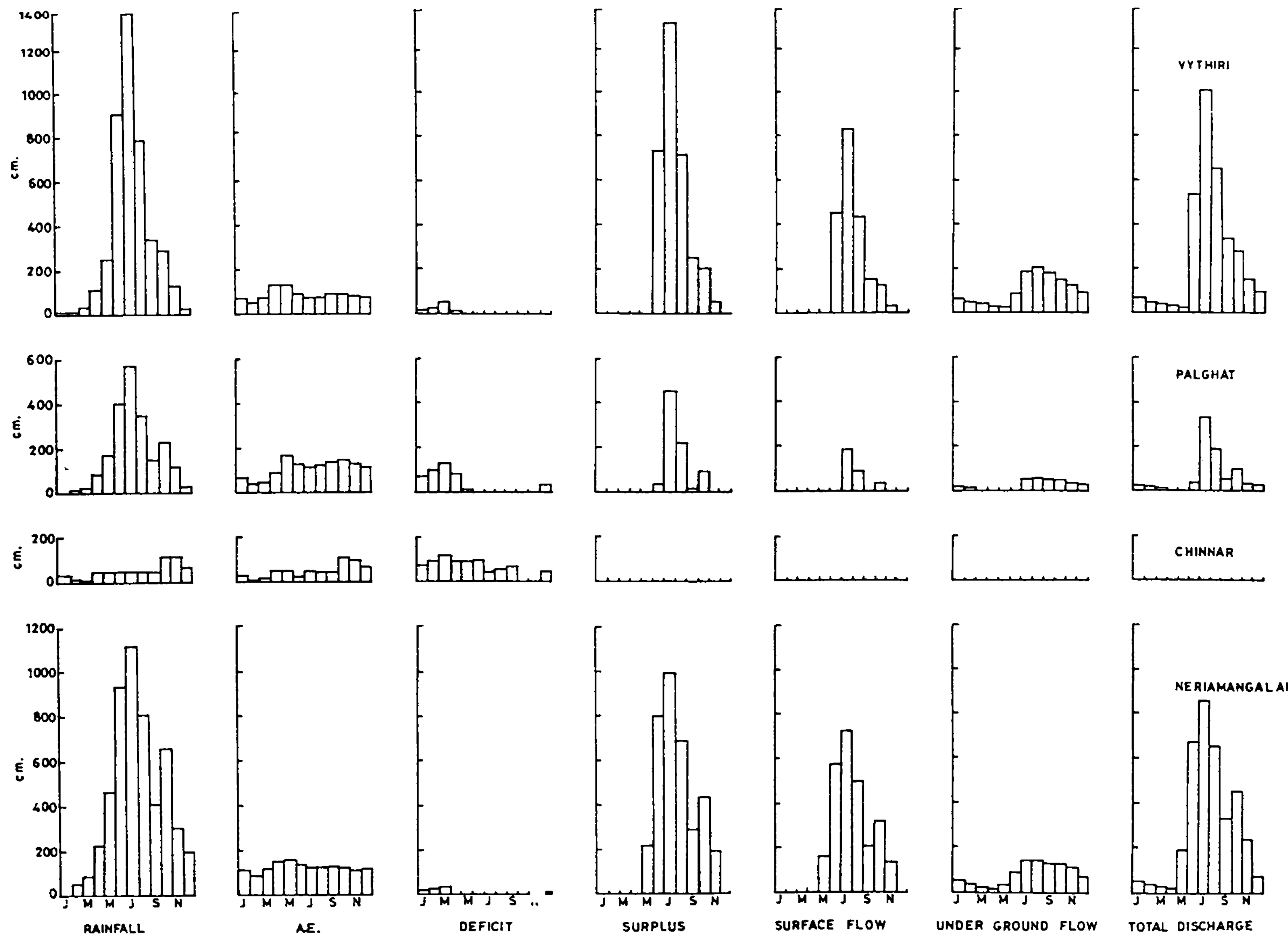


Fig. 4.7 Distribution of mean monthly values of hydrometeorological parameters for a few selected stations

January or February. It is interesting to note that there is a general trend of decreasing maximum rainfall towards south and an increasing trend in minimum rainfall amounts towards the same direction. But, for the station Chinnar, the maximum occurs in November. In the northern parts, the major contribution to the annual rainfall is the months of June, July and August; but in the southern districts it is more widely distributed among all the months. A double maxima can be observed at all stations, except in the extreme north. The secondary maximum which is due to the northeast monsoon, is very much pronounced in the south, where the average monthly rainfall for the whole north east monsoon period is very close to that of south west monsoon.

The highest variability of monthly rainfall of more than 400% has been observed in the extreme north region in February, and the lowest values (less than 30%) are also observed in the same region in June or July. In about 75% of the stations, minimum monthly variability has been observed in July. The monthly coefficient of variation patterns for a few stations are given in Fig. 4.8. One salient feature of this, compared to monthly rainfall pattern (Fig. 4.6 and 4.7) is that, for most of the stations the rainfall distributions show a bimodal structure, but the rainfall variability patterns show a trimodal structure. Two maxima of coefficient of variation correspond to two minima of rainfall, which are observed in the months of January or February and in September. A third maxima of variability is observed in the month of May, even though there is an increase in rainfall amounts. This is due to the early onset of monsoon in certain years. The variability in May is more than that of September for most of stations, even though the average rainfall in May is more than

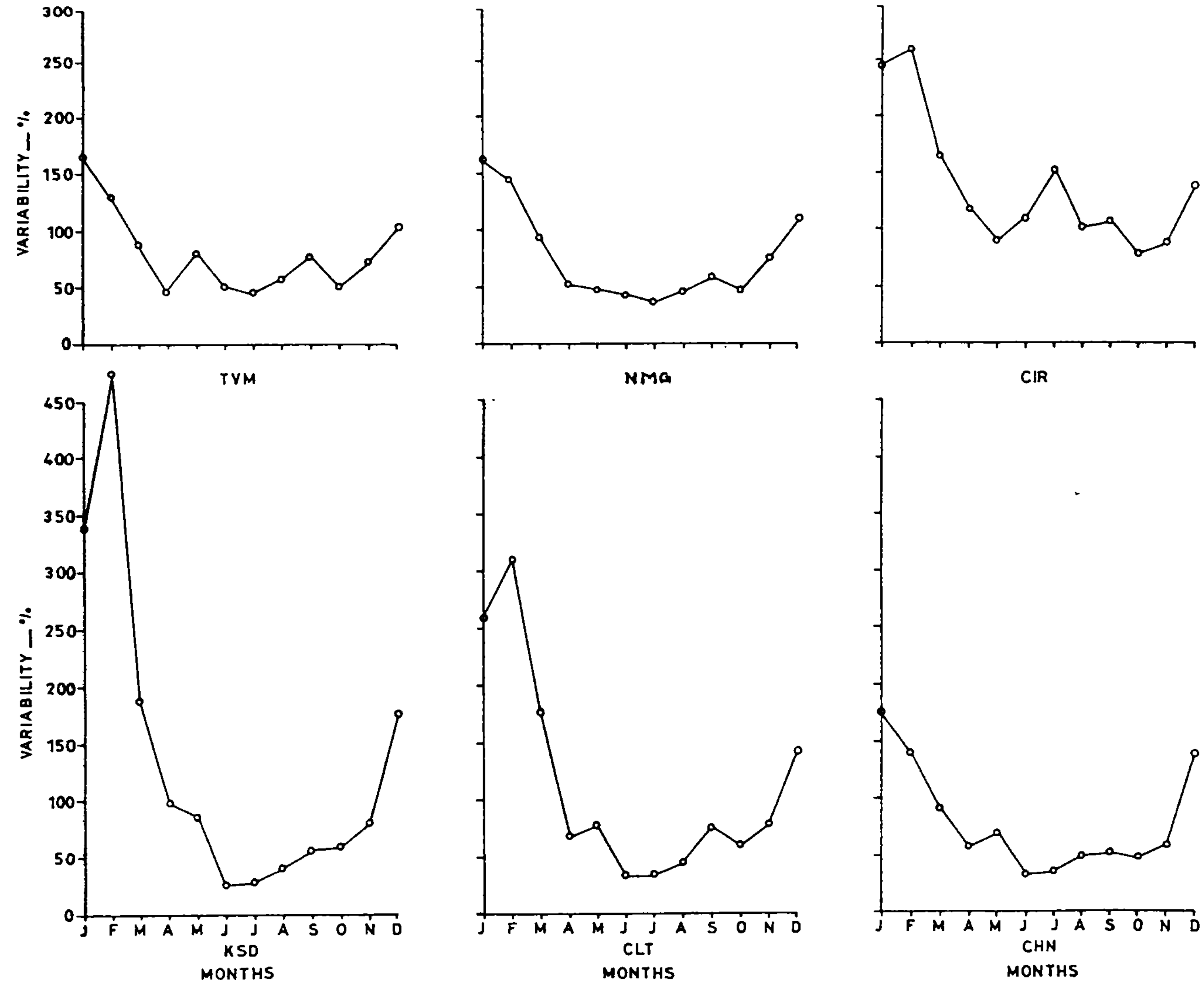


Fig. 4.8 Distribution of coefficients of variation of monthly rainfall at selected stations

that of September. For Chinnar and Marayur, maximum variability is in July.

Normal weekly distributions of rainfall for a few selected stations are given in Fig. 4.9. A sharp increase for almost all stations can be observed in the 23rd week (week beginning on 4th June), and is very prominent in north Kerala in association with the onset of monsoon. Many stations in the south have shown a peak in the same week. In the north, this maximum occurs in the 29th week (week beginning on July 18th). Highest normal weekly rainfall occurs at Vythiri (35 cm) during the 29th week, and this is the only station which experiences more than 30 cm of rainfall during weeks and more than 25 cm during 6 consecutive weeks.

In the extreme north, more than one third of the weeks experience less than 1 cm of rainfall while in more than 5 weeks, the rainfall exceeds 20 cm. But it is interesting to note that the number of weeks which have less than 1 cm of rainfall decrease towards south; and also none of the stations south of Malappuram district have more than 20 cm of weekly rainfall. In the north, the weekly distribution shows a slight secondary peak between 40th (week beginning on first October) and 43rd week, a fact which was not evident in the monthly distribution; while in the south, the secondary peak is very prominent during the same period.

4.2 <u>Potential Evapotranspiration:</u>

The mean annual and seasonal distributions of Potential Evapotranspiration (P.E.) over the State are shown in Fig. 4.10 and 4.11. Since P.E. depends mainly on temperature, isolines are very much parallel to the Ghats. Distribution of P.E. values are uniform in the coastal

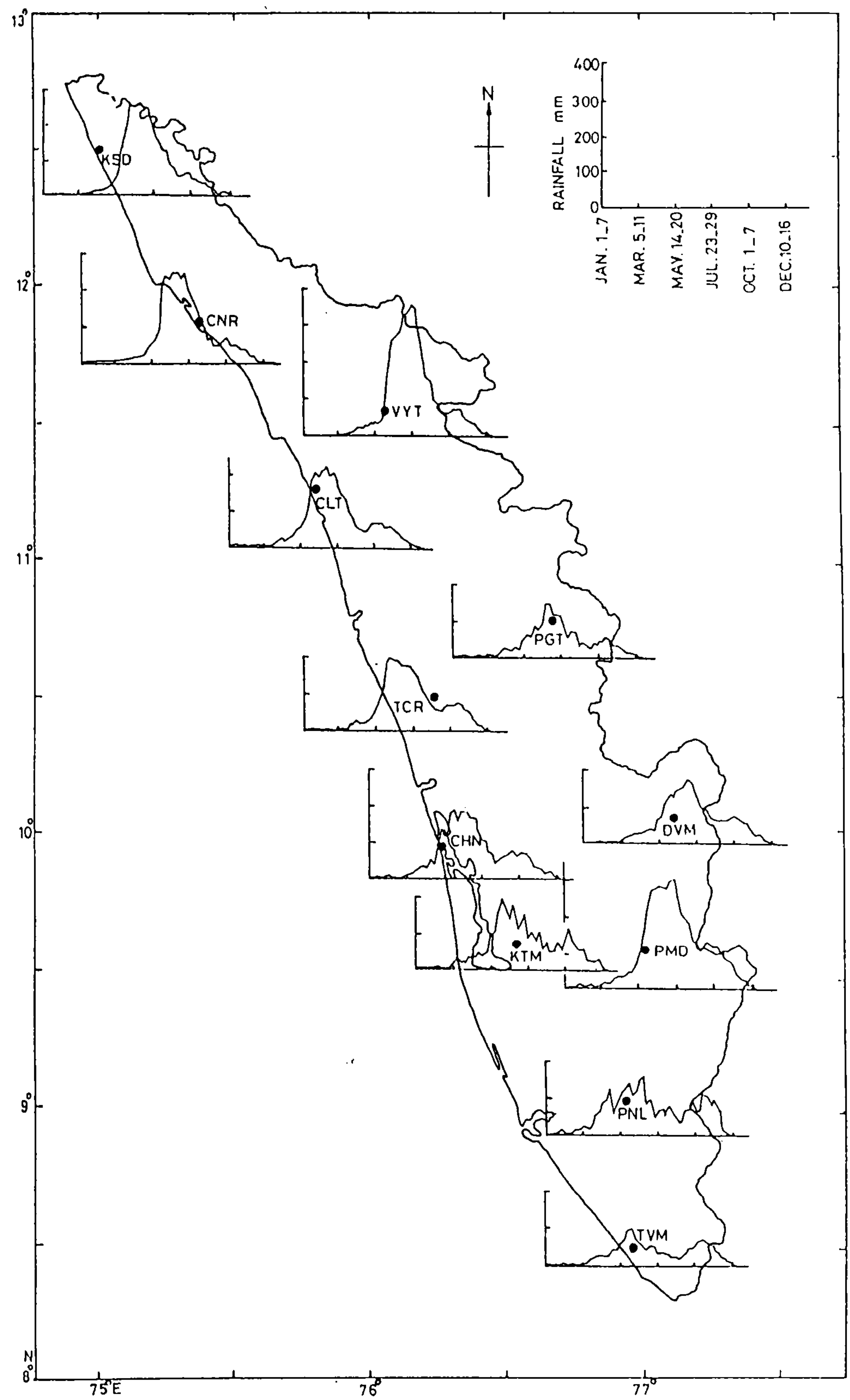


Fig. 4.9 Distribution of normal weekly rainfall at a few selected stations

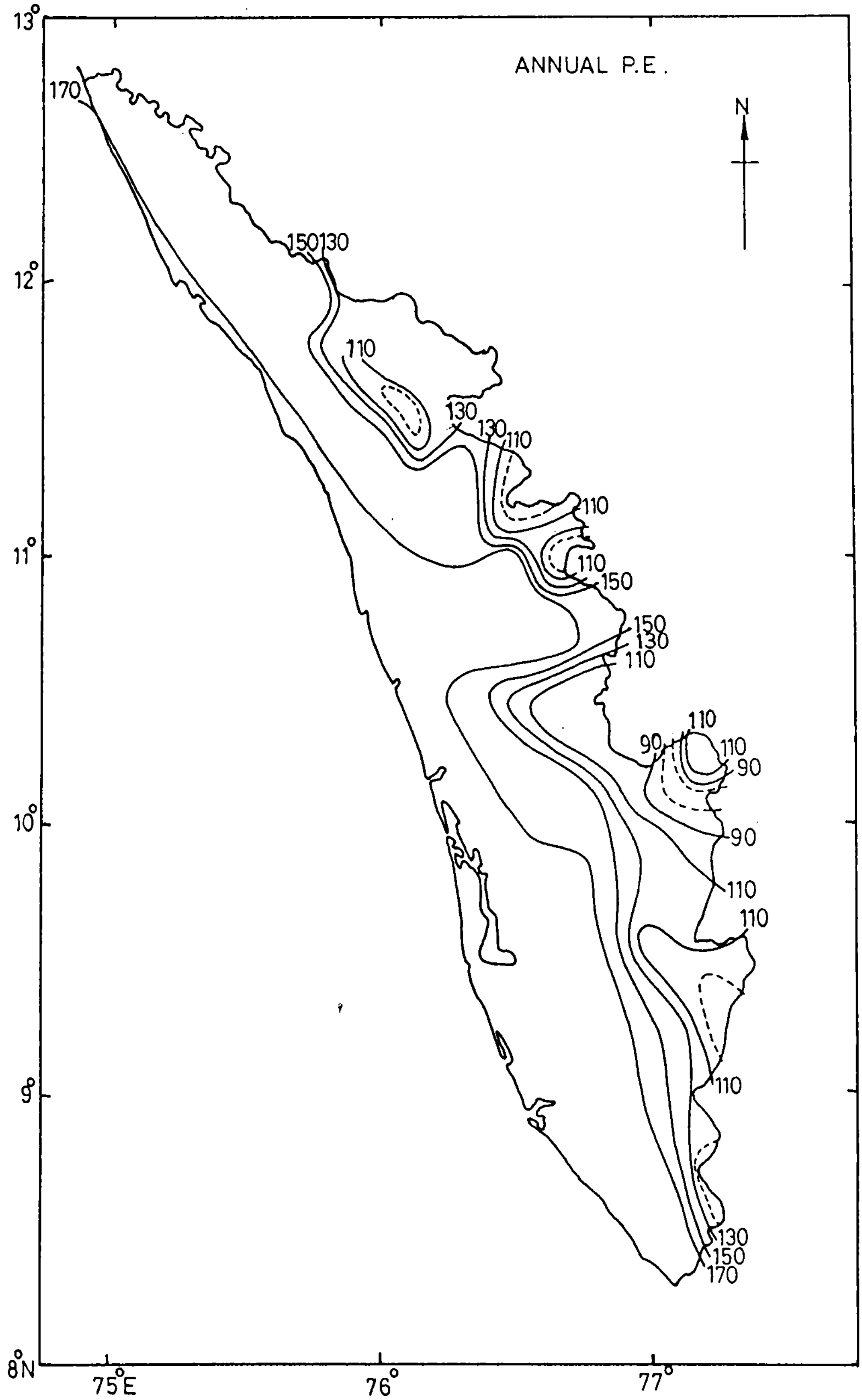


Fig. 4.10 Spatial distribution of annual P.E. over Kerala (cm)

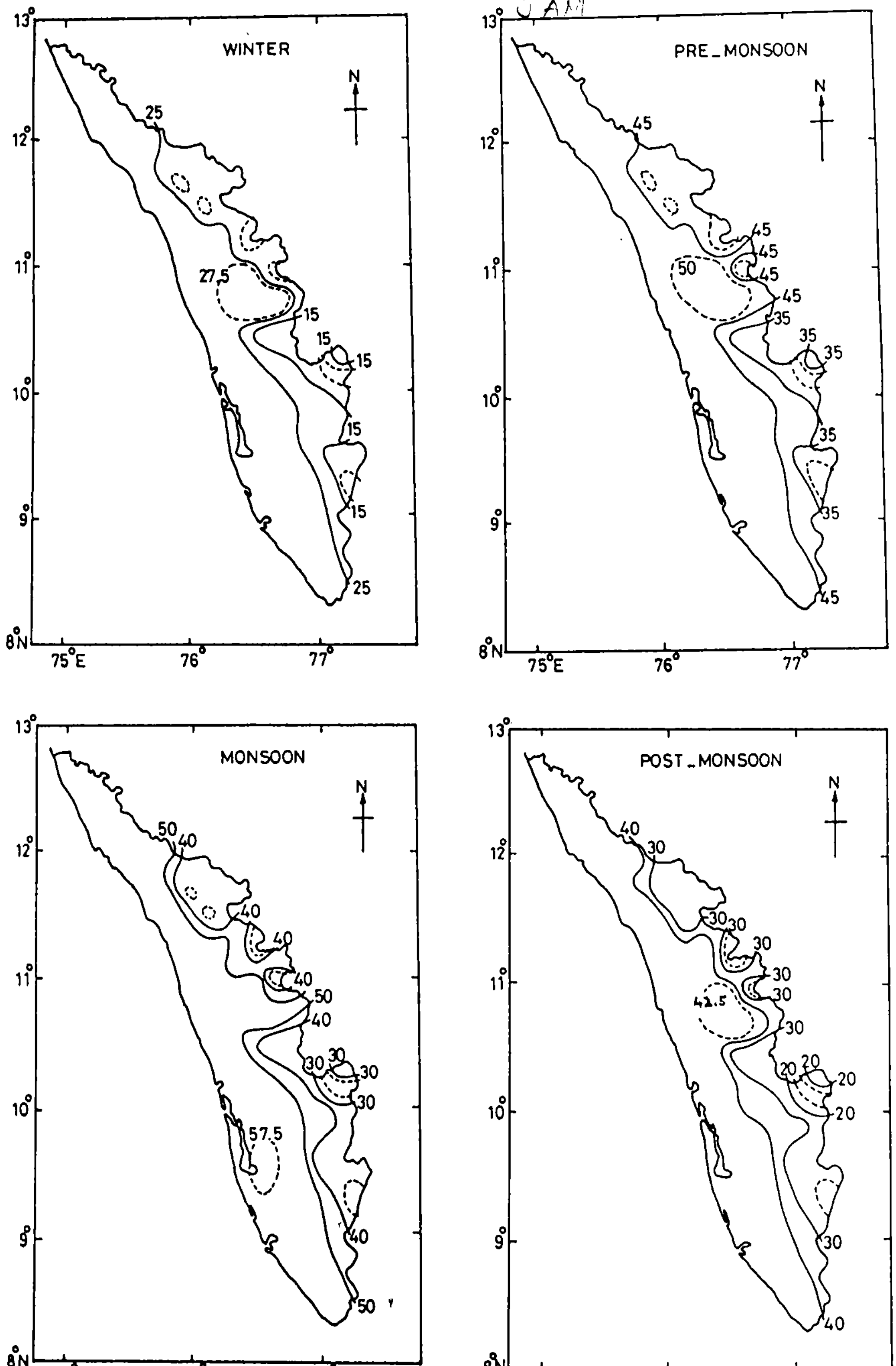


FIG. 4.11 Spatial distribution of seasonal P.E. over Kerala (cm)

tracts while there exist a few pockets of low values corresponding to the hill stations in the Ghats region. Lowland and midland areas of the State have comparatively high P.E. values. The annual distribution shows values more than 170 cm over the lowlands and midlands, and the highest value of more than 175 cm occurs over Palghat Gap region and in an area surrounded by Punelur. The lowest values of annual P.E. (less than 90 cm) is seen over Anamalai hills. The distribution pattern is more detailed than that given earlier by Nair (1987). The P.E. values are higher than that estimated by Krishna Kumar and Rakhecha (1986).

The average annual P.E. for the State, using 42 selected stations is about 160 cm of which 15% is in winter, 29% in pre-monsoon, 32% in monsoon and 24% in the post-monsoon season. At this point, it is worth remembering that the average precipitation over the State is 294 cm, which is distributed very unevenly among the stations, 1% in winter, 15% in pre-monsoon, 66% in monsoon and 18% in the post-monsoon seasons. The difference in the seasonal distribution of precipitation and P.E. (water need) determines the water balance of the State, and will be discussed in later Sections.

The highest P.E. values for winter, pre-monsoon and post-monsoon are seen over Palghat region, being around 29 cm, 52 cm, and 43 cm respectively, but for the monsoon season, the highest P.E. values of more than 55 cm are observed in south-western parts of the State. There is a slight increasing tendency towards south for P.E. values of the monsoon season, due to the comparatively low monsoon activity in the south. The lowest values of all seasons are seen over the peaks of Anamalai hills, being around 10 cm, 30 cm, 26 cm, and 15 cm in winter, pre-monsoon, monsoon and post-monsoon seasons respectively.

For most of the stations, maximum normal monthly P.E. occurs in May, but for Palghat region, normal monthly P.E. values are uniformly high in all the three pre-monsoon months (about 17 cm). The lowest P.E. values are observed in February or July and among the stations, Devikulam records the lowest P.E. values in all the months, ranging from 5 cm to 10 cm.

4.3 Actual Evapotranspiration:

The spatial distribution pattern of mean annual Actual Evapotranspiration (A.E.), Fig. 4.12, has a resemblance to that of P.E. distribution. But in this case, highest values are observed in the region extending from southwestern part of the State upto Neriamangalam in the northeast. The highest value of 165 cm is at Kanjirapally in Kottayam district, which experiences very heavy rainfall in all the seasons, except the monsoon season. At this station annual A.E. is more than 95% of its annual P.E.. An increasing trend towards south has been observed in A.E., which is not seen in the case of annual P.E.. This is because of the dependence of A.E. on rainfall: the rainfall being distributed more widely among the seasons in the southern districts. The lowest values of A.E. are not at the highest elevation, but over Chinnar area, which, as already discussed, is the lowest rainfall region of Kerala State. At Chinnar, the annual A.E. is about 60 cm and it is less than 45% of the annual P.E. value there. It is interesting to note that annual A.E. is equal to annual rainfall over this region, but this does not mean that there is neither water surplus nor water deficit.

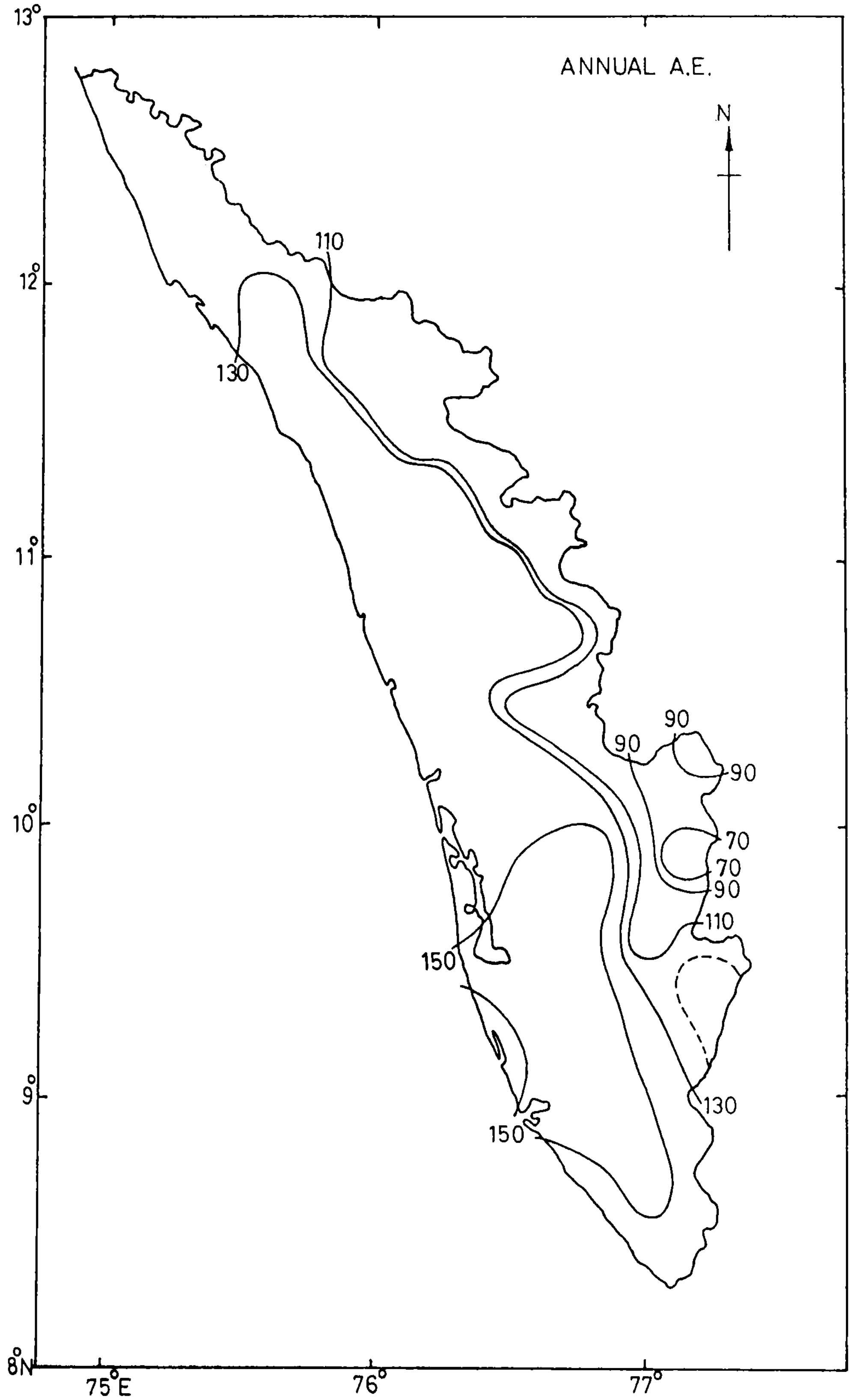


Fig. 4.12 Spatial distribution of annual A.E. over Kerala (cm)

The average annual A.E. for the State as whole is 133 cm, which is about 83% of annual P.E. and this is distributed in the four seasons as 10% in winter, 26% in pre-monsoon, 37% in monsoon, and 27% in post-monsoon. In comparison with rainfall, A.E. values have been more widely distributed among the seasons. The spatial coefficient of variability of A.E. over the State is less than that of rainfall, for all seasons and also for annual values.

Spatial distributions of A.E. over the State for different seasons are given in Fig. 4.13. During winter and pre-monsoon season, the distribution patterns of A.E. are very much different from that of P.E., but have a similarity to that of rainfall, having a concentration of high values over South Kerala, indicating that the limiting factor of A.E. in these seasons is the rainfall amount. During the winter season, highest values of about 20 cm have been observed over Neriamangalam in Ernakulam district and Kanjirapally in Kottayam district and the lowest value of A.E. (around 4 cm) have been observed over Chinnar region. Highest values of A.E. (around 47 cm) occur at Kanjirapally, followed by Konni in Pathanamthitta district for pre-monsoon season and lowest value of about 12 cm occurs over Chinnar.

A salient feature of the seasonal distribution of A.E. is that, during the monsoon period, A.E. equals P.E. all over the State except over a very small region surrounding Chinnar. So, isolines of A.E. almost coincide with that of P.E. in the monsoon season. The highest values of A.E. in the monsoon season (about 58 cm) and post-monsoon season (about 41 cm) occur in Alleppey and Kottayam districts and the lowest values

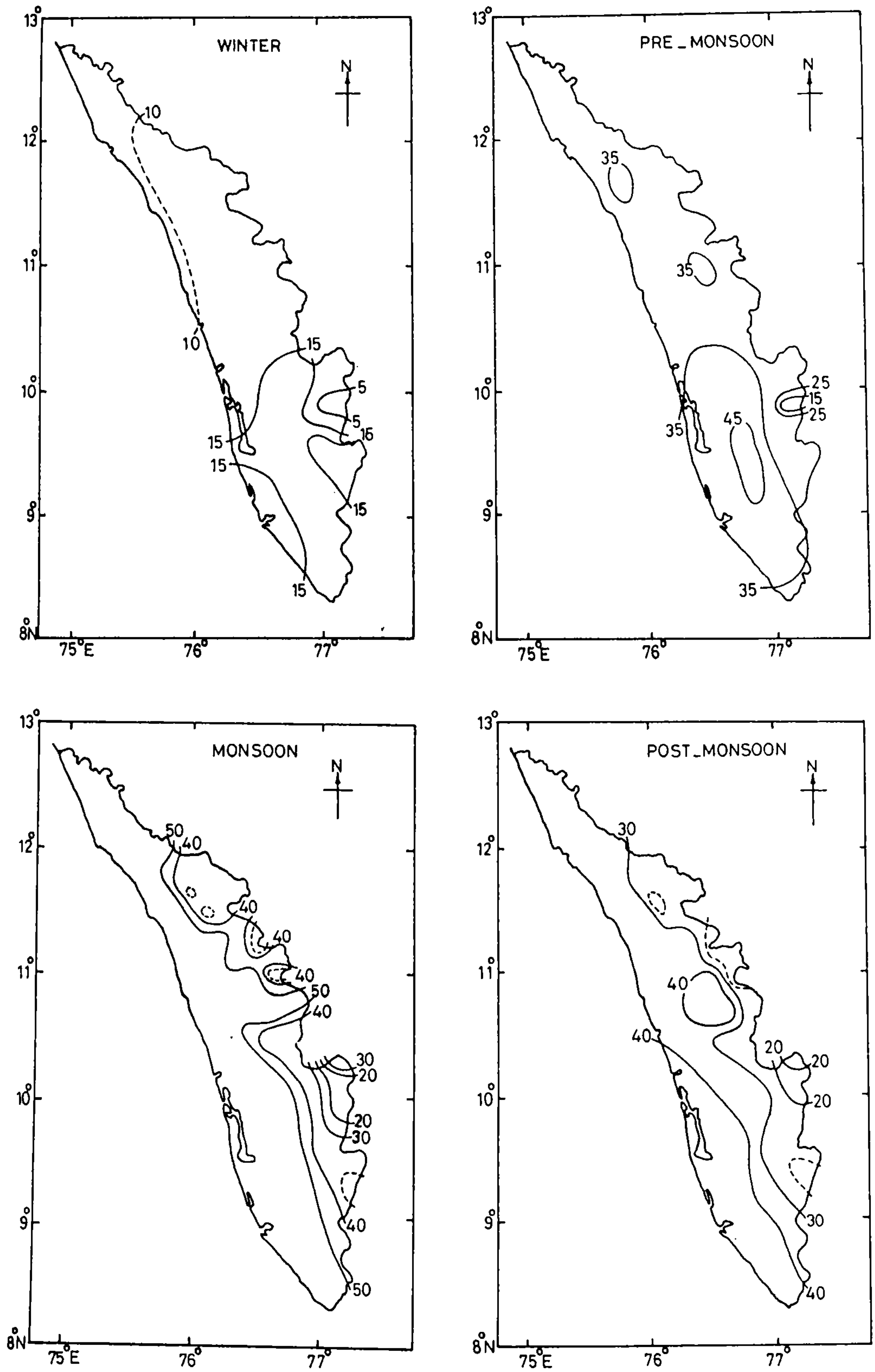


Fig. 4.13 Spatial distributions of seasonal A.E. over Kerala (cm)

during these seasons (about 17 cm and 15 cm respectively) are observed at Chinnar and at Devikulam respectively. Over high altitude stations in the south during the monsoon, A.E. equals the P.E. values.

Even though the rainfall in the northern parts is less during post-monsoon season, the A.E. distribution pattern is similar to that of P.E.. This is due to the fact that, the soil is at field capacity all over the State even upto November, except at a very few stations in the extreme north, and thus, an appreciable amount of soil moisture is available for utilisation. We have seen that P.E. values are lowest at Devikulam area for all seasons, but the minima of A.E. occur at Chinnar in all seasons, except in the post-monsoon season. An increasing trend towards south has been observed in the annual and seasonal values of A.E.. This is because, except in the monsoon season, rainfall distribution increases toward south, and therefore, the difference between rainfall and P.E. values also become less towards south. In the case of monsoon season, even though rainfall is more than P.E. at almost all stations, an increase in A.E. is observed towards south, due to the increase of P.E. in the same direction.

Fig. 4.14 shows the annual A.E. as the percentage of annual P.E., which is defined as the Index of Moisture Adequacy (I_{ma}) (Subrahmanyam et al., 1963). This index provides an objective indication of the moisture status of the region in relation to the water need. It is to be noted that all over the State the index of moisture adequacy is higher than 70%, except over a small area around Chinnar, where it is about 45%. Subrahmanyam et al. (1963) have shown that regions of more than 40% of moisture adequacy index is suitable for crop culture, and an interesting

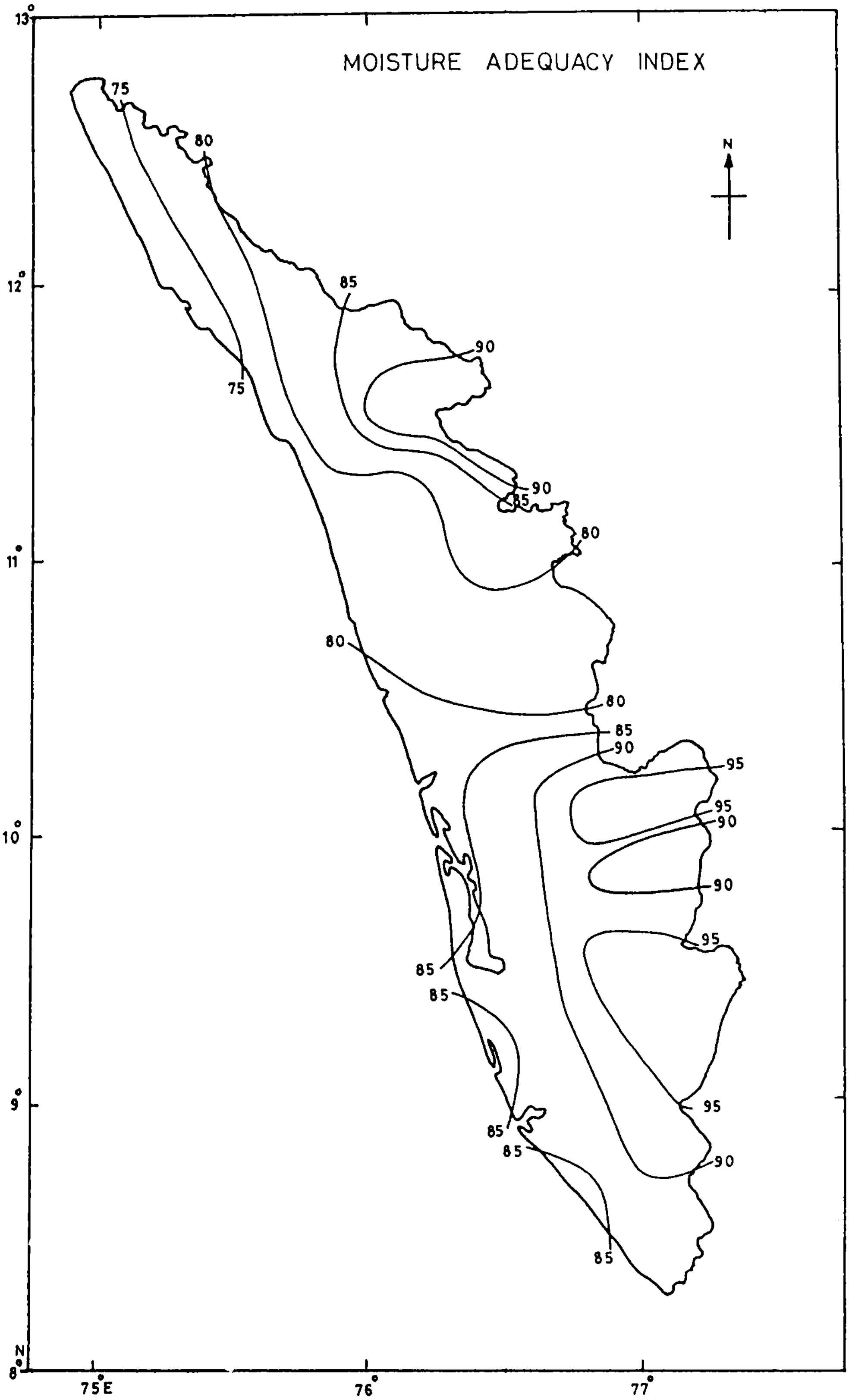


Fig. 4.14 Spatial distribution of Index of Moisture Adequacy (%)

conclusion emerging from the study is that the State as a whole is suitable for a wide variety of agricultural crops.

Mean monthly distributions of A.E. for a few selected stations are given in the Fig. 4.6 and 4.7. For all stations, A.E. is highest in the month of May even though the rainfall is highest in the months of June or July. The high values of mean monthly A.E. is found to occur at a few stations over Palghat region and over extreme northern parts (about 17 cm). This is because P.E. is highest in the month of May, for most of the stations and there is sufficient rainfall to attain this value, except in the low rainfall regions of the State. Since P.E. is low in all the months, for the high altitude stations Devikulam and Peermede, the rainfall is sufficient to fulfill the water need except in the first three months of the year. But for all other stations except Chinnar, A.E. equals P.E. during the monsoon months. For most of the stations, lowest A.E. values are observed in the month of February but for a few stations in the north, it is observed in March. The lowest A.E. values for all the months except October, November and December, occur over Chinnar region, and for October, November and December they occur over Devikulam area.

Compared to monthly rainfall pattern, monthly A.E. values are more uniform, especially from May to November. This is because for most of the stations, since rainfall is abundant from May to November, monthly A.E values during this period are controlled by P.E. values. But for all other months, it is regulated very much by rainfall values. The role of moisture utilisation can be clearly seen by comparing the distribution of A.E. and rainfall values. A close observation of monthly A.E. distribution pattern shows a secondary maximum in September or October, which is only due to post-monsoon rainfall.

4.4 Water Deficits:

From Fig. 4.15, it can be seen that the mean annual water deficits increase from 24 cm in the southwest to about 47 cm in the northwestern parts of the State, with peaks over Chinnar (77 cm) and over Palghat region (42 cm). This may appear to be paradoxical, considering that the mean annual rainfall also increases in the same direction. However, it is to be noted that the rainfall in the northern parts of the State is concentrated only in the monsoon months, with meagre rainfall in the other seasons of the year. The deficit decreases towards the east, since the water need (P.E.) reduces to the east, except in the Palghat Gap and in the Chinnar region. The spatial distribution of annual deficit follows that of P.E. distribution, with two major differences. The important one is that there is an area of very large deficit (more than $M + 1.5\sigma$) over Chinnar region, where the rainfall is least. This particular station has a deficit of 77 cm, which is about twice that at any other station. There are two other regions - extreme north and the Palghat Gap regions - which experience large deficit (more than $M + \sigma$). Devikulam region which has the lowest value of annual P.E. in the State records the least deficit of only 2 cm.

The average annual deficit for the State is about 26 cm with a spatial standard deviation of 15 cm. Statistical parameters of the spatial distribution of mean, annual and seasonal water deficits are summarised in Table 4.5. The average annual deficit over the State is about 16% of the average need of the State.

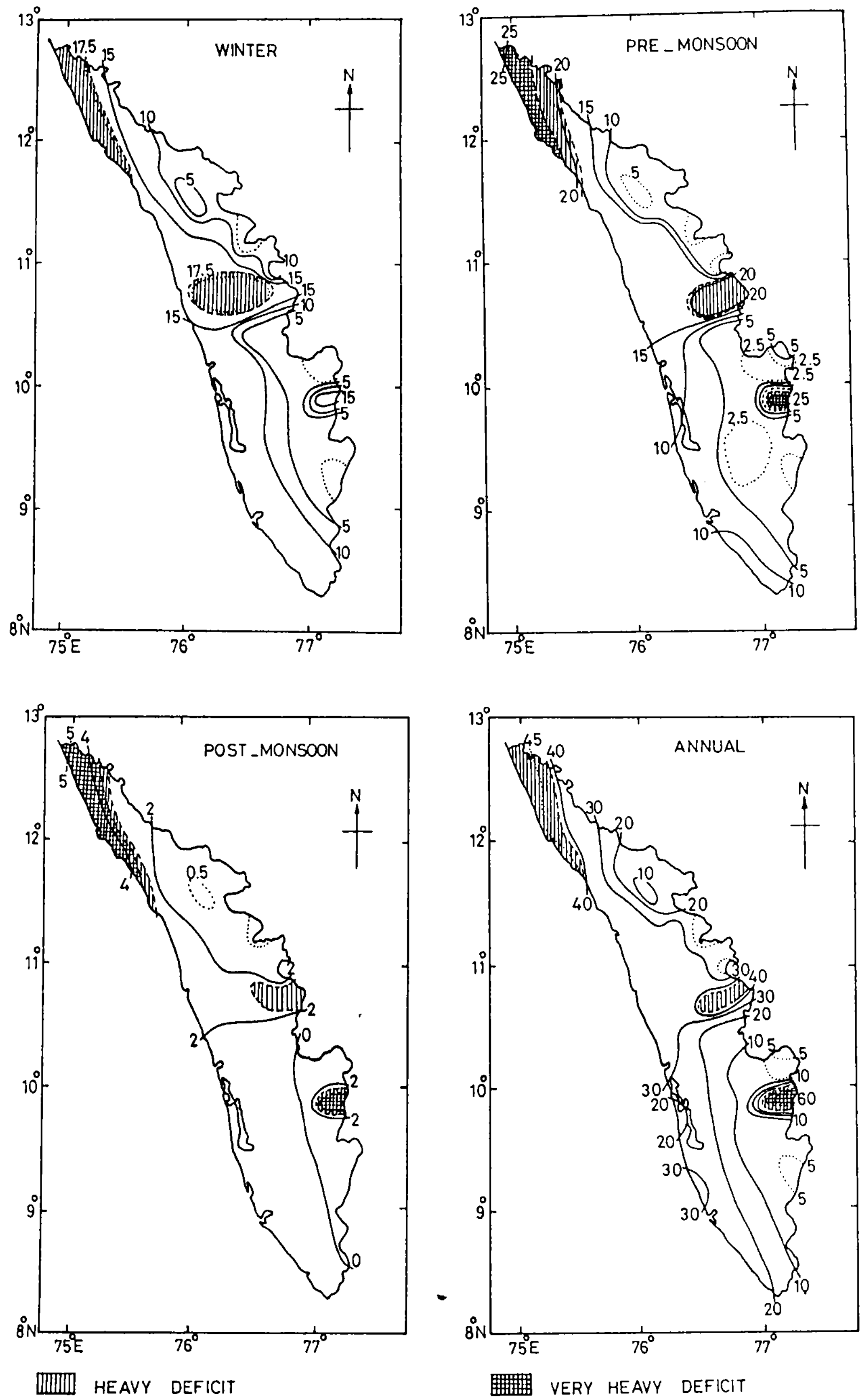


Fig. 4.15 Spatial distributions of annual and seasonal water deficits over Kerala (cm)

Parameters	Winter	Pre-monsoon	Monsoon	Post-monsoon	Annual
Mean (M)	11	12	1	2	26
% of annual	45	46	3	6	100
% of P.E.	47	26	1	4	16
Lowest value	1	.5	0	0	2
Station	DVM	KJY	-	-	DVM
Highest value	20	29	28	5	78
Station	CNR	CIR	CIR	KSD	CIR
Std.devi. (σ)	5	7	-	1	15
Coeff.of vari. %	46	61	-	80	59
M + σ	16	19	-	3	41
M + 1.5σ	19	23	-	4	49
M - σ	6	5	-	1	11
M - 1.5σ	4	1	-	-	4

Table 4.5 - Statistical parameters of spatial distribution of mean water deficits for Kerala State. (Deficit in cm)

Spatial distribution of seasonal deficits are also shown in the Fig. 4.15. Since in the monsoon period A.E. equals P.E., there are no deficits in this season over the State except over Chinnar region, which has a deficit of about 27 cm which is more than the average annual deficit of the State. Average winter deficit of the State is about 12 cm and varies from about 1 cm at Devikulam to about 20 cm at Cannanore. The percentage ratio of winter and pre-monsoon deficits to the annual deficit are almost the same (45%). The spatial coefficient of variation is more in pre-monsoon (61%) than in winter season (46%). The pre-monsoon deficit varies from about 0.5 cm at Kanjirapally to about 29 cm in Chinnar. Post-monsoon deficit is very low all over the State, with a State average of only 1.7 cm and varying from 0 cm over the eastern parts to about 5 cm in the northern parts of the State. For all the three seasons, winter, pre-monsoon and post-monsoon, the northern part and Palghat regions have seasonally large deficits (more than M + σ). But for pre-monsoon and post-monsoon periods, there are two regions of very large deficits (more than M + 1.5σ), one in the extreme north and the other over Chinnar. An increasing gradient towards north and towards east with two pockets of high values, over Palghat and Chinnar region is observed in all the three seasons. The severity of the deficit is clearly observed by comparing it with the water need (P.E.) of the corresponding season. This percentage ratio is about 27% in winter, 45% in pre-monsoon and 4% in post-monsoon season.

Monthly distribution patterns of deficits for a few selected stations are shown in the Fig. 4.6 and 4.7. Water deficits on a monthly basis do not exist for most of the stations from May to November, but for the station Chinnar there are deficits in all the months except October and November. High values of more than 13 cm occur in the extreme north and the highest monthly deficit has been observed in the month of March for most of the stations and in February for the others.

4.5 Water Surplus:

Mean annual water surplus for the State as a whole is 161 cm, varying from 0 cm at Chinnar to about 358 cm at Neriamangalam, with a spatial standard deviation of 81 cm. This average annual surplus is about 55% of the average annual rainfall of the State. The spatial distribution of the mean annual and seasonal surpluses are shown in the Fig. 4.16. Annual pattern is almost the same as that of annual rainfall, with an increase towards north especially in the coastal belt. There are two pockets of very large surplus (more than M + 1.5σ), but in comparison with rainfall pattern, the surplus region (more than M + σ) in the northern part is extended further up to the extreme north.

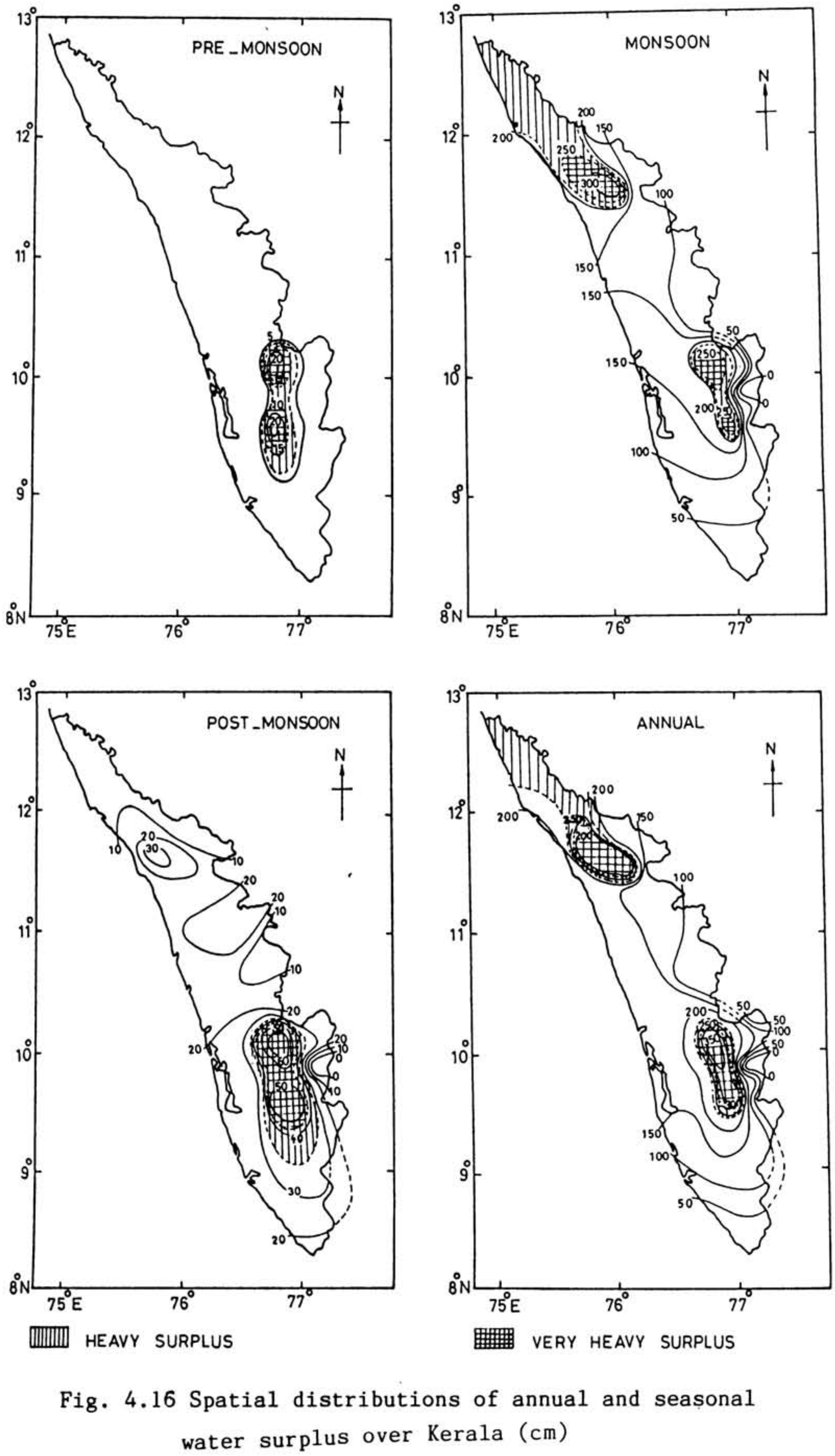


Fig. 4.16 Spatial distributions of annual and seasonal water surplus over Kerala (cm)

The seasonal surplus values for the State, and the percentage contribution of each season to the annual are given in Table 4.6. During the winter season, no station has any surplus. Similarly, almost all the stations, except those in the southern heavy rainfall pocket, do not have any surplus during pre-monsoon season. The highest value in this season occurs at Kanjirapally (25 cm). As mentioned earlier, 15% of the State's average annual rainfall is contributed by the pre-monsoon season but it adds only 1% of the surplus to annual value. This is because a major part of the pre-monsoon rainfall is utilised for satisfying its water need, and the excess precipitation over water need is made use for recharging the soil. About 85% of the State average annual surplus is during the monsoon period, though the percentage of the monsoonal rainfall to annual is only 66%. The spatial distribution pattern of surpluses in the monsoon is similar to the rainfall pattern, with an increasing trend towards north. The highest monsoon surplus of 301 cm occurs at Vythiri which is about 88% of its monsoon rainfall. As in the rainfall pattern, post-monsoon period has only one pocket of seasonally heavy surplus which is concentrated in the south, and this season contributes about 14% of the annual surplus. The average surplus values for the State as a whole for pre-monsoon, monsoon and post-monsoon seasons are 2 cm, 136 cm, 23 cm respectively.

Mean monthly distribution of surplus for a few selected stations are given in Figs. 4.6 and 4.7. The highest monthly surplus for most of the stations occurs in July, except for very few coastal stations in South Kerala, and high monthly values of more than 100 cm occur over Vythiri (133 cm), Kuttiyadi (117 cm), Irikkur (107 cm) and Hosdurg (102 cm), all in North Kerala. Kuttiyadi and Vythiri in the northern pocket, Neriamangalam

Parameters	Winter	Pre-monsoon	Monsoon	Post-monsoon	Annual
Mean (M)	0	2	136	23	161
% of annual	0	1	85	14	100
Lowest value	0	0	0	0	0
Station	-	-	CIR	CIR	CIR
Highest value	-	25	301	62	358
Station	-	KJY	VYT	NMG	NMG
Std.devi. (σ)	-	5	75	13	81
Coeff.of vari. %	-	284	55	57	50
M + σ	-	7	211	36	241
M + 1.5 σ	-	10	249	43	283

Table 4.6 - Statistical parameters of spatial distribution of mean water surpluses for Kerala State (Surplus in cm)

and Peermede in the southern pocket of heavy rainfall have 3 consecutive months of more than 50 cm of surplus (June, July and August). The station Chinnar does not have surplus in any of the months, while at Marayur surplus occurs from August onwards: this is the only station which has surplus in the month of December also. Even though the rainfall is distributed widely among the months on a climatic basis for all stations, the surplus is distributed only during June to November; but for a few stations in the southern half of the State, the soil moisture reaches field capacity by the month of May itself. A secondary maximum can be observed in post-monsoon season, except in the extreme north. It is to be noted that, over the extreme south of the State, the highest monthly surplus occurs in the month of October, even though the highest monthly rainfall is in June. This is because, the excess of rainfall over water need during the month of June is small and major part of this is utilised for recharging the soil.

Fig. 4.17 gives the station-to-station variation of annual deficits and surpluses from north to south, along with the State average and spatial standard deviation. At a first glance, it can be observed that annual surpluses are very high compared to annual deficits for all stations except Chinnar which has no surplus, but has the highest deficits. Another significant feature of this figure is that, in general, both annual deficits and annual surpluses decrease towards south, except in the regions of the heavy rainfall pockets and in the Palghat Gap. In the northern parts of the State, rainfall is concentrated in the monsoon months which causes large surpluses during this period, and large deficits in other seasons. All stations north of Cranganore in Trichur district, except high altitude stations, have annual deficits which are more than the State average, and stations south of this (except Chinnar) have values equal to or less than the State average. The figure shows that the stations in the extreme north have more surplus than State average and in the extreme south have less than State average. The station Marayur is characterised by comparatively low annual surplus and annual deficit. This is because the rainfall over this region is low but well distributed among the different months. The very high annual surplus stations, Neriamangalam, Vythiri and Peermede have very low annual deficits.

The seasonal values of both surplus and deficit are also presented in the Fig. 4.17. It can be easily seen that most of the surplus is contributed by the monsoon season; there is no station having surplus in the winter season. A few stations in the south central Kerala have slight pre-monsoon surplus, while almost all stations have post-monsoon surpluses. Similarly, all the stations have winter water deficit and most of the

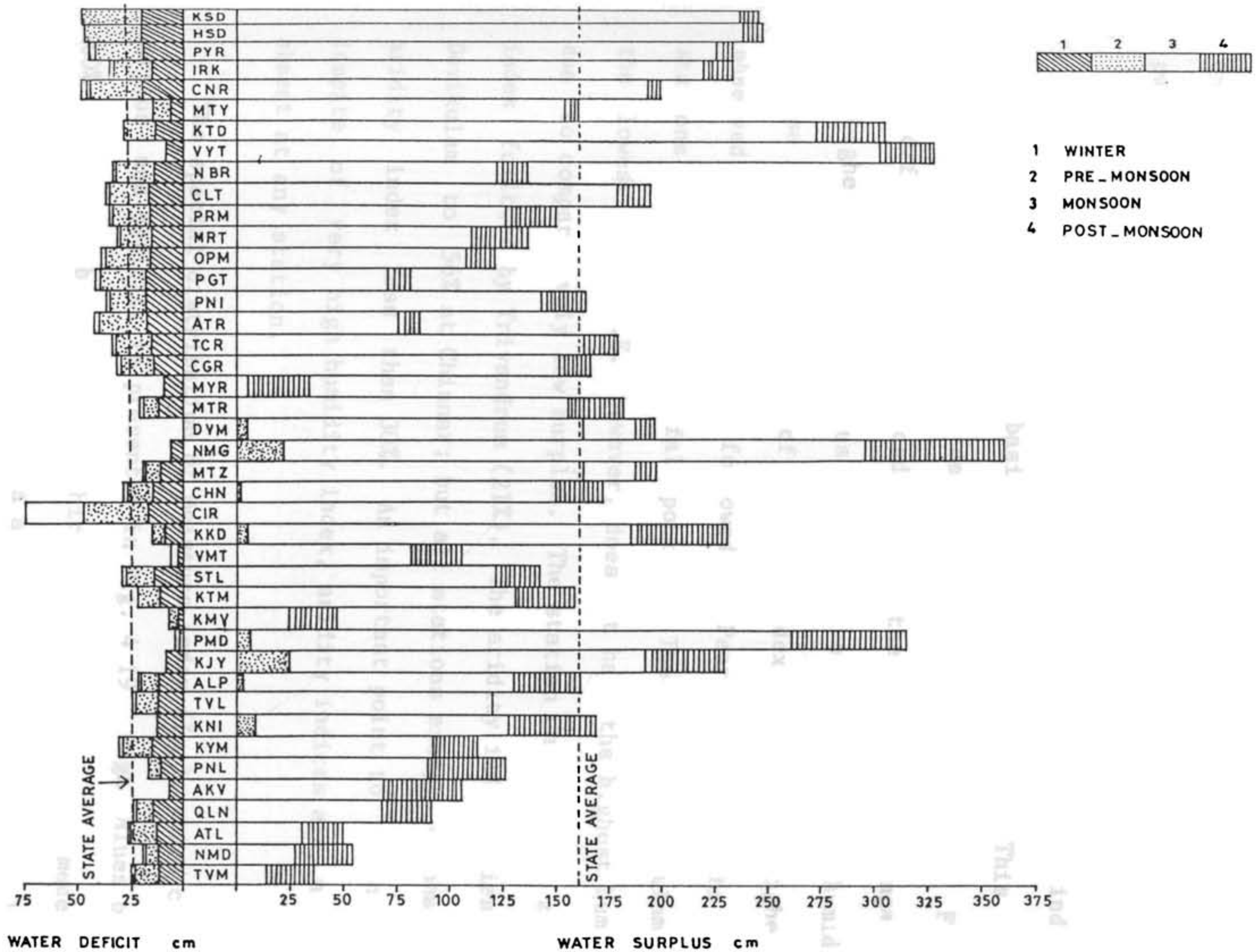


Fig. 4.17 North-South variation of water deficits and surpluses over Kerala State

stations except a few have pre-monsoon deficits too. No station (except Chinnar) has deficits in monsoon season, but experiences small deficits in post-monsoon months.

The pictorial representation of aridity and humidity indices for all stations on a latitudinal basis is shown in Fig. 4.18. This is very much similar to that of annual deficit and surplus pattern of Fig. 4.17. A major difference to be noticed is that, the station Neriamangalam which has the highest annual surplus does not have the highest humidity index. Because of the dependence of humidity index on P.E., the highest value is observed at Vythiri (297%), followed by Peermede (292%), the high altitude stations in the heavy rainfall pockets. The station Devikulam which has the lowest annual P.E., however, does not have the highest humidity index due to comparatively low surplus. The station Chinnar has zero humidity index followed by Trivandrum (21%). The aridity index varies from 2% at Devikulam to 56% at Chinnar; but all stations except Chinnar have the aridity index less than 30%. An important point to be noted is that inspite of very high humidity index, aridity indices are not altogether absent at any station.

The spatial distribution of moisture index (I_m), which considers both surplus and deficit, is presented in Fig. 4.19. High values of more than 200% have been observed over Vythiri in North Kerala, Peermede, Devikulam and Neriamangalam of South Kerala and lowest values (negative) have been found over Chinnar region. The moisture regime of climatic classification as per Carter and Mather (1966), of Kerala State is depicted in the same figure. One salient feature of this classification is that there is no

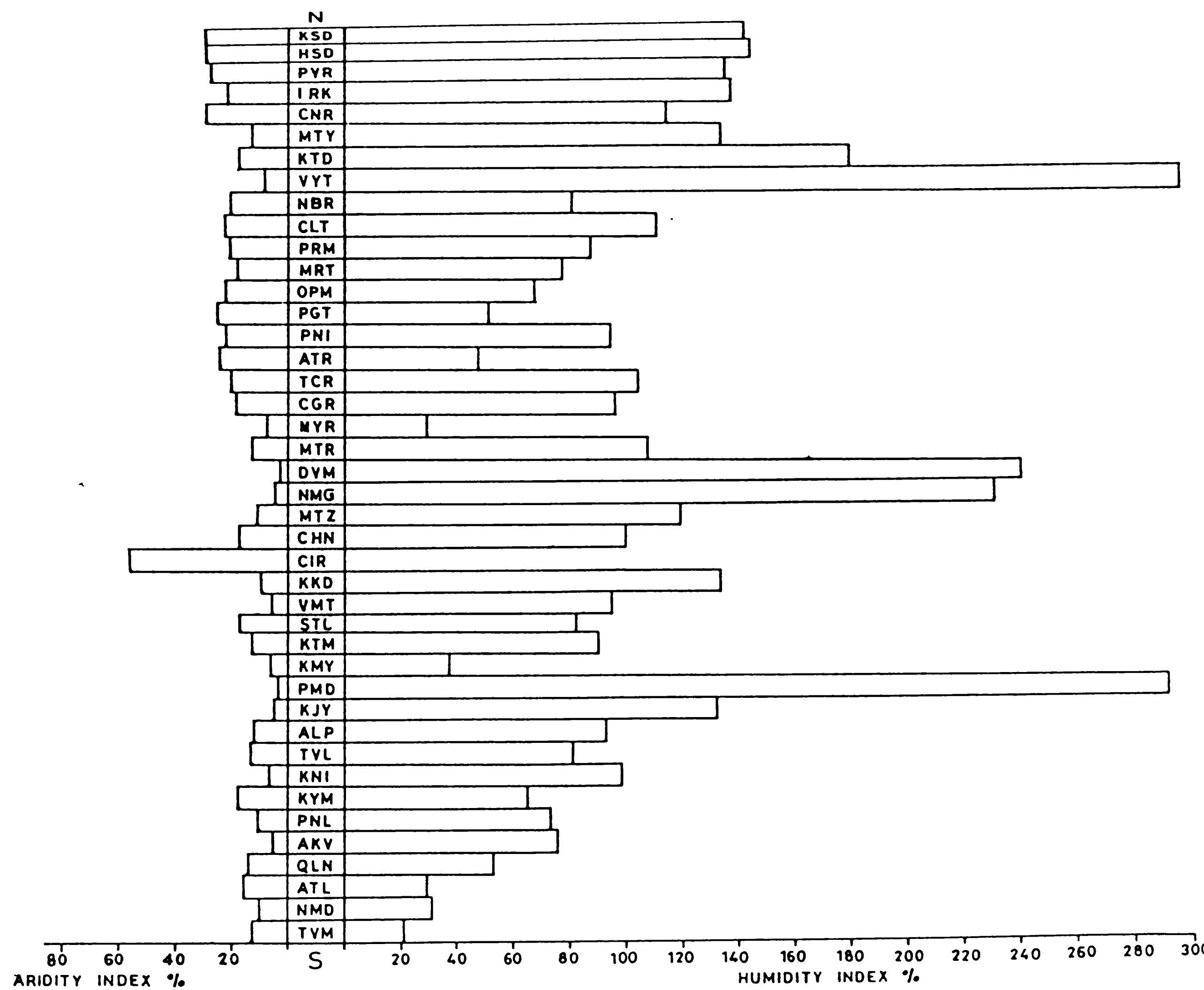


Fig. 4.18 Latitudinal variation of aridity and humidity indices over Kerala State

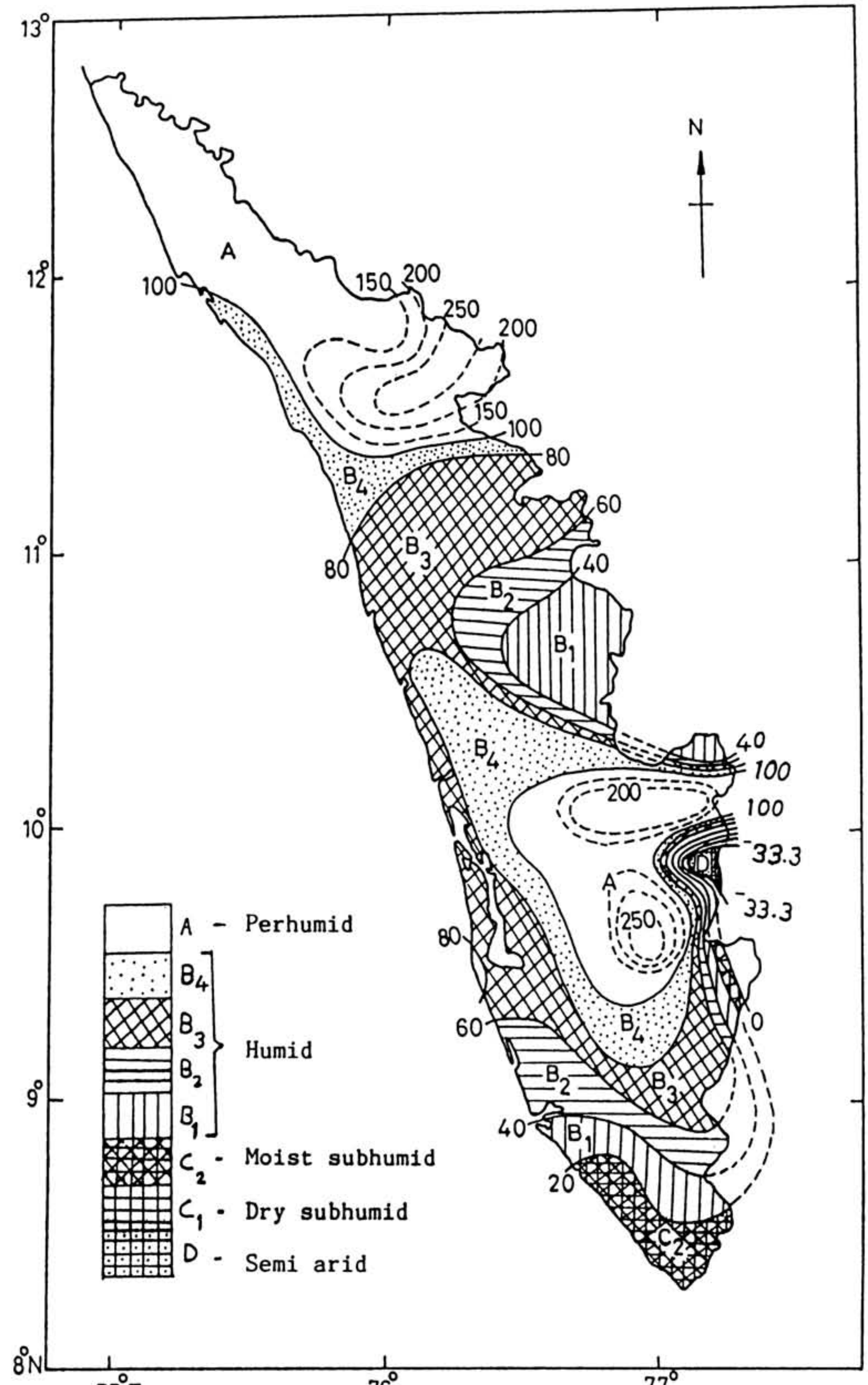


Fig. 4.19 Spatial distribution of moisture index (%) and climatic types (moisture regime) of Kerala

arid climate over Kerala State, while a small, area over Chinnar region belongs to the semiarid type of climate. North-east Kerala and area surrounded by the southern pocket of heavy rainfall have the perhumid type of climate. Between these perhumid regions, climate slightly varies to the last group of humid type (B_1, $I_m < 40$). From the southern region of perhumid type, the climate gradually changes to moist subhumid over the extreme southern part of the State. This classification is more detailed than that of Nair (1987).

Fig. 4.20 shows the thermal regime of climatic classification of Kerala State. Most parts of the State, except eastern high altitude stations have megathermal type of climate. This confirms the findings of Subrahmanyam (1958) that the distribution of thermal efficiency is more than adequate to support an efficient and luxuriant growth of vegetation.

Figs. 4.21 and 4.22 show the climatic water balance diagrams of a few selected stations in the State. The variations of rainfall, P.E. and A.E. can be clearly seen from the figures. Comparison of water surplus, water deficits, soil moisture utilisation and soil moisture accretion is possible from the figures. Fig. 4.22 gives a rough latitudinal variation of all these parameters.

4.6 <u>Surface Flow:</u>

Surface flow is a part of water surplus, and is controlled by the runoff factors. The spatial distribution pattern of surface flow, both annual and seasonal, is almost similar to that of surplus; and are given in Fig.4.23. The average annual surface flow in the State as a whole is about 19 cm, which is about 60% of the average annual water surplus, and 30% of

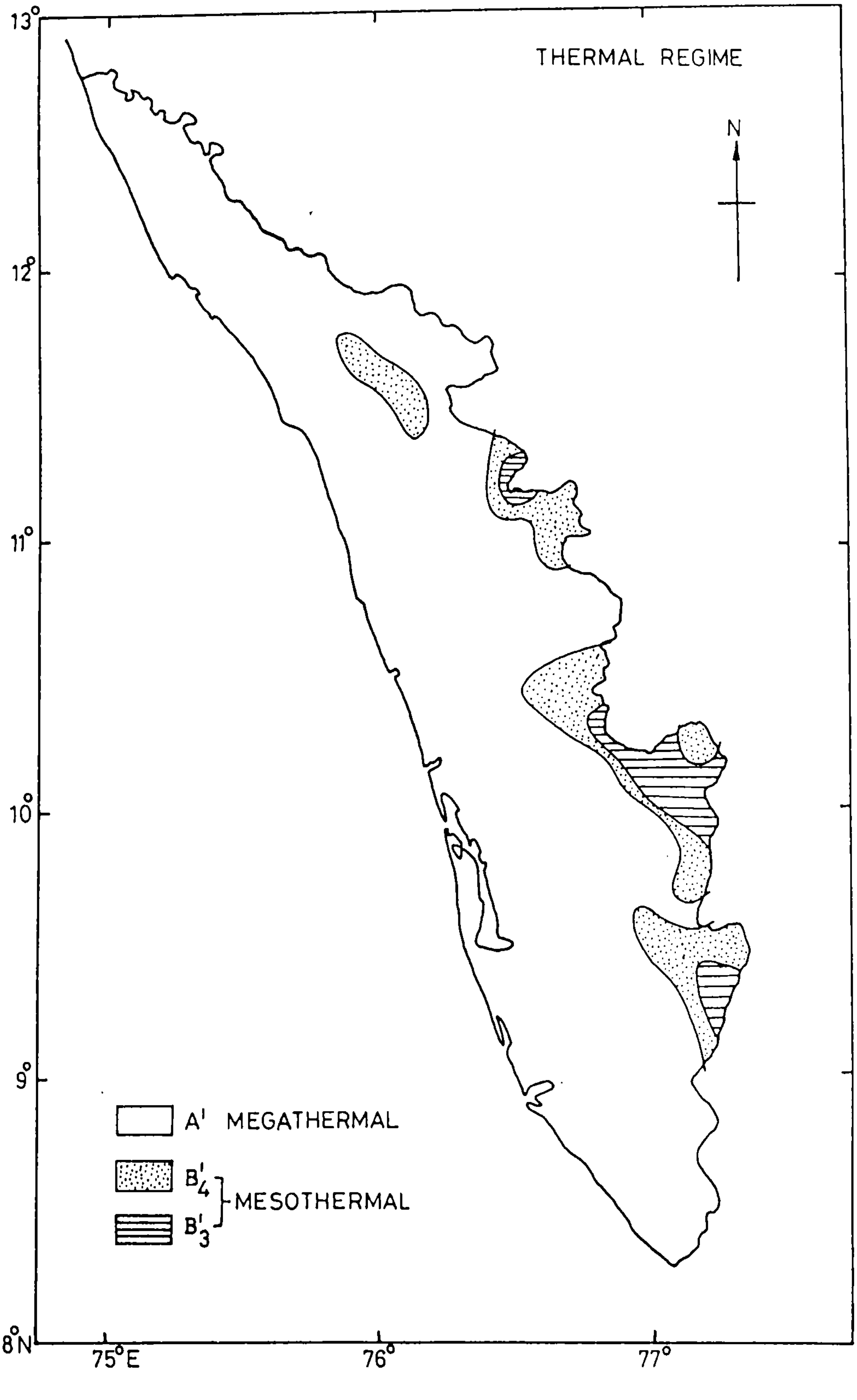


Fig. 4.20 Climatic classification - thermal regime

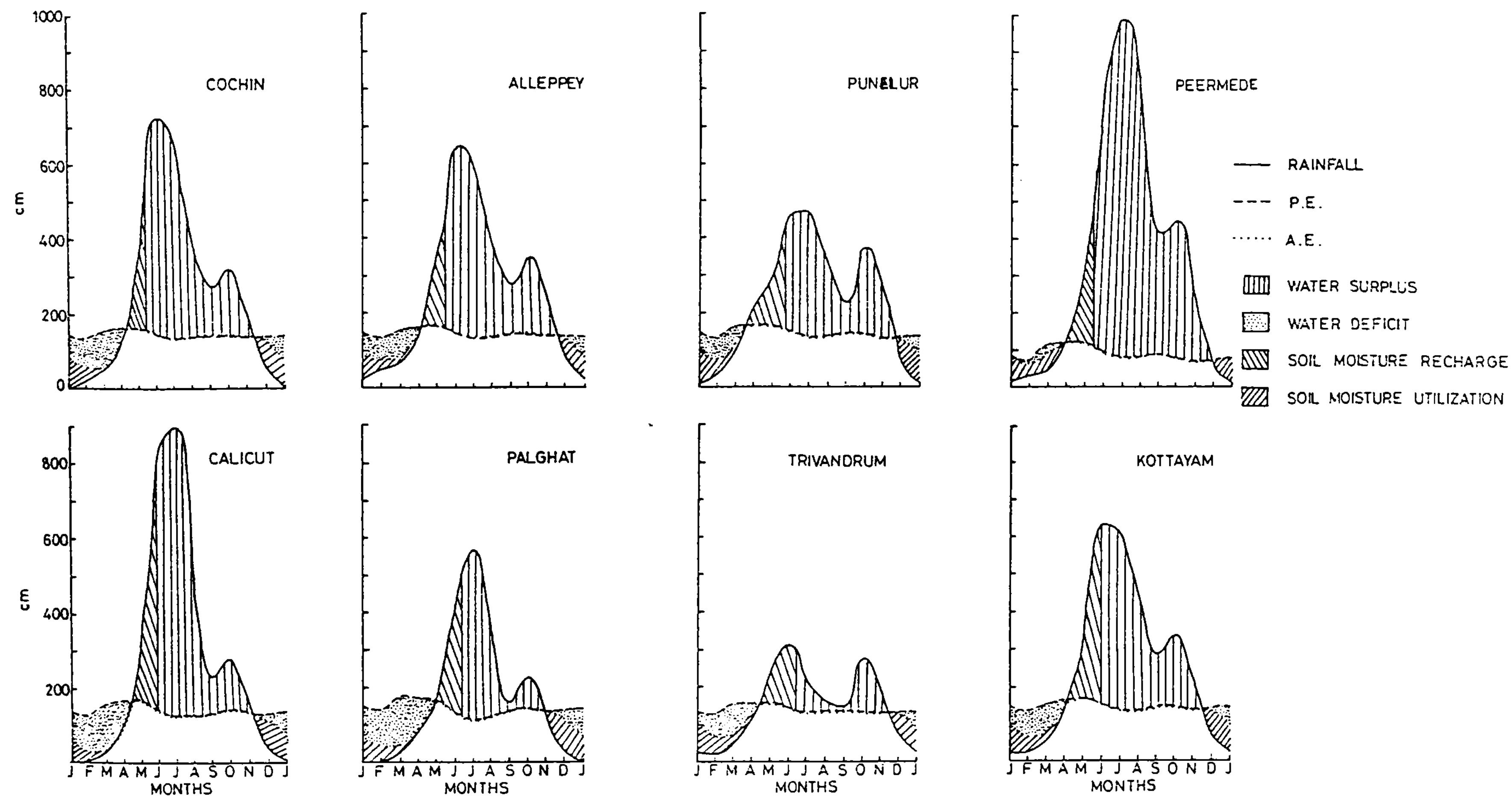


Fig. 4.21 Climatic water balance diagrams for some selected stations

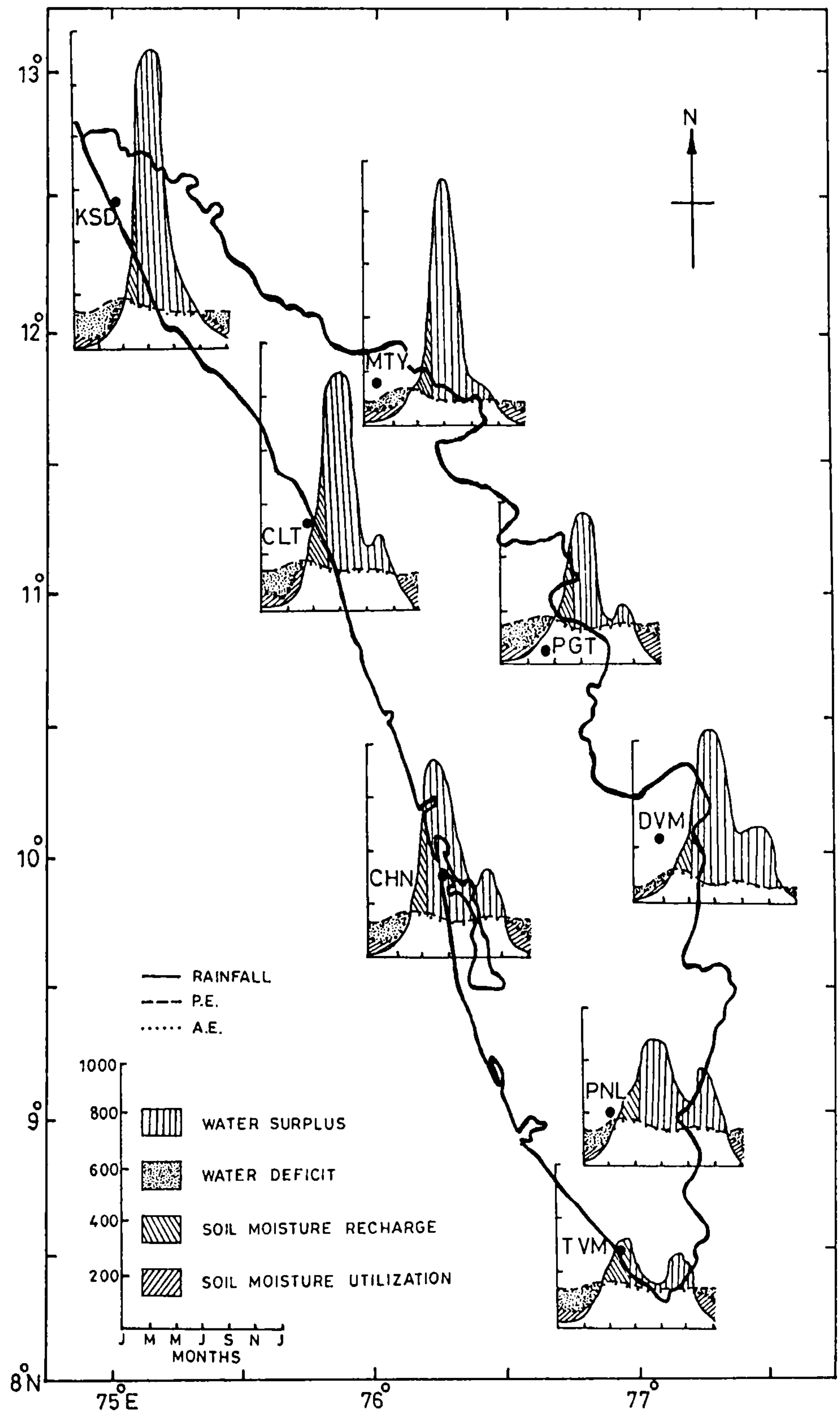


Fig.4.22 Climatic water balance diagrams for some selected stations

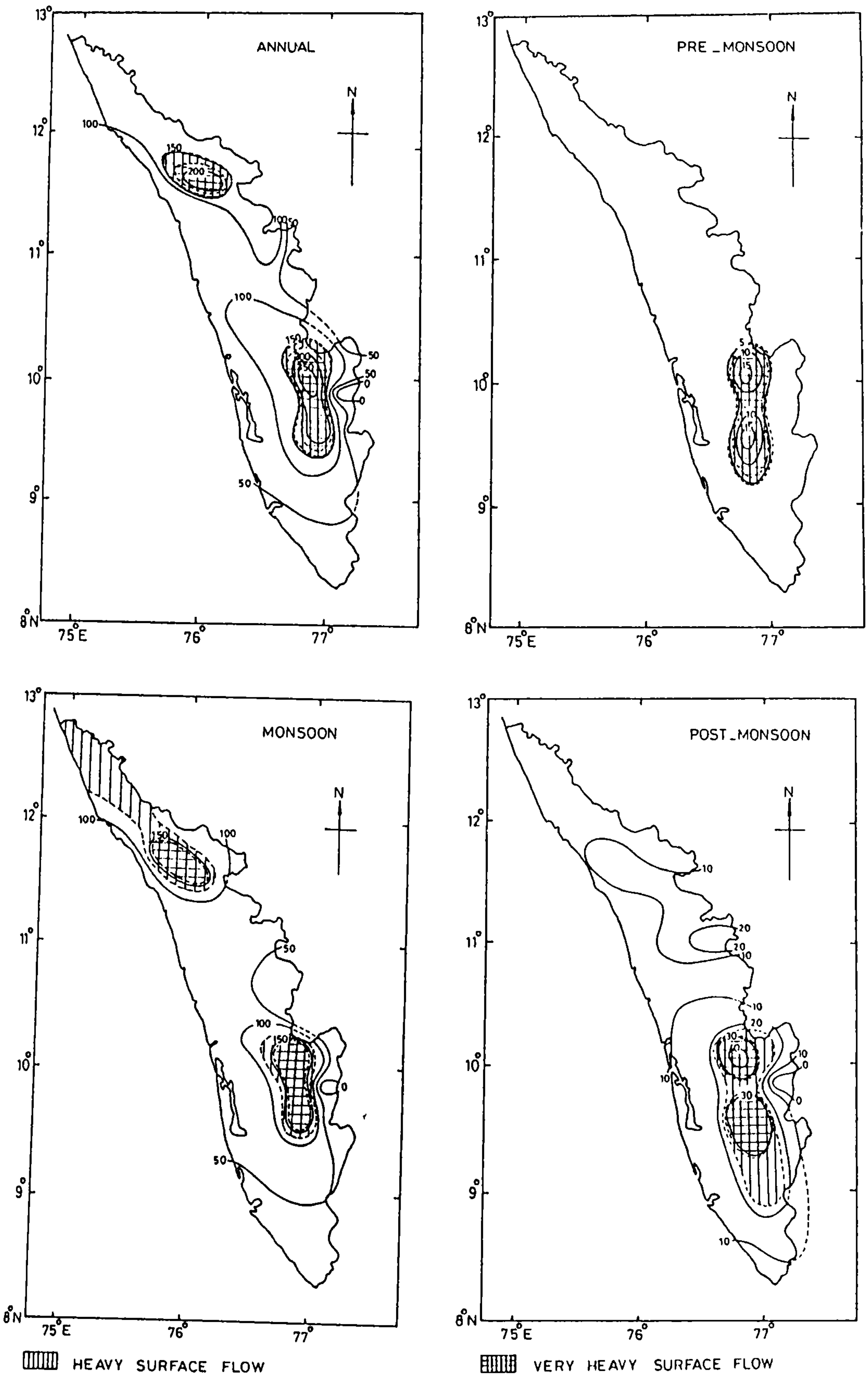


Fig. 4.23 Spatial distributions of annual and seasonal surface flow over Kerala (cm)

the average annual rainfall. It varies from 0 cm at Chinnar to about 260 cm at Neriamangalam. Monsoon and post-monsoon seasons contribute about 84% and 15% respectively to the annual values. For both the seasons, Neriamangalam has the highest and Chinnar the lowest value. Contribution of winter season to the average annual surface flow is zero. The details of the surface flow characteristic are given in Table 4.7.

Parameters	Winter	Pre-monsoon	Monsoon	Post-monsoon	Annual
Mean (M)	-	1	82	14	97
% of annual	0	1	84	15	100
% of rainfall	0	3	42	27	33
% of surplus	0	67	60	63	60
Lowest value	0	0	0	0	0
Station	-	CIR	CIR	CIR	CIR
Highest value	0	18	199	45	260
Station	-	KJY	NMG	NMG	NMG
Std.dev. (σ)	-	4	48	10	54
Coeff.of vari. %	-	-	59	68	56
M + σ	-	5	130	24	151
M + 1.5 σ	-	7	153	29	179

Table 4.7 - Statistical details of spatial distribution of surface flow characteristics of Kerala State (Surface flow in cm)

Mean monthly distribution for a few selected stations is given in Figs. 4.6 and 4.7. Patterns are very much similar to that of surpluses, but the values are decreased.

4.7 Underground Flow:

As mentioned earlier, monthly underground flow has been determined by the total groundwater for that month, which is the sum of groundwater storage and groundwater recharge. This latter parameter is determined by the runoff factors. As already indicated, the total annual groundwater recharge is 40% of the annual surplus on a climatic basis. Average annual groundwater flow for the State as a whole is 64 cm, which is 22% of the annual rainfall, and it varies from 0 cm at Chinnar to 126 cm at Vythiri. Even though the ratio of the surface flow to water surplus (expressed in percentage) remains constant for months or seasons, the percentage of surplus as underground flow varies, based on groundwater storage. The State average annual underground flow is distributed as 11%, 8%, 50% and 31% respectively among the four seasons, even though there is no surplus in the winter season. Winter groundwater flow is 216% of this season's rainfall. Percentage ratio of groundwater to surplus is the lowest in the monsoon season, when the surplus is maximum, and the highest in winter when the rainfall is minimum. This is because, the surplus and underground recharge are confined mainly to the monsoon months, but the groundwater storage is released in all seasons, on an exponential basis.

Figs. 4.24 and 4.25 show the spatial distribution of groundwater flow on annual and seasonal bases. These patterns are very much different from that of rainfall or surplus patterns. A very prominent factor of these figures is that high values are observed over the northwestern part of the State, even though the rainfall or surplus is higher in the southern pockets; western parts of the State too have comparatively higher values than the eastern parts. This is mainly due to the role played by the runoff factors. The regions of the heavy surplus pocket in the south have comparatively low groundwater recharge, and hence low groundwater flow. A relatively very high recharge in the monsoon months over the northwestern region causes a comparatively high groundwater storage over this region in

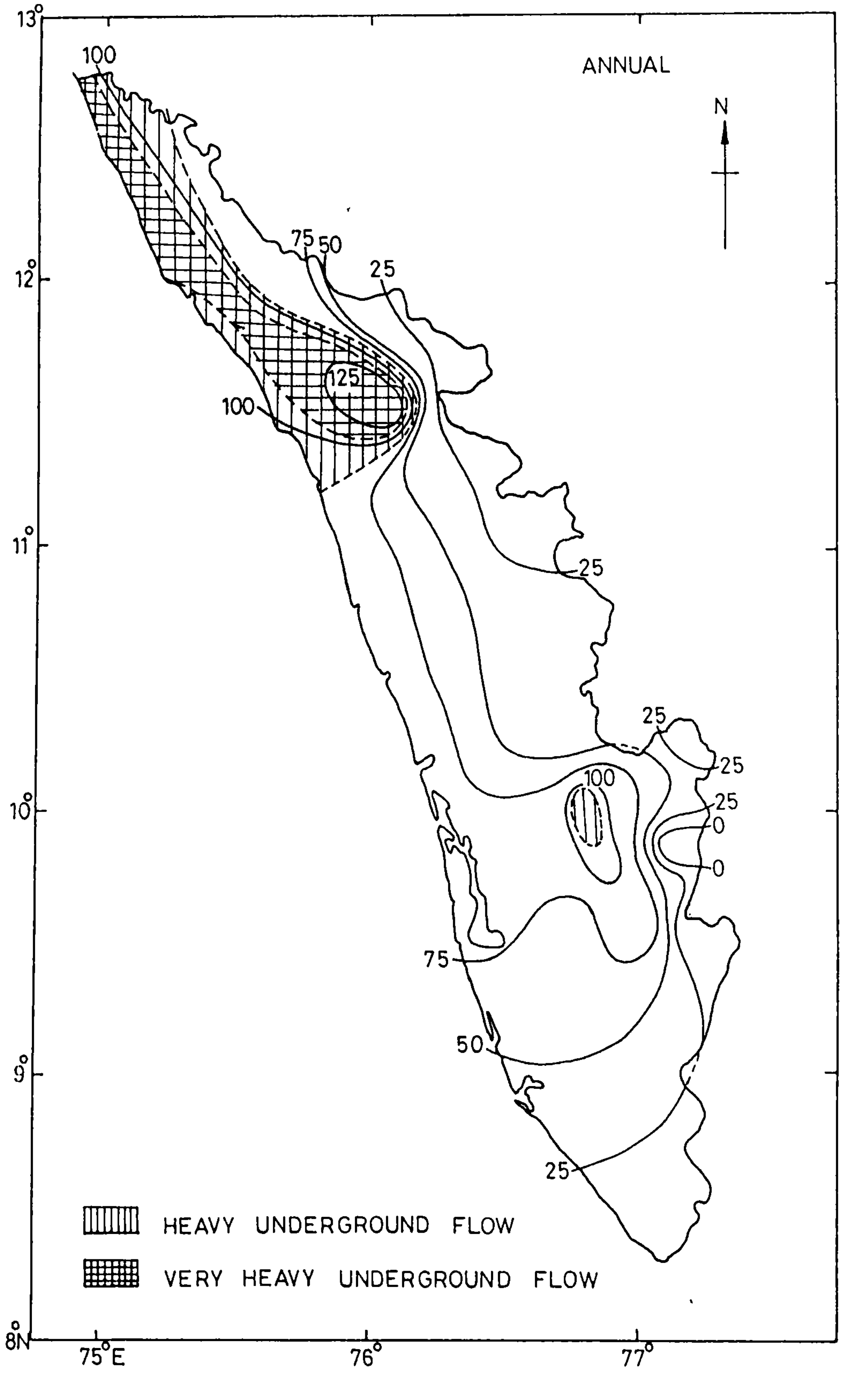


Fig. 4.24 Spatial distributions of annual underground flow over Kerala (cm)

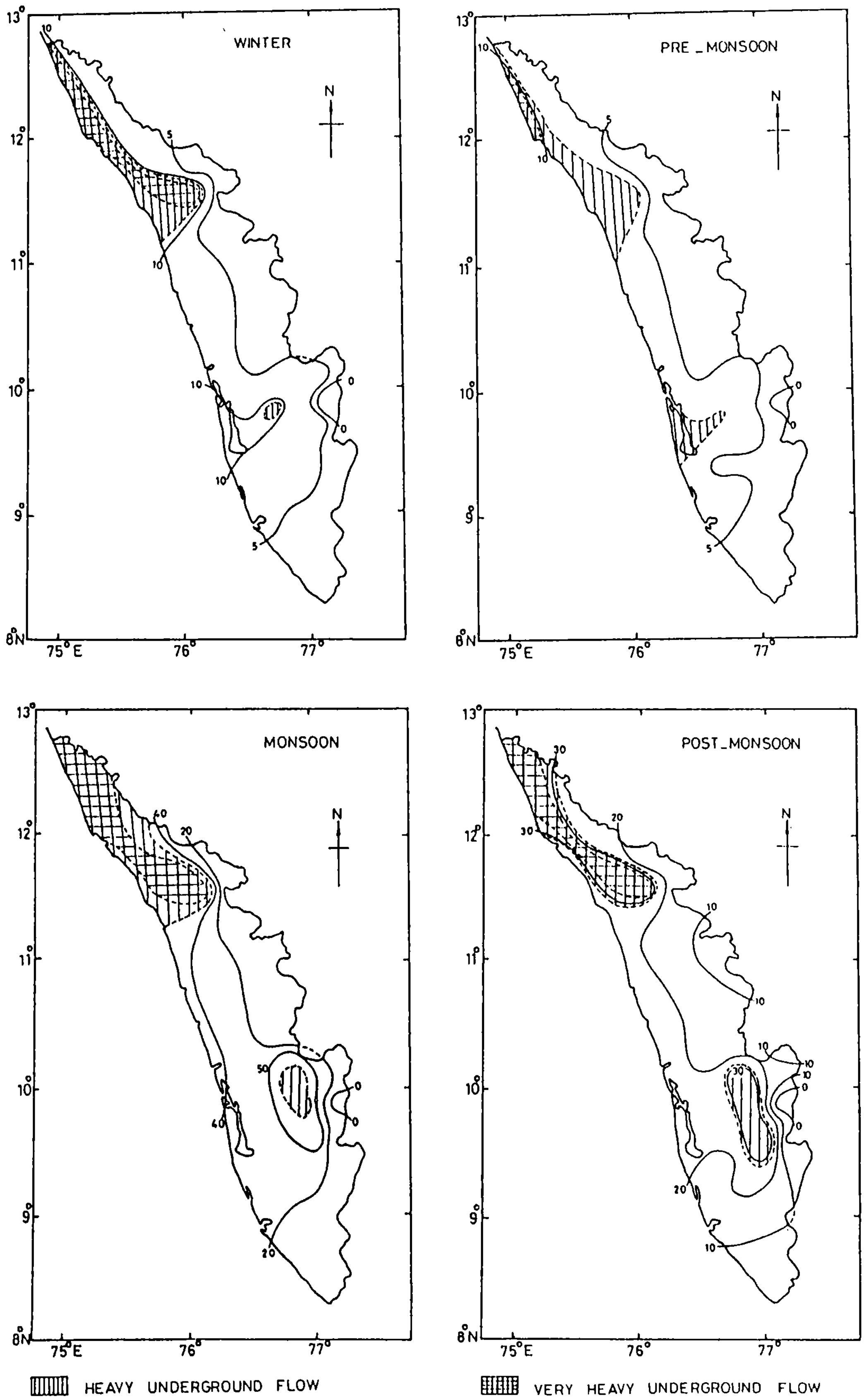


Fig. 4.25 Spatial distributions of seasonal underground flow over Kerala (cm)

all seasons, on a climatic basis. No groundwater flow is observed over Chinnar region in any season, since there is no surplus in any season. Highest groundwater flow is during winter and pre-monsoon months, when there is least recharge over the extreme northern parts of the State. But, during monsoon and post-monsoon seasons, the highest values occur over Vythiri.

For the State as a whole, underground flow is more than surface flow except in the monsoon season, but during monsoon season, the underground flow is less than half of surface flow. For the State as a whole, the annual surface flow is more than that of groundwater flow, and is about 1.5 times that of groundwater flow. Ali (1982) observed the same results in Godavari river basin. More details about groundwater flow is given in Table 4.8.

Mean monthly distribution of underground flow for a few selected stations are shown in Fig. 4.6 and 4.7. A comparison of this with the surplus pattern reveals some interesting features. Even though there is no surplus upto the month of June, there is groundwater flow, and this groundwater flow is more than monthly rainfall during December, January and February. As stated earlier, the rainfall and surplus are maximum in June or July, but the highest monthly groundwater flow occurs in August for most stations, indicating a lag of atleast one month. This is because, during the month of June, July and August, the groundwater recharge is more than the groundwater flow and so an accumulation of groundwater storage occurs during these months. The secondary maximum observed in rainfall and surplus, during the post-monsoon months are not much pronounced in the case

Parameters	Winter	Pre-monsoon	Monsoon	Post-monsoon	Annual
Mean (M)	7	6	32	20	65
% of annual	11	8	50	31	100
% of rainfall	216	13	16	37	22
% of surplus	-	311	23	85	40
Lowest value	0	0	0	0	0
Station	CIR	CIR	CIR	CIR	CIR
Highest value	14	12	67	37	126
Station	KSD	KSD	VYT	VYT	VYT
Std. devi. (σ)	4	3	18	9	34
Coeff. of vari. %	51	55	57	48	52
M + σ	11	9	50	29	98
M + 1.5 σ	12	10	58	34	114

Table 4.8 - Statistical details of spatial distribution of underground flow characteristics of Kerala State. (underground flow in cm)

of underground flow. Mean monthly distribution patterns of groundwater flow have a similarity to that of A.E.: both do not have sharp variations and the lowest values are observed in April or May.

4.8 Total Discharge:

On a climatic basis, total discharge is same as that of total annual surplus. A major difference is that surplus is concentrated mostly during monsoon and post-monsoon months, but the mean annual discharge is distributed among all seasons. The spatial distribution of annual total discharge (Fig. 4.26) is exactly the same as that of mean annual surplus, with the lowest discharge of 0 cm at Chinnar and the highest at Neriamangalam (359 cm). The State average annual total discharge is distributed as 4%, 4%, 71% and 21% among the four different seasons. But, the distribution of surplus is 0%, 1%, 85% and 14% in the corresponding seasons. In winter season, there is no surface flow, so the total

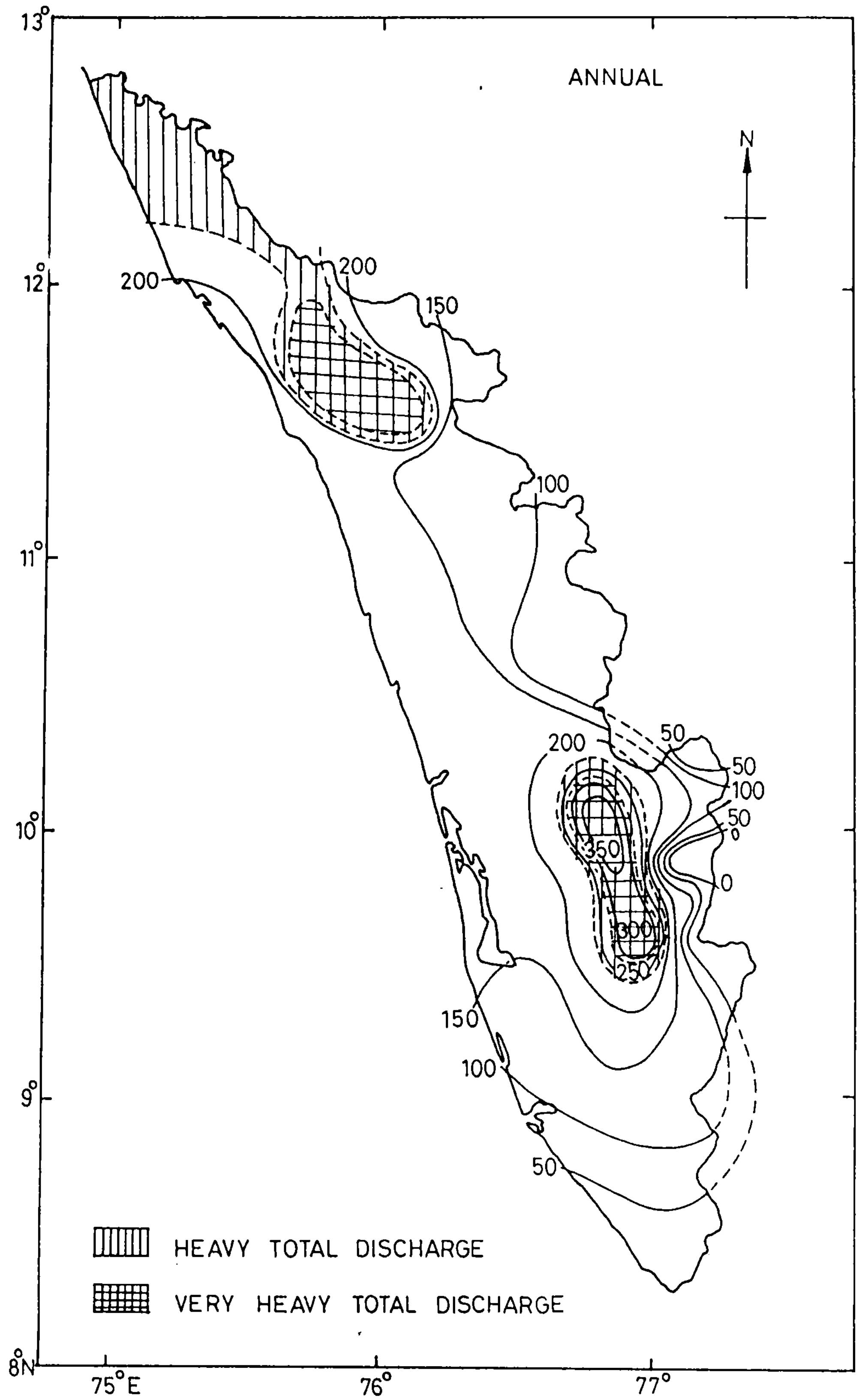


Fig. 4.26 Spatial distribution of annual total discharge over Kerala (cm)

discharge during this season is only due to the underground flow; the flow produced from the stored groundwater. Therefore, the distribution pattern of winter total discharge is exactly the same as that of the underground flow in winter. The spatial distribution of seasonal values are given in Fig. 4.27 and the statistical characteristics of annual and seasonal values are given in Table 4.9.

Parameters	Winter	Pre-monsoon	Monsoon	Post-monsoon	Annual
Mean (M)	7	7	113	34	161
% of annual	4	4	71	21	100
% of rainfall	216	16	58	65	55
Lowest value	0	0	0	0	0
Station	CIR	CIR	CIR	CIR	CIR
Highest value	14	24	252	76	359
Station	KSD	KJY	VYT	NMG	NMG
Std. devi. (σ)	4	5	63	14	81
Coeff. of vari. %	51	74	56	42	50
M + σ	11	12	176	48	242
M + 1.5 σ	12	15	208	55	282

Table 4.9 - Statistical details of spatial distribution of total discharge characteristics of Kerala State. (Total discharge in cm)

Mean monthly distribution patterns show a combined effect of surface flow and underground flow and are given in the Figs. 4.6 and 4.7. The minimum total discharge occurs in the month of May as in the case of groundwater flow, but the highest values occur in June or July, as in the case of surface flow.

Table 4.10 enables a comparative study of all water balance parameters on a seasonal and annual basis for the State as a single unit, together with percentage contributions of each season to the annual.

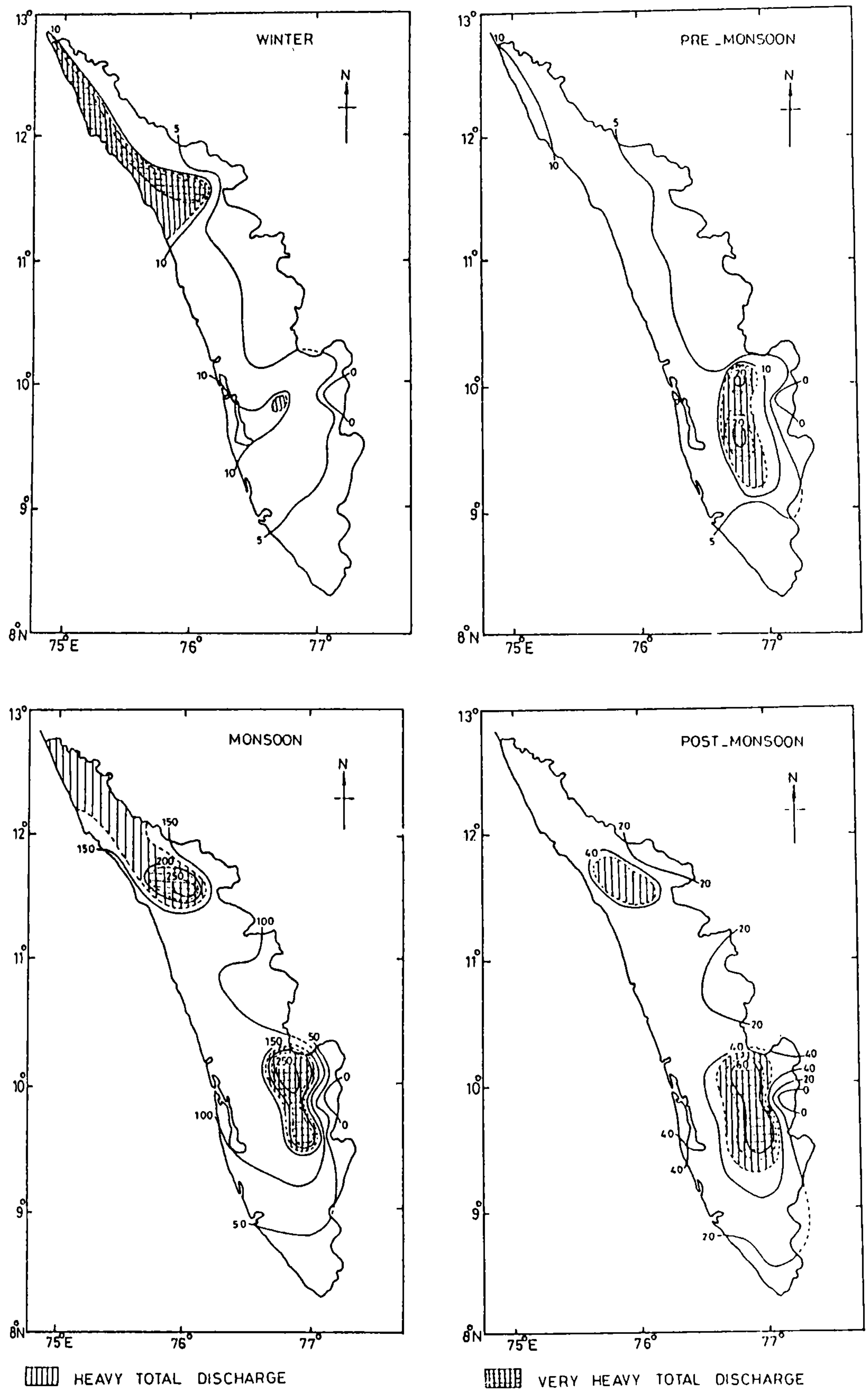


Fig. 4.27 Spatial distributions of seasonal total discharge over Kerala (cm)

Parameter		Winter	Pre-monsoon	Monsoon	Post-monsoon	Annual
R.	Average	3	43	195	53	294
	% of annual	1	15	66	18	100
P.E.	Average	25	46	51	38	160
	% of annual	15	29	32	24	100
P.E.	Average	13	34	50	36	133
	% of annual	10	26	37	27	100
W.D.	Average	12	12	1	2	26
	% of annual	45	46	3	6	100
W.S.	Average	0	2	136	23	161
	% of annual	0	1	85	14	100
S.F.	Average	0	1	82	14	97
	% of annual	0	1	84	15	100
U.F.	Average	7	6	32	20	64
	% of annual	11	9	50	30	100
T.D.	Average	7	7	113	34	161
	% of annual	4	4	71	21	100

P. - Rainfall P.E. - Potential Evapotranspiration
W.D. - Water Deficit A.E. - Actual Evapotranspiration
W.S. - Water Surplus U.F. - Underground Flow
S.F. - Surface Flow T.D. - Total Discharge

Table 4.10 - Seasonal and annual values (in cm) of all water balance parameters for the State and their percentages

CHAPTER V

TEMPORAL VARIATION OF HYDROMETEOROLOGICAL PARAMETERS OVER KERALA STATE

5.1 Coefficients of variation of hydrometeorological parameters

Spatial distribution patterns of coefficients of annual values of Rainfall, A.E., Water Deficit and Water Surplus are shown in Fig. 5.1. The coefficient of variation of annual rainfall varies from 15% at Ponnani to 42% at Chinnar. For most stations it varies between 15% and 25%. The distribution pattern of the coefficients of variation of A.E. shows that they are comparatively uniform and stable,generally less than 10%. The highest value of about 40% occurred over Chinnar, which has the highest variability for annual rainfall too. A secondary maximum has been observed over Attingal region, a region of high value of rainfall variability. Low values (less than 5%) have been observed over South Central region, an area having heavy rainfall during winter, pre-monsoon and post-monsoon seasons.

The coefficients of variation of annual deficits over the northern half of the State vary from 20 to 30%, but in the southern half they are more than 30%. Towards south and east of Cochin, there is a sharp upward increase in deficit, resulting in the highest value of about 70% at Attingal in the south and Devikulam in the east.

This general feature has been observed in annual surplus values too. Very high values - more than 225% - have been observed over Chinnar. The extreme southern parts of the State also exhibit comparatively high values of variability. It is interesting to note that values of annual water

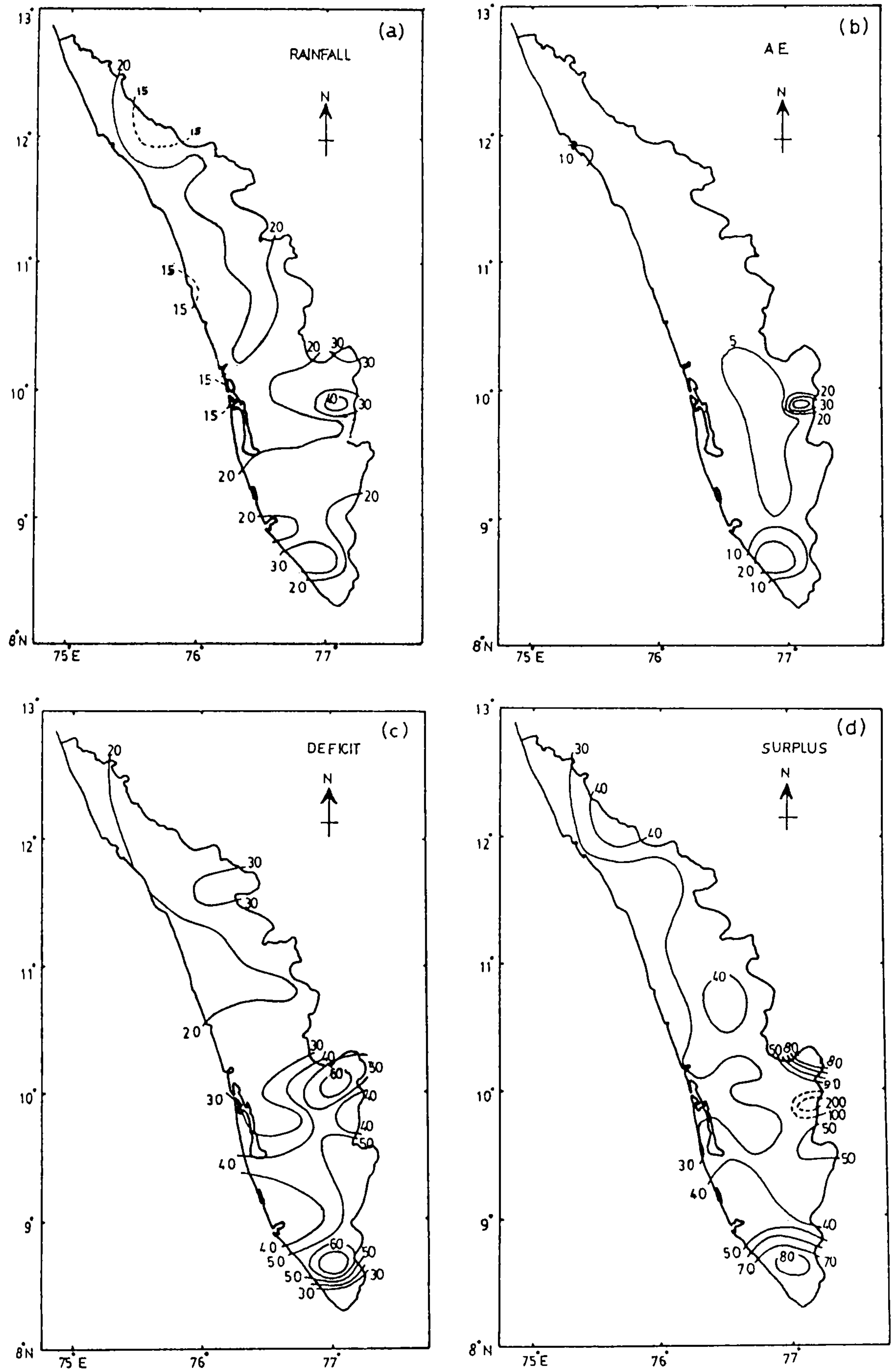


Fig. 5.1 Spatial distributions of coefficient of variation of annual values of hydrometeorological parameters over Kerala (%)

deficits and water surpluses over the north-western parts of the State are lower than the values over south-eastern parts of the State.

5.2 Trend Analysis of Hydrometeorological Parameters:

Climatological time series of annual values of rainfall, A.E., water deficit and water surplus of all stations have been subjected to advanced statistical tests such as Mann-Kendall statistic test, and Student's t-test, in order to examine the presence of any trends in the series.

To get the nature of the trend, time series for all parameters of all stations have been subjected to low pass filtering. The nature of the trends of 5 selected stations - Calicut, Palghat, Peermede, Punelur and Trivandrum - have been presented here.

Trend analysis on a seasonal basis for all parameters has been carried out for nine selected stations spanning all regions of the State; of these, six are I.M.D. stations. This study has been carried out only for monsoon and post-monsoon seasons, since these are the major rainy periods over the State. The stations selected are Kasargode, Cannanore, Vythiri, Calicut, Palghat, Cochin, Peermede, Punelur and Trivandrum. Of these, Kasargode and Trivandrum are in the northern and southern extremes of the State. Vythiri and Peermede are two high range stations, one in the northern half and the other in the southern half of the State, while Vythiri has the record of the highest mean monsoon rainfall of the State. Cochin is a central coastal station and has approximately the same amount of mean annual rainfall as that of the State. Punelur is in the southern half of the State and has shown a very significant decreasing trend (at 99% level) in annual rainfall by both the tests. Palghat is important by its position in the gap region and Cannanore is in the northern coastal region of the State.

5.2.1 Rainfall:

Stations which exhibit trends at various significant levels by any one of the two tests are shown in Fig. 5.2. Many of the stations in the southern half of the State have shown significant decreasing trends in annual rainfall values: about half of them are significant even at 99% level. But, in the case of stations in the northern half, only two of them exhibited such a decreasing trend. It is to be noted that none of the stations in the State showed any significant increasing trend even at 90% level. Parthasarathy and Dhar (1978) prepared such a figure for India, showing trends at different significant levels.

The differences between the means of the annual rainfall of the first half and second half of the study period for each station are plotted in Fig. 5.2b. From the figure, it is clear that the entire area of the southern half of the State, except the extreme eastern part, has shown a decreasing tendency.

The above mentioned differences have varied from -165 cm at Neriamangalam to +21 cm at Perintalmanna. But, it is interesting to note that the region of maximum decrease experiences the heaviest annual rainfall in the State. Three pockets exhibit departures of more than -50 cm: one centered at Kanjirapally, the second surrounding Punelur and Nedumangad and the third around Irikkur in the north.

It is worth noting that the Palghat Gap region, coastal tracts of the northern half of Kerala and leeward side of the Western Ghats in the

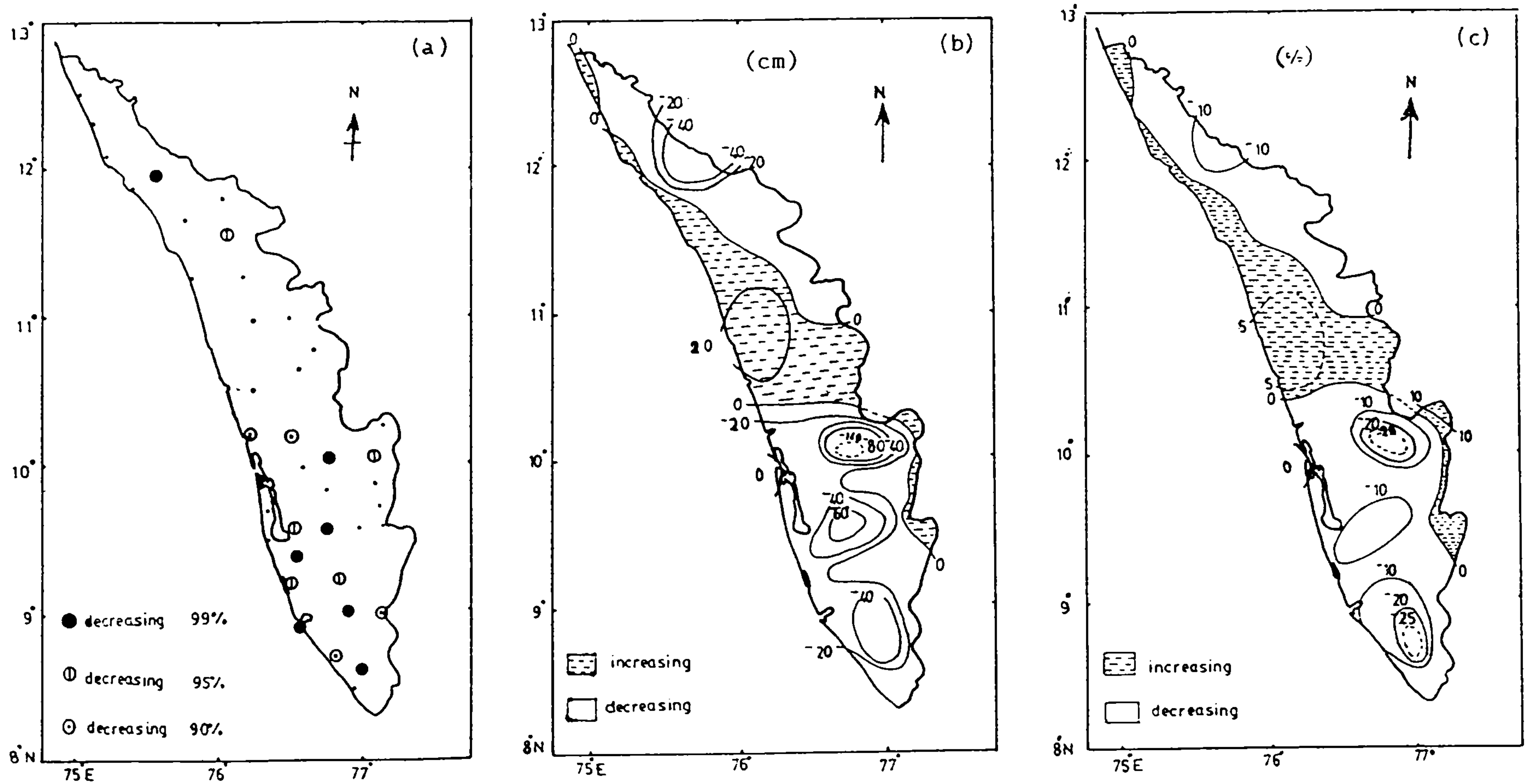


Fig. 5.2 Trend aspects of annual rainfall series

southern half show a slight increasing tendency in annual rainfall. Regions west and north-west of Palghat Gap show the highest increases in the State - more than 20 cm - but none of these changes is statistically significant. The regions which showed this increasing tendency are shaded in the figure.

The difference between the means of the second half and first half for each station, expressed as the percentage ratio of first half is depicted in Fig. 5.2c. This figure is similar to Fig. 5.2b. The ratio is maximum at Neriamangalam (-28%) while another pocket of high value (about -25%) has been observed in the extreme south, centered at Nedumangad. Regions west and north-west of Palghat Gap have shown an increasing value of more than +5%. Marayur, a station in the eastern part of the southern half of the State has shown a comparatively large percentage of increase (more than +15%): it is to be noted that this is one of the stations having very low annual rainfall in the State. These findings are in agreement with the results of Singh and Soman (1987), who had analysed the rainfall means of South Kerala and North Kerala separately. They had observed, on an annual basis, a significant decreasing trend only for South Kerala.

But, in the present study, it has been found that many of the stations in the South exhibit significant decreasing trends, but, these stations are randomly distributed. Some stations in the coastal belt also exhibit significant decreasing trends even at 99% level. But, the study of the differences between half-period averages shows that this decreasing tendency is larger over the windward side of the Western Ghats than on the leeward side, where some of the stations even show a slight increasing tendency. Soman et al. (1988), using an 80-year data set (1900-1980) observed a significant decreasing trend all over the eastern parts (Ghats) of the State. This difference in the results, may be due to the difference in the data period used for the study.

Table 5.1 enables a comparison of trends at different significant levels for the monsoon, post-monsoon and annual rainfall values. Of the 9 stations selected, only one shows a significant decreasing trend in monsoon rainfall, while none has shown any significant increase. At Punelur, the decreasing trend is significant at 95% level by Student's t-test and at 90% level by Mann-Kendall statistic test. For this station, departure of mean of the second half from the first half is -21 cm and its percentage ratio to the first half is -13.2%. The departure for both high altitude stations - Vythiri and Peermede - have shown a slight decreasing tendency (not statistically significant). The other six stations have shown an increasing tendency; for the northern coastal stations, this positive departure as a percentage of the first half period average is more than 5%.

In the case of post-monsoon season rainfall, four stations show a significantly decreasing trend and at Punelur, it is significant even at 99% level. Except for Palghat the departures of the half-period averages have shown a decreasing tendency. A comparatively higher negative departure of more than 16 cm (approximately 21%) occurred at Peermede and Punelur, both in the south central portions of the State.

One salient point is that, at Palghat, monsoon, post-monsoon and annual rainfall values have shown increasing tendencies. Vythiri, Peermede and Punelur have shown decreasing tendencies for monsoon and

		Mean	Coeff. vari.	M.K. signi.	Diff.	% D	t-test signi.
	Annual	3609	17	-	171	5	-
KSD	Monsoon	2999	17	-	213	7	-
	Post-Monsoon	325	42	*	-33	-10	-
	Annual	3221	20	-	90	28	-
CNR	Monsoon	2615	21	-	184	7	-
	Post-Monsoon	306	49	-	-33	-10	-
	Annual	4249	21	*	-177	-4	-
VYT	Monsoon	3438	23	-	-38	-1	-
	Post-monsoon	439	38	**	-71	-15	-
	Annual	3244	17	-	22	1	-
CLT	Monsoon	2381	21	-	141	6	-
	Post-monsoon	443	44	-	-38	-8	-
	Annual	2084	19	-	49	2	-
PGT	Monsoon	1453	21	-	71	5	-
	Post-monsoon	362	34	-	26	7	-
	Annual	3113	15	-	11	1	-
CHN	Monsoon	2031	18	-	153	8	-
	Post-monsoon	530	40	-	-87	-15	-
	Annual	4139	27	-	-458	-11	-
PMD	Monsoon	2922	32	-	-92	-3	-
	Post-monsoon	708	36	*	-168	-21	**
	Annual	2794	20	***	-513	-17	***
PNL	Monsoon	1460	26	*	-207	-13	**
	Post-monsoon	672	34	**	-163	-22	***
	Annual	1795	20	-	-14	-1	-
TVM	Monsoon	831	29	-	38	5	-
	Post-monsoon	527	37	-	-53	-10	-

* decreasing trend at 90% significant level
** decreasing trend at 95% significant level
*** decreasing trend at 99% significant level

@ increasing trend at 90% significant level
@@ increasing trend at 95% significant level
@@@ increasing trend at 99% significant level

Table 5.1 - Statistical parameters of trend analysis of rainfall for selected stations

post-monsoon seasons and also for annual rainfall. For most of the selected stations, it has been observed that the percentage ratio of departure is more in the case of post-monsoon season. At both the stations in the high ranges, the actual values of departures are more in the case of post-monsoon rainfall than that of monsoon. But, at the other five stations, the monsoon rainfall has shown an increasing tendency, while post-monsoon rainfall has shown a decreasing tendency. For all coastal stations, the departure of means for monsoon rainfall is much more than that of annual rainfall values.

The actual yearly values of rainfall and filtered values together with the means for the 5 selected stations for annual, monsoon and post-monsoon seasons are given in Figs. 5.3 to 5.5. It is quite evident from the figures that the variations are not linear. From the significance tests, we have already seen that the stations Calicut and Palghat did not exhibit any significant trends even at 90% level for annual, monsoon and post-monsoon rainfall values. During the period 1935-1950 and 1967-1983, the filtered series of annual rainfall were generally steady. The filtered series of annual and monsoon season rainfall values of Palghat have shown a more cyclic nature. The filtered series have shown peaks in monsoon and annual rainfall values during 1959-1962 corresponding to the highest monsoonal and annual rainfall values (1961) at both Calicut and Palghat.

At Punelur, the picture is very much different from that of Calicut and Palghat. Significance tests have shown that there is a decreasing trend for all the three cases: annual, monsoon and post-monsoon rainfall. It is observed that there are three separate periods: 1939-1953 when

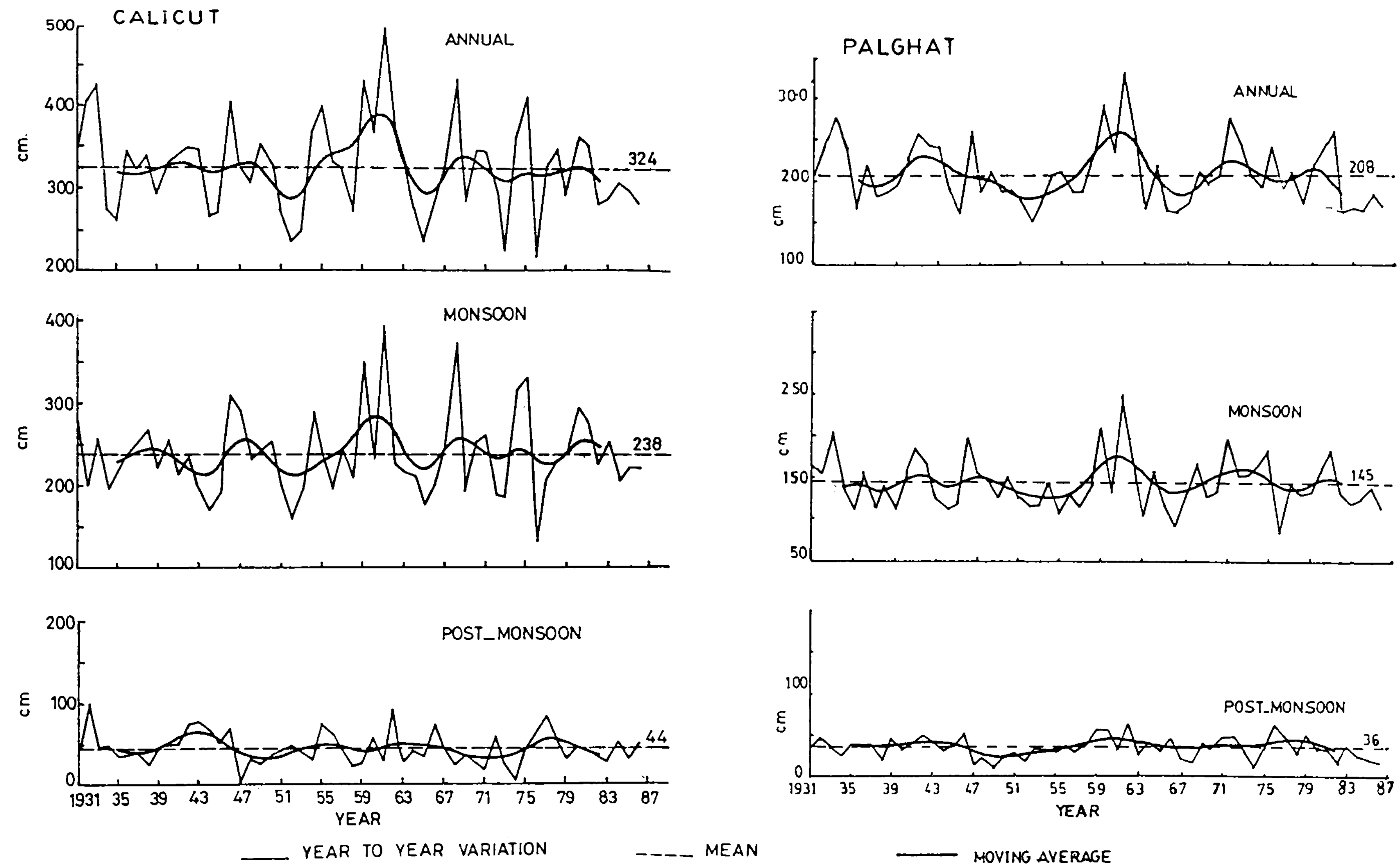


Fig. 5.3 Nine-point filtered series of rainfall

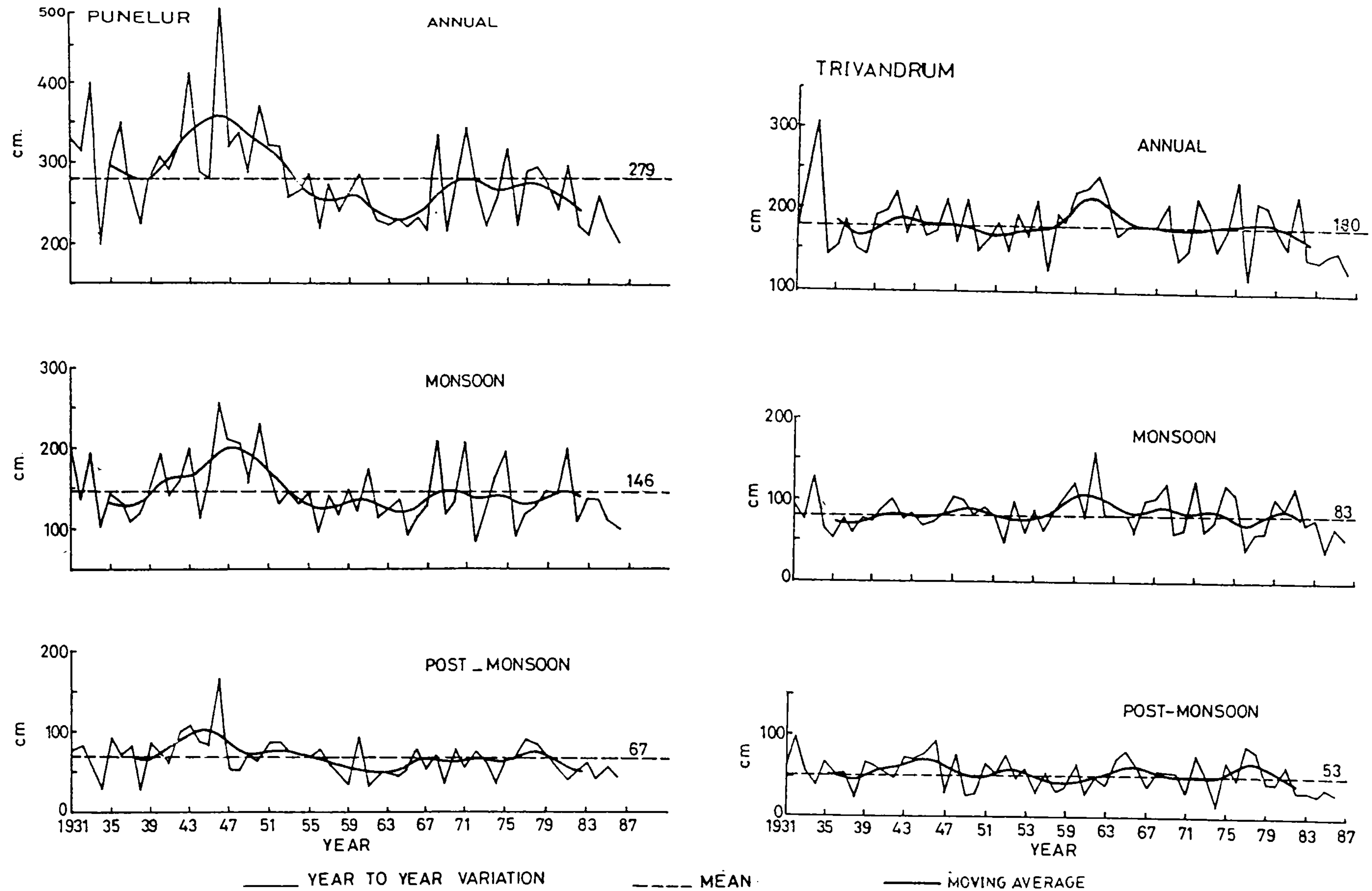


Fig. 5.4 Nine-point filtered series of rainfall

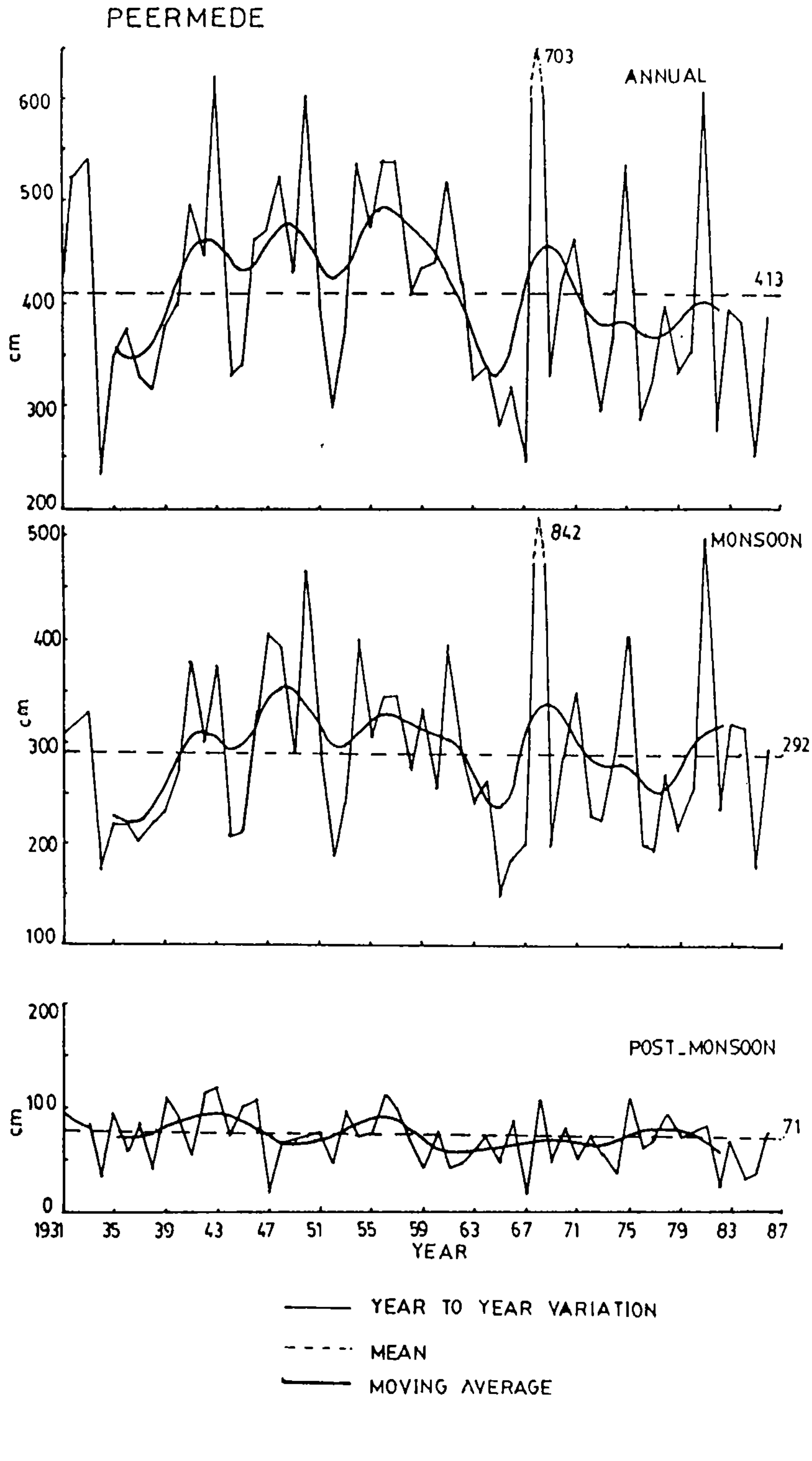


Fig. 5.5 Nine-point filtered series of rainfall

rainfall values were above normal, and included the heaviest rainfall year, 1954-1970 with below normal rainfall and the period from 1971 onwards when the series is comparatively steady. This shows that the rainfall here is not continuously decreasing with time. It is to be noted that, after 1954, annual and monsoon season rainfall amounts have been below normal. However in the post-monsoon season, a short period between 1974-1979 exhibited above normal rainfall. This particular station has also shown a positive correlation between monsoon and post-monsoon rainfall.

Trivandrum also did not exhibit any significant trend in monsoon, post-monsoon and annual rainfall values. In comparison with the three stations already discussed, rainfall here has been steadier and the filtered series moved very close to the normal values. As in the case of Calicut, the maxima in the filtered series for monsoon and annual rainfall occurred during 1959-1963, the peak in monsoon rainfall series occurred in 1961, but annual rainfall was maximum in 1933. Similarly, a negative correlation has been observed between monsoon and post-monsoon rainfall as in the case of Calicut. For the high range station Peermede, the filtered series of monsoon and annual rainfall data were above normal for the period 1940-1962 with the highest monsoonal and annual rainfall occurred in 1961.

Except for Punelur and Peermede the highest filtered values for annual rainfall were in 1960 or 1961: in Peermede it was in 1956 and in Punelur in 1946. The filtered series for annual, monsoon and post-monsoon have not shown common characteristic.

One interesting aspect common to all these series is that annual rainfall was near normal during 1978-1979, but a sharp decrease has been observed after that at all stations. This feature has been observed to a certain extent in monsoon rainfall data also. Therefore, the rainfall series for 1970-1989 has been analysed using a three-point filter with weightages of 0.25, 0.5 and 0.25 to get a more detailed insight into the decreasing trend.

Three-point filtered series together with actual values and means for 1931-1980 are shown in Figs. 5.6 and 5.7. Filtered values of annual rainfall of Palghat were below normal during the period 1976-1979 and above normal during 1980-1982. A decreasing trend started in 1982 and the rainfall became below normal by 1983 and thereafter decreased even further. But for Calicut, the decreasing tendency started by 1980, rainfall became below normal by 1982, but from 1988, the series showed an increasing tendency. Though rainfall was below normal upto 1988 annual series of Cochin has shown a decreasing tendency by 1977 and become below normal by 1982 but from 1987 onwards, a slight increasing tendency has been observed. The series for Trivandrum has shown an oscillating nature about the mean from 1971-1979 and from 1980 onwards, a decreasing trend has been observed. The series however, has shown an increasing nature by 1987 and the values become normal by 1988. Punelur and Peermede also have shown such a decreasing nature by 1979 and 1982 respectively. For Punelur, the filtered series was below normal from 1973 onwards except in the year 1978.

The filtered series of rainfall of the monsoon season at all stations have shown a decreasing tendency from 1980 or 1981, and were below normal by 1983 or 1984 and reached a minimum value by 1986 or 1987 and then exhibited an increase.

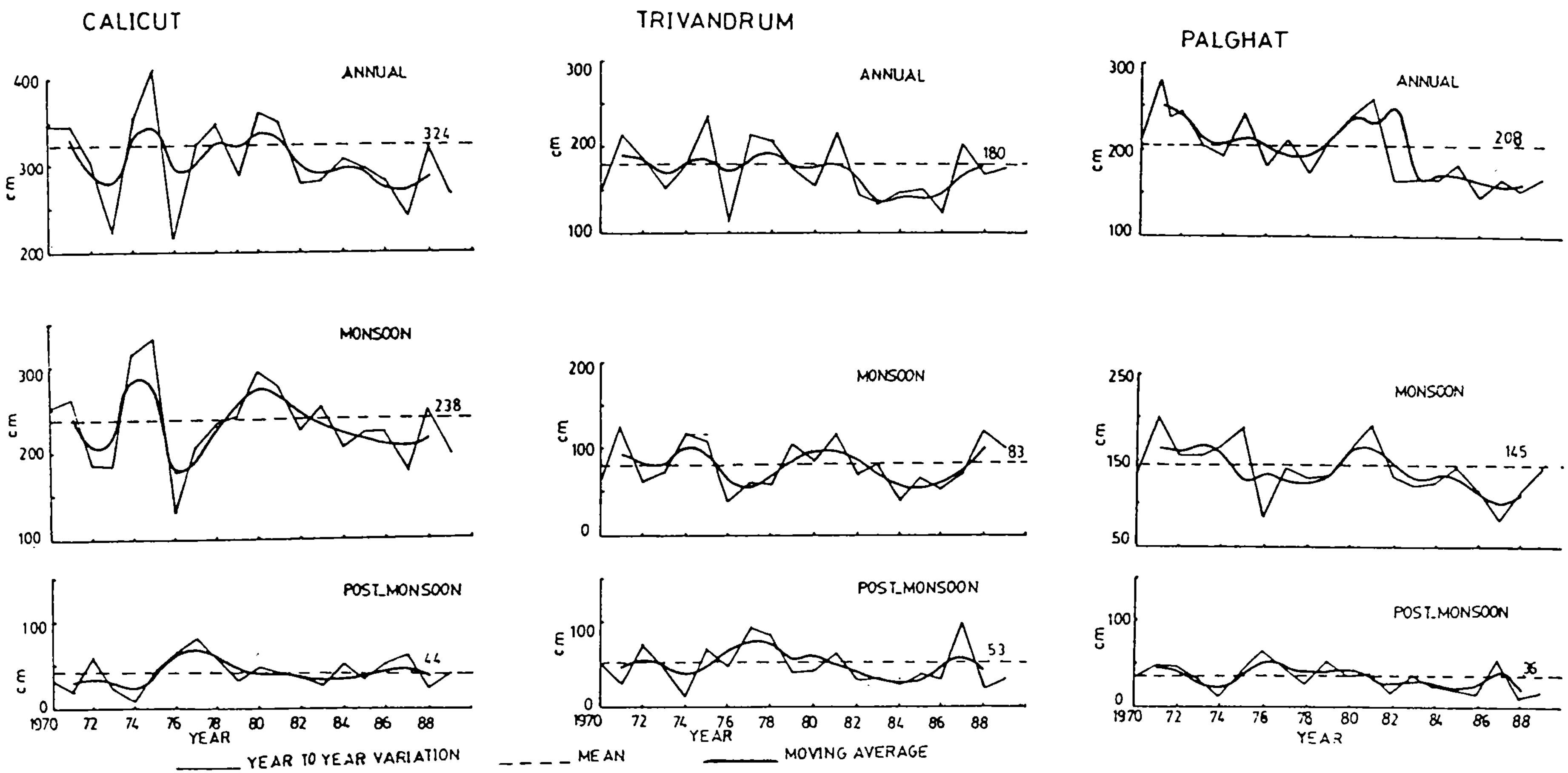


Fig. 5.6 Three-point filterd series of rainfall for three selected stations

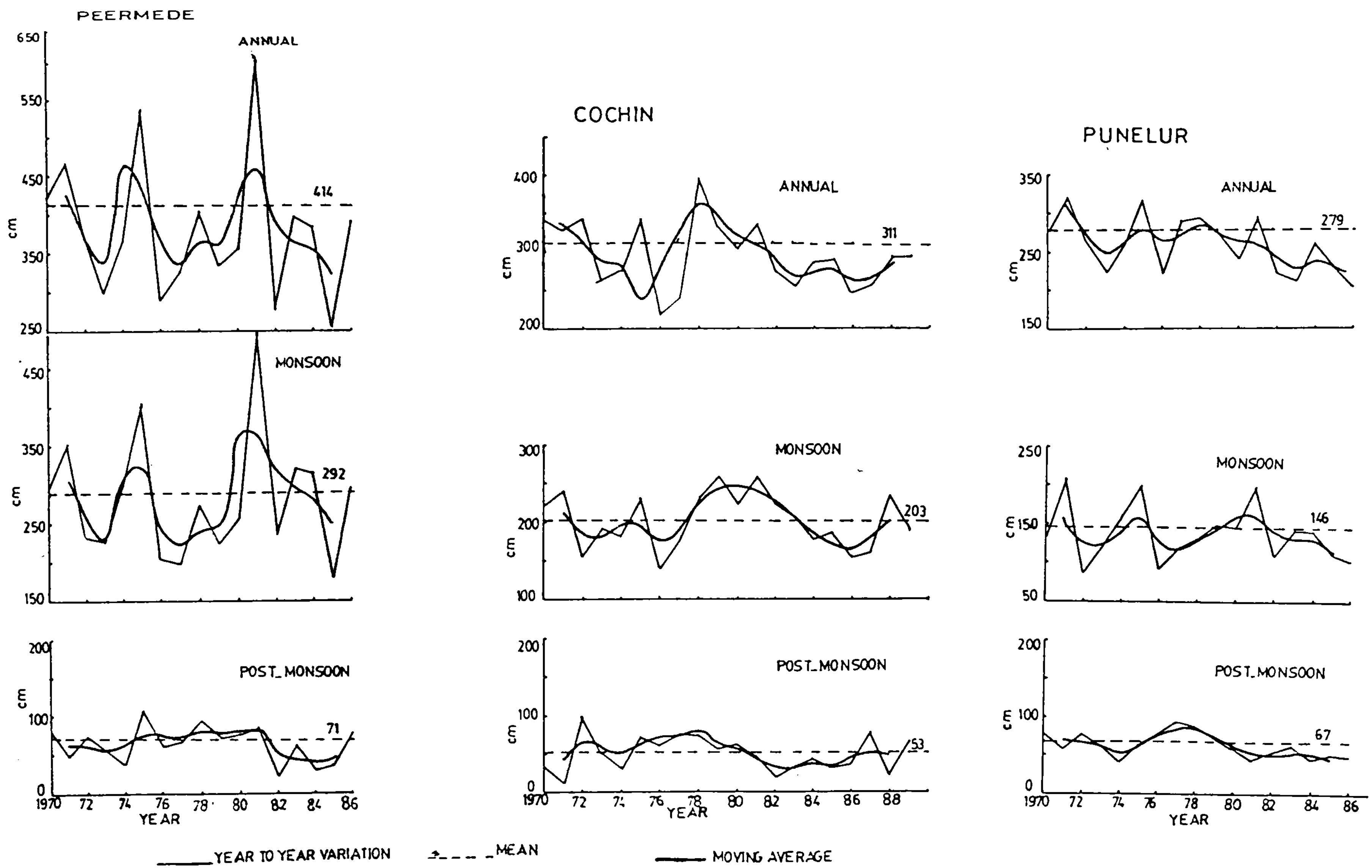


Fig. 5.7 Three-point filtered series of rainfall for three selected stations

5.2.2 Actual Evapotranspiration:

Fig. 5.8a shows the presence of trends in annual A.E. values for different stations at different significant levels. More than one third of the stations chosen for this study show a significant decreasing trend in annual A.E. values, of which a few stations especially in the lowland regions of southern half of the State, exhibited this decreasing trend even at 99% level. From the figure, it is observed that the stations which exhibited significant trends in A.E. values are randomly distributed. Another salient feature is that many of the stations which do not exhibit any significant trend in annual rainfall even at 90% level and also some stations which exhibited a slight increasing tendency in annual rainfall values have shown a significant decreasing trend in annual A.E.. On the other hand, some of the stations which exhibited a significant decreasing trend at 99% level in annual rainfall do not show any significant decreasing trend in annual A.E. even at 90% level. Karikode, the only station to show a significant increasing trend (99%) in annual A.E. did not exhibit any significant increasing or decreasing trend in annual rainfall even at 90% level. In general, it is observed that almost all the stations in the southern half of the State which exhibited decreasing trends in annual rainfall values have shown decreasing trends in annual A.E. too: these stations are mostly confined to lowland and midland regions.

Fig. 5.8b shows the distribution of the differences between the half-period averages of A.E.. The shaded portions represent the areas of increasing tendency. From Figs. 5.2b and 5.2c it has already been seen that there is a slight increasing tendency in annual rainfall in the

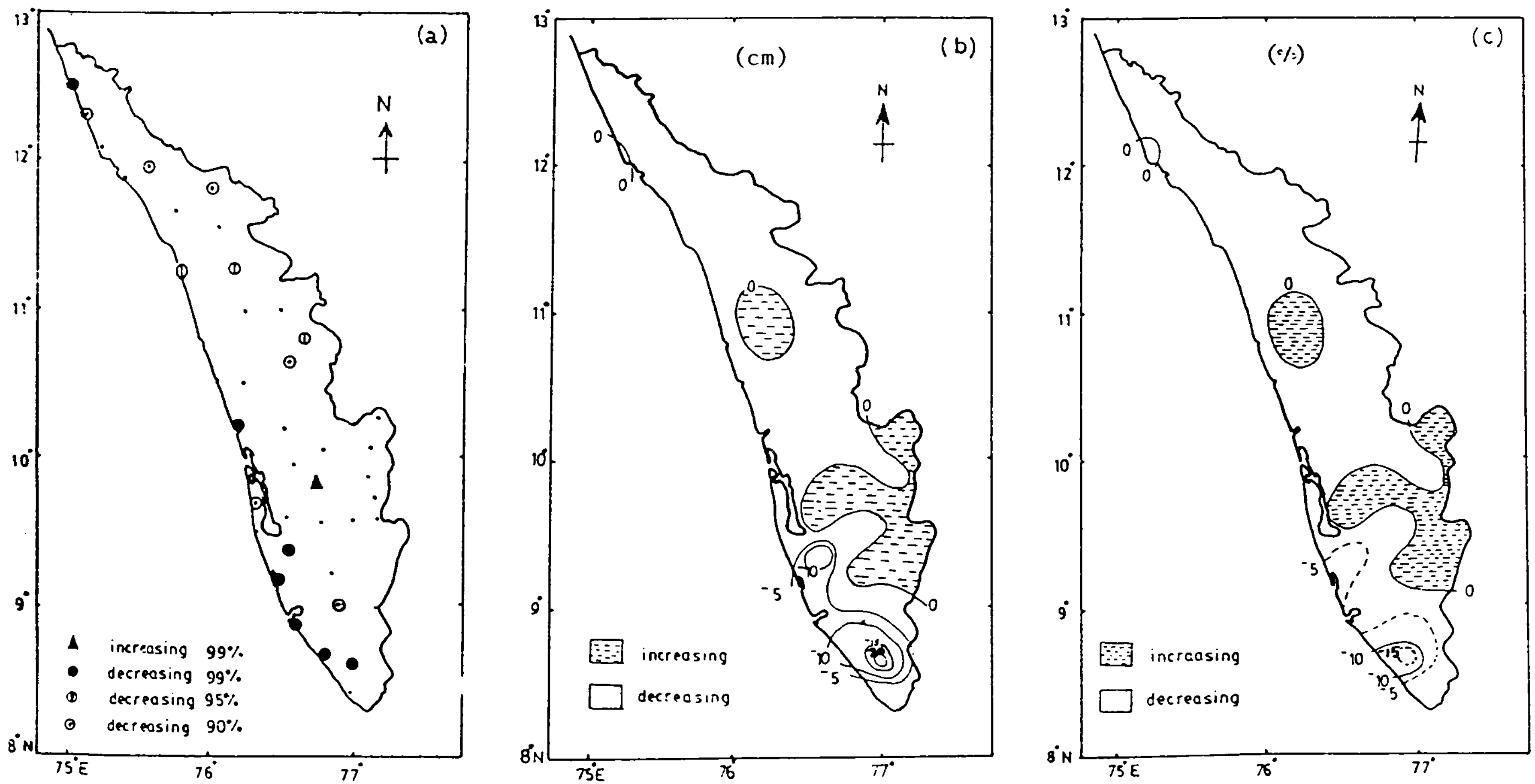


Fig. 5.8 Trend aspects of annual A.E. series

Palghat Gap region and an area extending to the extreme north of the State through the coastal belt and over the extreme eastern parts of the southern half of the State. It is observed that the area of increasing tendency of annual A.E. in the northern half of the State have decreased in comparison to the rainfall pattern, but have increased in the southern half of the State, extended more towards west. A very small area surrounding Perintalmanna, west of Palghat Gap, has shown an increasing tendency (4 cm). In the southern half of the State, more areas (especially the Ghat region) have shown this increasing tendency. The maximum increase occurred at Karikode (about 5 cm), which is statistically significant. Neriamangalam and Kanjirapally which showed a large decrease in annual rainfall do not exhibit much difference in annual A.E. (only less than 3 cm). Maximum decrease of annual A.E. of more than 20 cm occur over Nedumangad region in the southern part of the State.

The distribution of percentage ratio of the departure of A.E. values with respect to the first-half is given in Fig. 5.8c. Neriamangalam which showed the highest percentage ratio of departure (-28%) in the case of annual rainfall records only -2.7% departure in the case of annual A.E.. This percentage ratios of departures of annual A.E. have varied from -15% at Nedumangad region to about +4% at Marayur.

The decreasing (increasing) trend in annual A.E. may be due to decreasing (increasing) trend in annual rainfall, decreasing (increasing) trend in P.E. or the seasonal distribution of rainfall. The trend analysis of P.E. has shown that there is an increasing trend in P.E. over central and south central Kerala. But, at the same time, many of these stations exhibit significant decreasing trends in annual rainfall too. The effect of these changes on A.E. are in opposite directions. It should, however, be remembered that a trend in P.E. indicates only a marginal difference in P.E. values. Stations in the northern half of the State did not record significant decreases in rainfall or significant increases in P.E., but some of these stations exhibited significant decreasing trends in annual A.E. values. This implies that the seasonal distribution of rainfall may be playing a major role in these changes. It is important to note that, a small decreasing trend in winter or pre-monsoon rainfall will certainly affect the A.E. values, but need not affect much the annual rainfall values. This may be the case with some stations in the northern half of the State too. Similarly, if there is a decreasing trend in monsoon or post-monsoon rainfall, it need not have much effect on annual A.E. values, but will certainly affect the annual rainfall values. For the station Karikode, which exhibits an increasing trend in A.E., there is a significant increase in P.E. values, without significant change in annual rainfall amount.

Table 5.2 gives a comparison of trends at different significant levels for monsoon, post-monsoon and annual A.E. values. Cochin and Peermede have shown an increasing trend in A.E. for the monsoon period, while the latter exhibited an increasing trend in post-monsoon A.E. also. It has already been noted that Cochin exhibited a slight increasing tendency in monsoon rainfall, but this increase was not seen at Peermede. It is clear that for these two stations a slight increase or decrease in monsoon or post-monsoon rainfall does not make much change in corresponding A.E.. So, this increasing tendency may be due to the increasing trend in

		Mean	Coeff. vari.	M.K signi.	Diff. of means	%D	t-test signi
	Annual	1141	8	***	-45	-3	*
KSD	Monsoon	535	4	-	3	1	-
	Post-monsoon	343	10	-	-11	-3	-
	Annual	1118	10	-	-48	-4	-
CNR	Monsoon	532	4	-	2	0.5	-
	Post-monsoon	326	16	-	-13	-4	-
	Annual	955	6	-	-18	-2	-
VYT	Monsoon	327	7	-	4	0.1	-
	Post-monsoon	230	6	-	3	1	-
	Annual	1242	7	*	-35	-3	-
CLT	Monsoon	534	4	-	3	0.5	-
	Post-monsoon	360	11	-	2	1	-
	Annual	1205	8	*	-22	-2	-
PGT	Monsoon	503	6	-	-8	-1.5	-
	Post-monsoon	362	9	-	0.4	0.1	-
	Annual	1352	7	-	-14	-1	-
CHN	Monsoon	544	4	@@@	19	3	@@@
	Post-monsoon	377	-	-	-7	2	-
	Annual	931	5	-	-4	-0.4	-
PMD	Monsoon	312	8	@@@	16	5	@@
	Post-monsoon	211	6	@@@	11	5	@@@
	Annual	1503	5	-	-41	-3	**
PNL	Monsoon	558	4	-	8	1	-
	Post-monsoon	386	6	-	-4	-1	-
	Annual	1371	6	-	-14	-1	-
TVM	Monsoon	531	5	-	3	0.5	-
	Post-monsoon	376	7	-	-8	-2	-

* decreasing trend at 90% significant level
** decreasing trend at 95% significant level
*** decreasing trend at 99% significant level

@ increasing trend at 90% significant level
@@ increasing trend at 95% significant level
@@@ increasing trend at 99% significant level

Table 5.2 - Statistical parameters of trend analysis of A.E for selected stations

P.E. over these areas.

The other seven stations do not exhibit any significant trend (increasing or decreasing) for both the seasons. But, it is interesting to note that 4 of these stations exhibited significant decreasing trends in annual A.E.. Similarly, Cochin and Peermede which exhibited increasing trends in seasonal A.E. do not exhibit any significant trend in annual A.E..

Mean, yearly values and filtered series of A.E. are plotted together for Calicut, Palghat, Trivandrum, Punelur and Palghat in Figs. 5.9 to 5.11 respectively. It has already been seen that annual A.E. series for Calicut and Palghat have decreasing trends at 90% level by Mann-Kendall statistic test. Such a slight decreasing trend can be seen in the filtered series also. For Calicut, filtered values were above normal for the period 1935-1951 and below normal from 1971 onwards. Punelur has exhibited a statistically decreasing trend for annual A.E. by Student's t-test at 95% level. Such a decreasing nature can be easily observed in the filtered series also. Filtered values were above normal up to about 1955 and below normal thereafter. For this station, the series of monsoon and post-monsoon A.E. are very steady. Variation of A.E. for Trivandrum supports the results obtained from significance test: the series does not show any significant trend in A.E. of annual, monsoon and post-monsoon periods.

Annual A.E. values of Peermede are highly stable compared to all other stations. The A.E. for monsoon season shows a slight increasing tendency from 1970 onwards. The variation pattern of A.E. for Palghat has a good resemblance to that of Trivandrum.

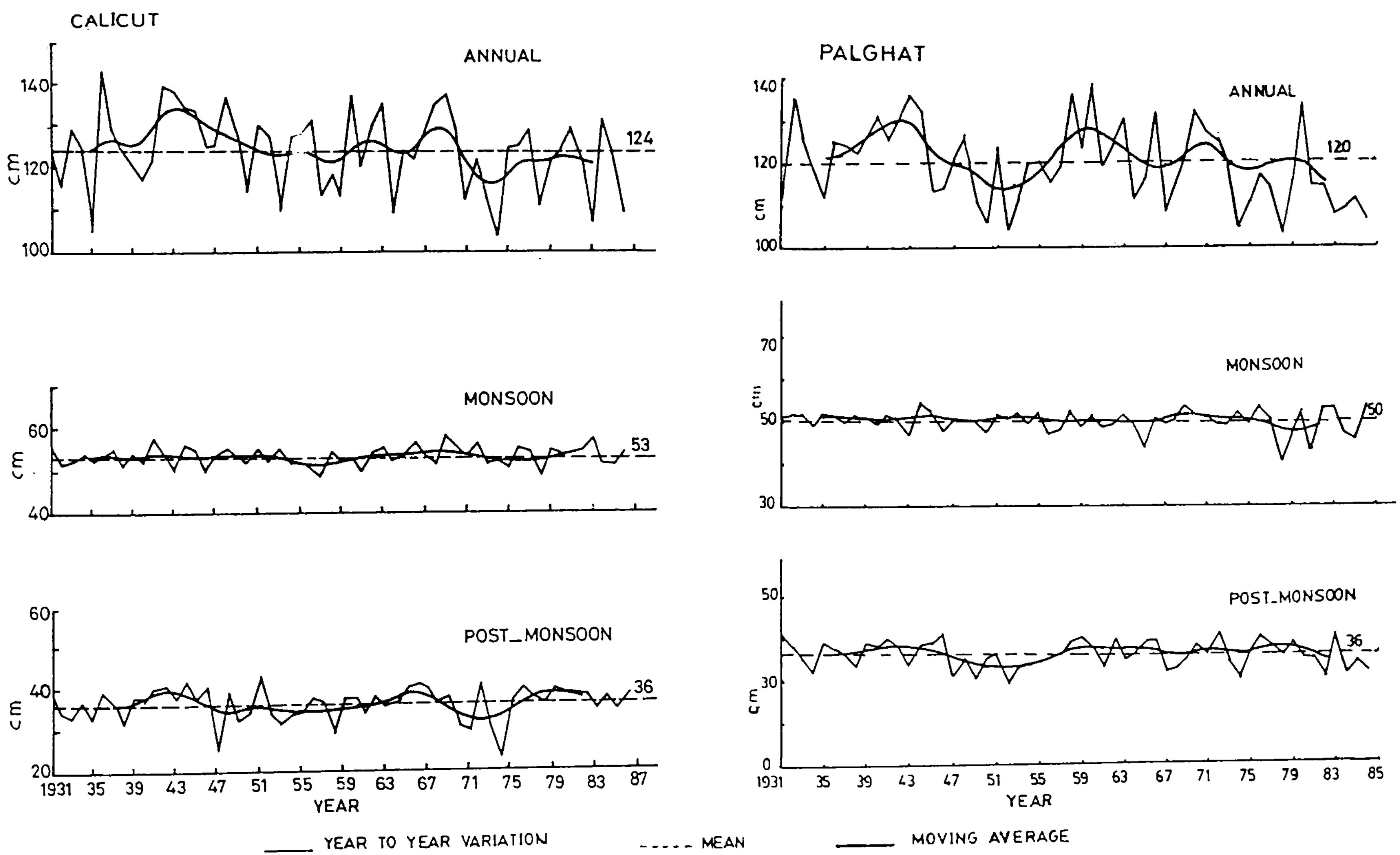


Fig. 5.9 Nine-point filtered series of A.E.

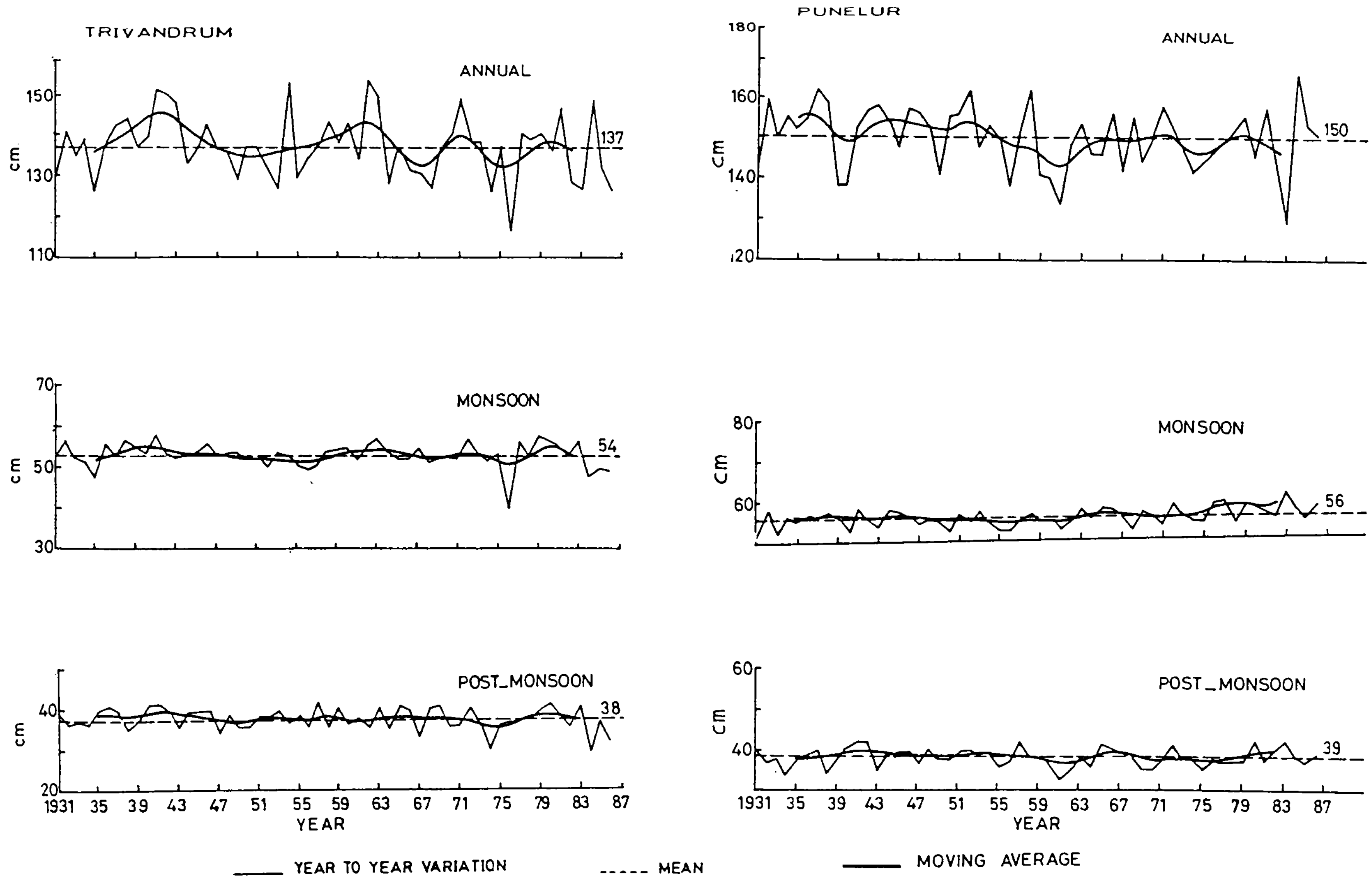


Fig. 5.10 Nine-point filtered series of A.E.

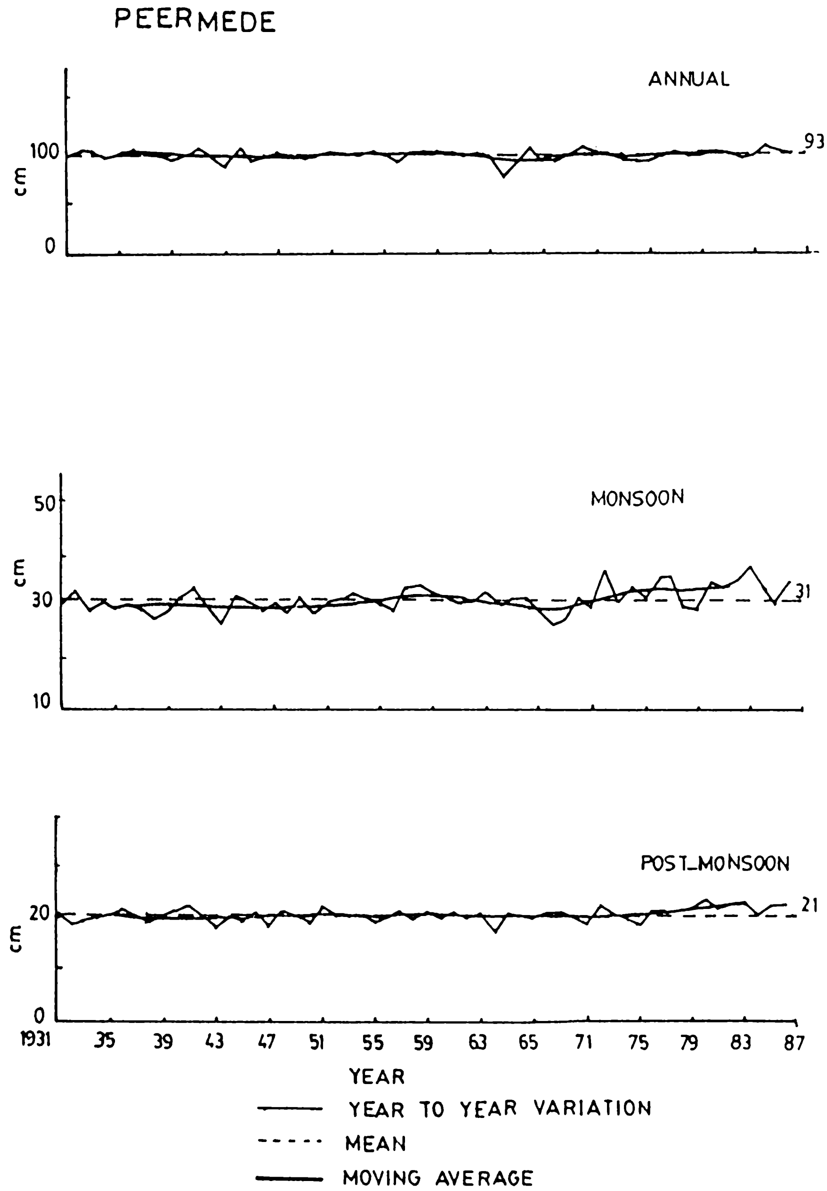


Fig.5.11 Nine-point filtered series of A.E.

Monsoon and post-monsoon series for all stations have shown that the filtered values move along with the mean values. A comparison of annual A.E. with monsoon and post-monsoon A.E. has shown that variation of annual A.E. is mainly due to the variation of A.E. in winter and pre-monsoon season, even though there is a low positive correlation between annual A.E. and post-monsoon A.E.. A comparison with rainfall series has shown that a high positive correlation exists between rainfall and A.E. for post-monsoon season, especially for Punelur and Palghat. But for Peermede, A.E. and rainfall are not correlated in all the three cases. For the monsoon season, rainfall series has shown an irregular variation about the mean, but A.E. is very stable. This is due to the increased water availability vis-a-vis need during this season. Such a pattern can be observed to a certain extent for the southern stations also where there is comparatively higher rainfall during the post-monsoon season.

5.2.3 Water Deficit:

The trends of annual deficits at various levels for different stations are given in Fig. 5.12a. It has been observed that about two thirds of the stations exhibited significant increasing trends: at about one third of the stations increases are significant even at 99% level. None of the stations showed any significant decreasing trend even at 90% level, except Perinthalmanna. Stations which exhibited significant increasing trend appeared to be distributed at random. A few of the stations which did not exhibit decreasing trends in rainfall or A.E., showed an increasing trend in annual deficit values. Similarly, the stations in the southern half of the State which exhibited significant trends in annual rainfall have not shown any increasing trend in annual

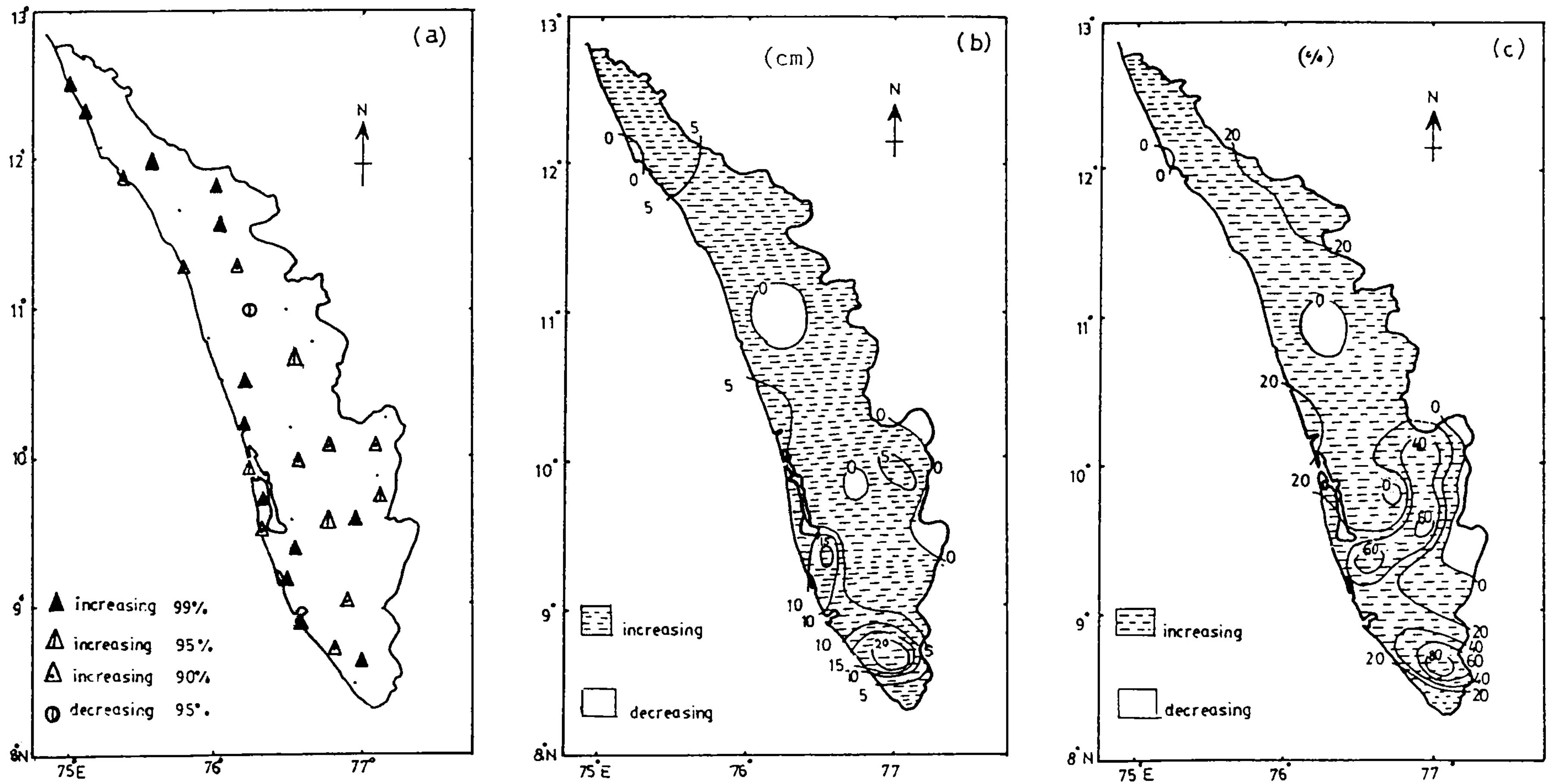


Fig.5.12 Trend aspects of annual water deficit series

deficits.

Figs. 5.12b and 5.13c show the distributions of differences between the first-half period means of annual deficits and the percentage ratios of these departures to the first-half period mean. In both the figures, the shaded regions represent an increasing tendency. Water deficits exhibit increasing tendency for most parts of the State and comparatively higher values in the south-western part of the State with the maximum increase of 22 cm at Nedumangad followed by Thiruvalla (16 cm). The regions which experienced departures in annual rainfall do not show much variation in annual deficits. Neriamangalam, which showed the maximum negative departure in annual rainfall (165 cm) has a departure of only 4 cm in annual deficit. On the other hand, stations which showed large departures in annual deficits, have comparatively higher rainfall departures. From the study of annual rainfall (Fig. 5.2) it was seen that there is a slight increasing tendency over Palghat Gap region and in an area extending to the north through lowland and midland regions, and in the leeward side of Western Ghats in the southern half (not statistically significant). But in the case of annual deficits, the corresponding decreasing tendencies are limited to very small areas.

Only five stations have shown a slight decreasing tendency in annual deficits, with largest decrease of nearly 5 cm at Perintalmanna, a station to the north-west of Palghat. Stations on the leeward side of the Western Ghats of the southern half of the State have shown only a slight decreasing tendency or comparatively low increasing tendency in annual deficits.

The percentage ratio of departures of annual deficit is maximum around Nedumangad region: more than 90%, which corresponds to a region where there is a comparatively very large negative departure in annual rainfall (25%). The two other regions of comparatively large decrease in annual rainfall, show a comparatively large increase in annual deficits too. The most significant point is that percentage increase of annual deficit is more than twice the percentage decrease of annual rainfall for most of the stations. Only two stations have negative departure of more than 25% in annual rainfall, but in the case of annual deficit, more than 10 stations have shown a positive departure of more than 25%. Similarly, most of the stations over the Palghat Gap and an area extending to the north through the coastal tracts which have shown a slight increasing tendency in annual rainfall have also shown an increasing tendency in the case of annual deficit. This shows that the area of increasing tendency of annual deficit is much more than the area of decreasing tendency of annual rainfall.

Since water deficit is defined as the difference between P.E. and A.E., the increase in deficits can be due to increase in P.E. or decrease in A.E.: since A.E. is a function of P.E., changes in P.E. can cause changes in A.E. and thus can alter the deficits. It is seen that some of the stations in the central parts of the State exhibit an increasing tendency in annual P.E.. But, as stated earlier, the magnitudes of changes in P.E. values are comparatively small. So, the major factor causing increases in annual deficits is the decrease in annual A.E. values. All stations which exhibit significant decreasing trends in annual A.E. (except Palghat) have shown significantly increasing trends in annual deficits, even at higher significant levels. A few stations, mainly in south central Kerala, which have not shown any significant decreasing trend in annual A.E. even at 90% level, have shown significant increasing trends in annual deficits. This may be due to the increasing trend in P.E. over this area. In comparison to the area of increasing tendency of annual A.E., the area of decreasing tendency of annual deficit is smaller, and in the latter case it is mainly confined to the leeward side of the Western Ghats in the southern half of the State.

Table 5.3 shows the details of the trends in water deficits observed at selected stations for monsoon season, post-monsoon season and on an annual basis. It has already been observed that mean water deficits for monsoon season for most stations are very small and the coefficients of variation are very high. Results of Mann-Kendall statistic test have shown a significant decreasing trend in deficits for almost all stations, even at 99% level, but Student's t-test has shown comparatively steady deficits. These differences in results are due to high variability of monsoon deficits. At Cochin, the decrease was significant by Student's t-test too, at 90% level. The departure values in all these cases are less than 3 cm. So the significance shown by statistical tests does not have any practical significance. But, it is to be noted that none of the stations exhibited any increasing tendency in this season.

In the case of post-monsoon season, three stations - Kasargode, Cannanore and Trivandrum -exhibited statistically significant increases (90% or 95% levels). It is interesting to note that only the two high range stations have shown a decreasing tendency of deficits during this

		Mean	Coeff.V. vari.	M.K. signi.	Diff.	% D	t-test signi.
	Annual	566	16	@@@	51	9	@@
KSD	Monsoon	1.7	354	***	-2	-66	-
	Post-monsoon	71	48	@	9	13	-
	Annual	588	20	@@	52	9	@
CNR	Monsoon	5.2	170	***	-1	-23	-
	Post-monsoon	88	62	-	15	19	@@
	Annual	133	34	@@@	24	20	@@
VYT	Monsoon						
	Post-monsoon	8	103	-	-1	-13	-
	Annual	469	20	@@	40	9	-
CLT	Monsoon	4.3	186	***	-2	-39	-
	Post-monsoon	55	69	-	-2	-2	-
	Annual	522	18	-	10	2	-
PGT	Monsoon	5.4	157	***	-1	-33	-
	Post-monsoon	57	60	-	1	2	-
	Annual	353	30	-	49	15	@
CHN	Monsoon	2	29	***	-2.5	-82	*
	Post-monsoon	36	68	-	3.5	10	-
	Annual	81	56	@@@	38	63	@@@
PMD	Monsoon						
	Post-monsoon	4	114	-	-0.1	-4	-
	Annual	220	38.1	@	49	25	@@
PNL	Monsoon	4.3	184	***	-32	-54	-
	Post-monsoon	25	80	-	7	36	-
	Annual	331	26.2	-	22	7	-
TVM	Monsoon	25	126	-	1.5	6	-
	Post-monsoon	28	94	@@	12	52	-

* decreasing trend at 90% significant level
** decreasing trend at 95% significant level
*** decreasing trend at 99% significant level

@ increasing trend at 90% significant level
@@ increasing trend at 95% significant level
@@@ increasing trend at 99% significant level

Table 5.3 - Statistical parameters of trend analysis of water deficit for some stations

season. As in the case of monsoon season, at all stations the departures are comparatively lower during this season.

It has already been observed that most of the stations exhibited significant increase in annual deficits even at 99% level. But, the stations selected for seasonal studies have shown that the departures for both monsoon and post-monsoon seasons are comparatively lower and that monsoon season deficits show a decreasing trend, while the post-monsoon deficit have shown an increasing tendency. This implies that comparatively higher increases might have occurred during the other two seasons.

A comparison with rainfall trends has revealed that, Punelur which experienced a decreasing trend in monsoon rainfall show a decreasing trend in deficit too, even though this decrease is very meagre in amount. It has already been discussed that a decrease in monsoon rainfall need not result in a change in A.E., because, from June to August rainfall exceeds the need (P.E.). At this point, it is worthwhile to remember that the mean deficit for the monsoon season for this station is only about 4 cm.

Figs. 5.13 and 5.14 show filtered series of water deficits at different stations. Filtered series of annual water deficit for Calicut, Punelur and Peermede have shown a clear increasing trend, which has already been proved by significance tests. Trivandrum does not exhibit any significant trend by both tests, but, a slight increasing trend has been observed in the filtered series.

At Calicut, Punelur, Peermede and Palghat, the deficit during monsoon period were very meagre, the mean value being less than 5 mm. As

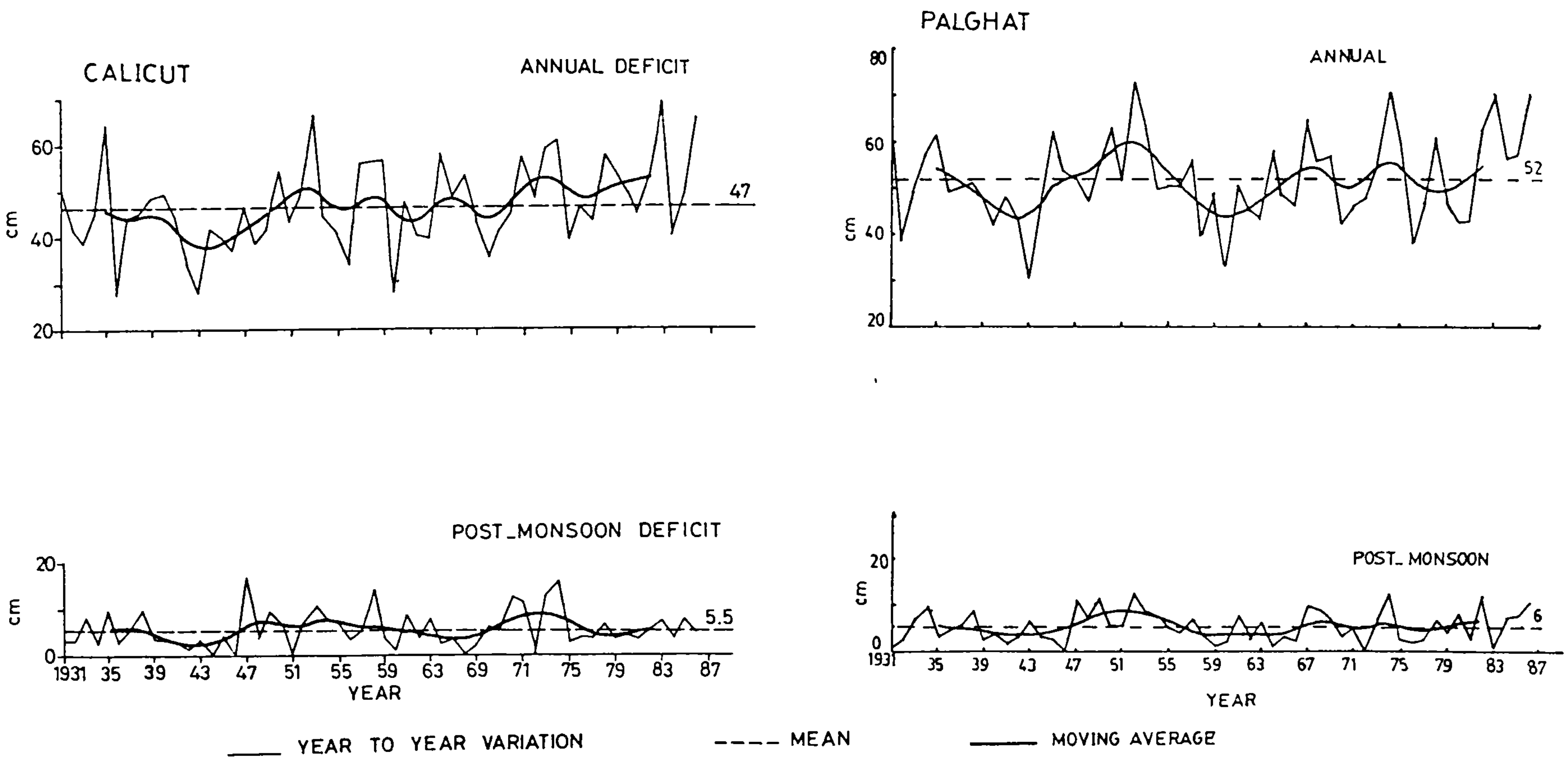


Fig. 5.13 Nine-point filtered series of water deficit

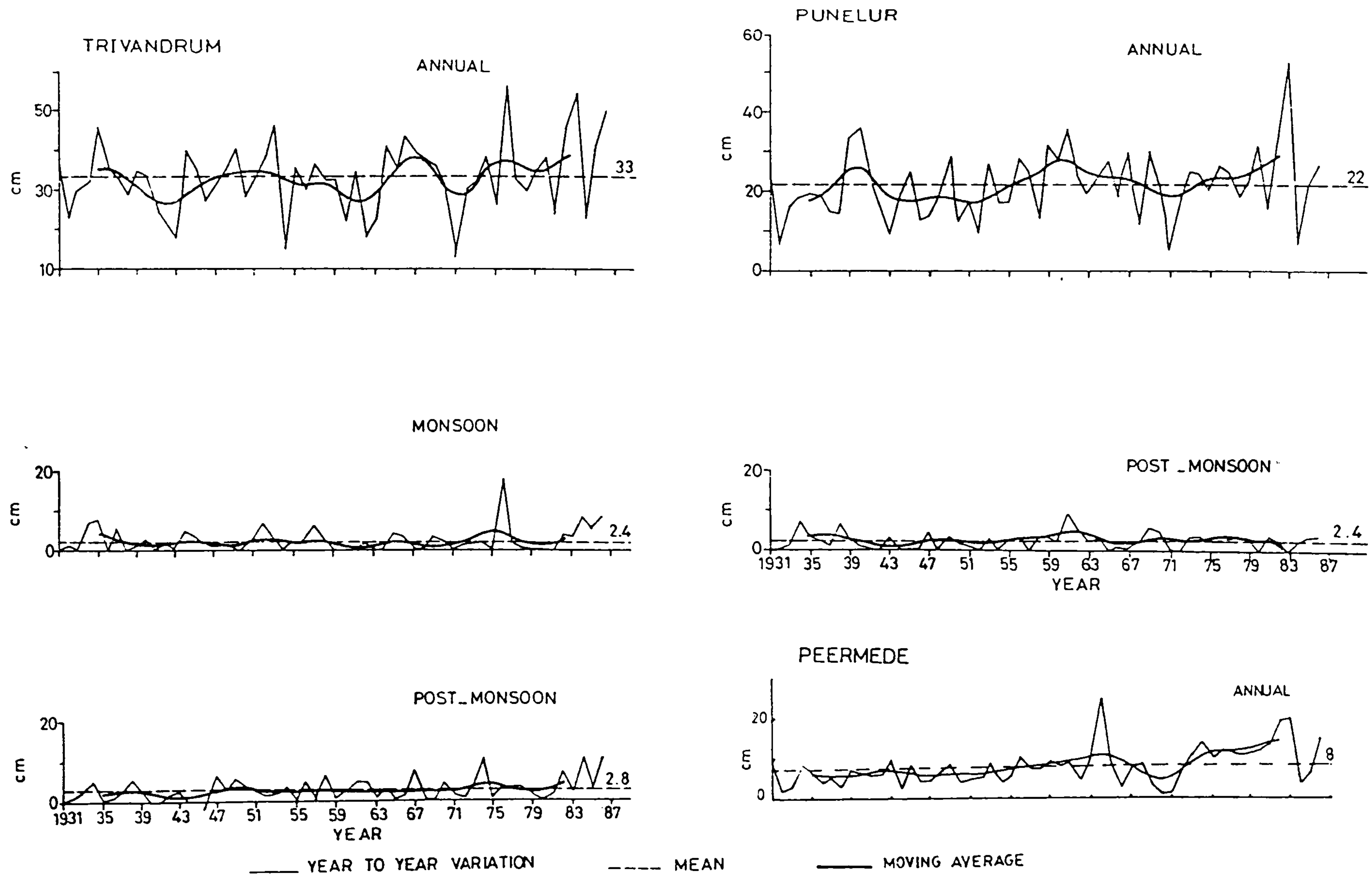


Fig. 5.14 Nine-point filtered series of water deficit

already stated, even though there is a slight statistically decreasing trend (by Mann-Kendall test) for monsoon period water deficit, it does not have any practical significance. Because of this fact, the water deficit series of these stations have not been analysed here. Trivandrum has a comparatively higher deficit, but as in the significance test, filtered series does not show any trend.

It is important to note that for all the stations, comparatively higher values of annual deficits occurred during 1982 and 1983 and the filtered values were above normal from 1975 onwards, except for Palghat.

A comparison of deficit with rainfall series gives some interesting results. Annual rainfall series and annual deficit series do not appear to be correlated at Calicut and Trivandrum. This appears to be paradoxical, since we expect an increase in deficit as the rainfall decreases. There is a peak in the rainfall series during the period 1955-1962 for Calicut, but, corresponding to that there is no sharp decrease in deficit. Similarly, for the period 1935-1950, the annual rainfall was approximately normal, but, there was a sharp decrease in annual deficit. This may be due to the decrease in winter and pre-monsoon rainfall. But at Peermede, Punelur and Palghat, a negative correlation has been observed between annual rainfall and water deficit. Filtered values of rainfall of Peermede for the period 1939-1962 was above normal, but that of deficit was normal or below normal; from 1970 onwards, rainfall series was below normal while that of deficit series was normal or above normal. Similarly, for Punelur, the three major periods of annual rainfall are associated with a complementary variation in annual deficits.

5.2.4 Water Surplus:

Stations which have shown trends in annual water surplus at different significant levels are presented in Fig. 5.15a. All the stations which have exhibited trends in annual rainfall have exhibited trends in annual surplus too. Many stations in the southern half of the State revealed the presence of decreasing trends even at 99% significant level; but in the northern half, only two stations showed such significant decreasing trends. In this case, for a few stations there is a decrease in the levels of significance compared to rainfall trends. The station Chinnar which did not exhibit any trend in annual rainfall has shown a significant decreasing trend in surplus at 99% level. None of the stations selected for this study has shown any increasing trend in annual surplus even at 90% level. This implies a decrease of hydrologically available water and lesser possibilities of severe flooding over the State, especially in the southern half. These results confirm the findings of Soman et al. (1988), who they analysed the extreme rainfall values for different return periods. It is interesting to note that, many stations in the southern half of the State exhibited significant decreasing trends in annual surplus and increasing trends in annual water deficits. But in the northern half, many stations have shown significant increasing trends in annual deficits, but only two stations have shown significant decreasing trends in annual surplus.

Figs. 5.15b and 5.15c depict the departures of the half period averages and the percentage ratio of this departure to the mean of the first half for annual water surplus. In both the cases, the shaded regions represent areas of increasing tendencies. Both these figures are similar to the corresponding figures of annual rainfall departures. A slight

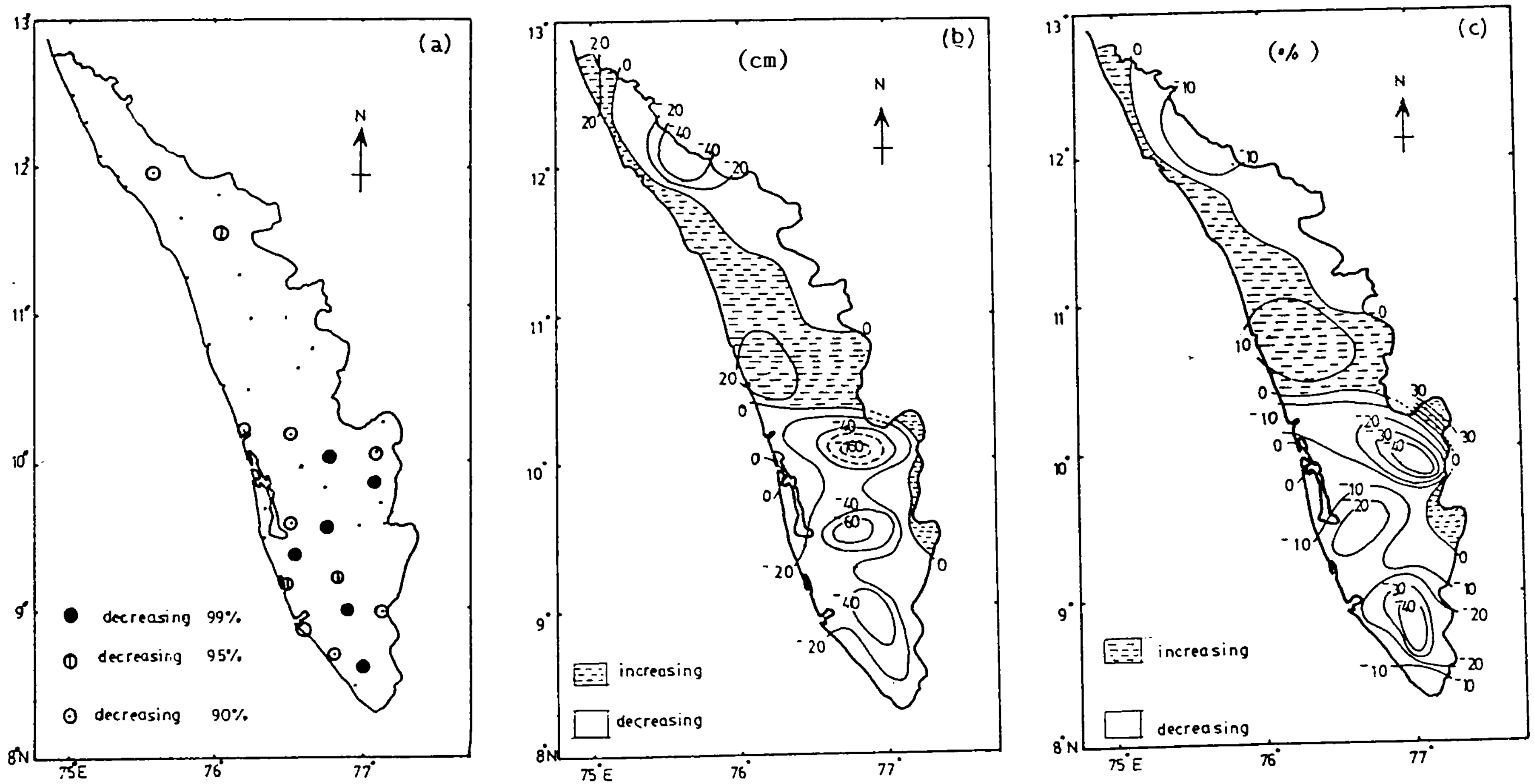


Fig. 5.15 Trend aspects of annual water surplus series

increasing tendency over Palghat region and the area extending to the extreme north through the coastal and midland region is observed. The leeward side of the Western Ghats in the southern half shows a slight increasing tendency. Three pockets of comparatively high departures have been observed. These departures range from -163 cm over Neriamangalam to +20 cm at Trichur.

On comparison, it is clear that the values of departures of annual surpluses and departures of annual rainfall are approximately equal in amount for many stations. But, it has been observed that there is a slight decrease in the departures of annual surplus values compared to departure of annual rainfall values over the the regions where it shows a decreasing tendency, and a slight increase of departure in annual surplus over regions having increasing tendency.

The distribution of percentage ratios also reveals three pockets of comparatively high reduction in annual surplus. An important point is that, in comparison with the percentage ratios of departures of rainfall, it has been observed that the percentage ratios of departures of annual surplus are very high, for almost all stations and it varies from -49% at Chinnar to +12% at Perintalmanna. The ratio of annual surplus departure is more than 40% over two regions: one around Neriamangalam and Chinnar area and the other over the extreme south surrounding Nedumangad. This indicates that hydrologically available water is getting reduced much faster than that of actual rainfall.

Details of the trend analysis of water surplus for a few selected stations are given in Table 5.4.

		Mean	Coeff. vari	M.K. signi.	Diff.	%D	t-test signi.
	Annual	2469	25	-	218	9	-
KSD	Monsoon	2335	23	-	210	9	-
	Post-monsoon	93	122	***	-3	-3	-
	Annual	2102	29	-	133	7	-
CNR	Monsoon	1975	29	-	179	10	-
	Post-monsoon	82	140	***	-16	-17	-
	Annual	3293	27	*	-160	-5	-
VYT	Monsoon	2977	28	-	-51	-2	-
	Post-monsoon	263	62	***	-79	-26	*
	Annual	2002	28	-	53	3	-
CLT	Monsoon	1763	29	-	134	8	-
	Post-monsoon	165	97	-	-34	-19	-
	Annual	880	40	-	72	9	-
PGT	Monsoon	780	42	-	45	6	-
	Post-monsoon	97	95	-	34	43	-
	Annual	1760	26	-	25	1	-
CHN	Monsoon	1417	27	-	101	7	-
	Post-monsoon	229	82	-	-82	-30	-
	Annual	3208	35	-	-455	-13	-
PMD	Monsoon	2532	38	-	-163	-6	-
	Post-monsoon	536	47	*	-176	-28	***
	Annual	1292	43	***	-474	-31	***
PNL	Monsoon	858	46	**	-274	-28	***
	Post-monsoon	348	61	**	-124	-30	**
	Annual	425	78	-	-3	-1	-
TVM	Monsoon	223	98	-	32	16	-
	Post-monsoon	174	98	**	-11	-6	-

* decreasing trend at 90% significant level
** decreasing trend at 95% significant level
*** decreasing trend at 99% significant level

@ increasing trend at 90% significant level
@@ increasing trend at 95% significant level
@@@ increasing trend at 99% significant level

Table 5.4 - Statistical parameters of trend analysis of water surplus for some stations

Only one station, Punelur has shown a significant decreasing trend in surplus during monsoon season. In the case of post-monsoon season, six stations out of nine have shown a decreasing trend even at 99% level, by Mann-Kendall statistic test. But, Student's t-test confirms the decreasing trend for the two high range stations and Punelur.

The departures of half period averages have shown that except the two high range stations and Punelur, all other stations exhibit an increasing water surplus in the monsoon season, (not statistically significant). At these three stations, a decreasing tendency in monsoon, post-monsoon and annual surplus values is observed: Punelur in particular has shown a significant decreasing trend in all the cases. It has been observed that for all coastal stations Kasargode, Cannanore, Calicut, Cochin, and Trivandrum, increases in monsoon surplus during second half of the study period over the first half were more than the corresponding increases in annual values. This implies that coastal stations might have shown comparatively larger increases in surplus during the monsoon season and decreasing tendency in other seasons.

None of the stations except Punelur has shown any significant trend, either increasing or decreasing, for monsoon surplus series as in the case of rainfall. However at Punelur, the decreasing trend in surplus was more significant than that of rainfall. In the post-monsoon season, four stations have shown significant decreasing trends for rainfall at 90% level, but in the case of surplus, six stations have shown such a decreasing trend. Palghat has shown an increasing tendency during this season in both rainfall and surplus values.

Filtered series of water surplus of various stations are given in Figs. 5.16 to 5.18. The filtered series of water surplus are similar to the filtered rainfall series, especially for the monsoon period. Even though the statistical tests have shown very significant decreases in annual, monsoon, and post-monsoon surplus values at Punelur, filtered series does not exhibit such a continuous decrease; the values were above normal up to 1953 and thereafter were below normal. Even though for many years, the post-monsoon surplus at Calicut and Trivandrum was zero, the filtered series were similar to the filtered series of post-monsoon rainfall.

Trends in annual values of different parameters shown by the stations at different significant levels are given in Table 5.5.

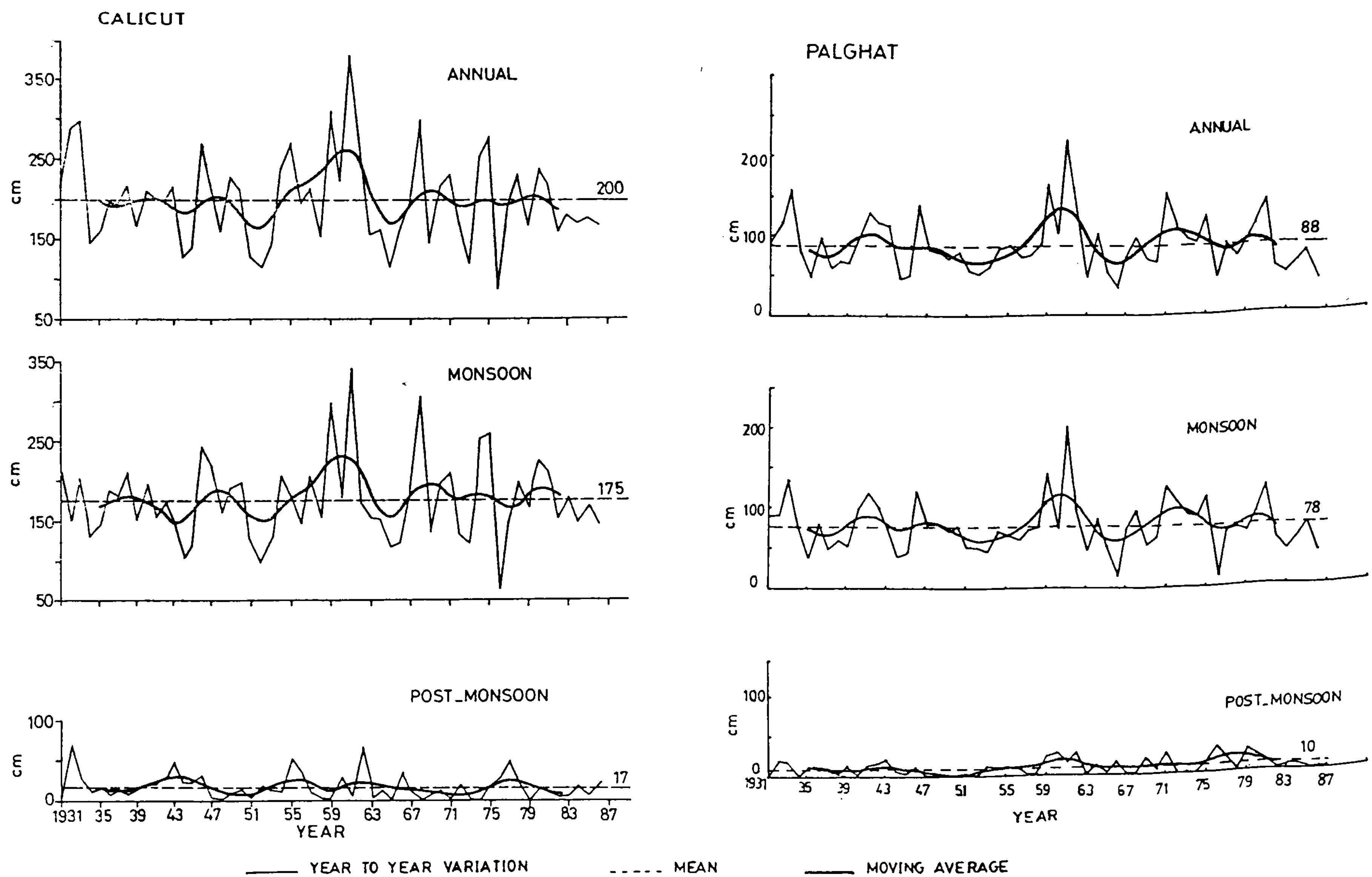


Fig. 5.16 Nine - point filtered series of water surplus

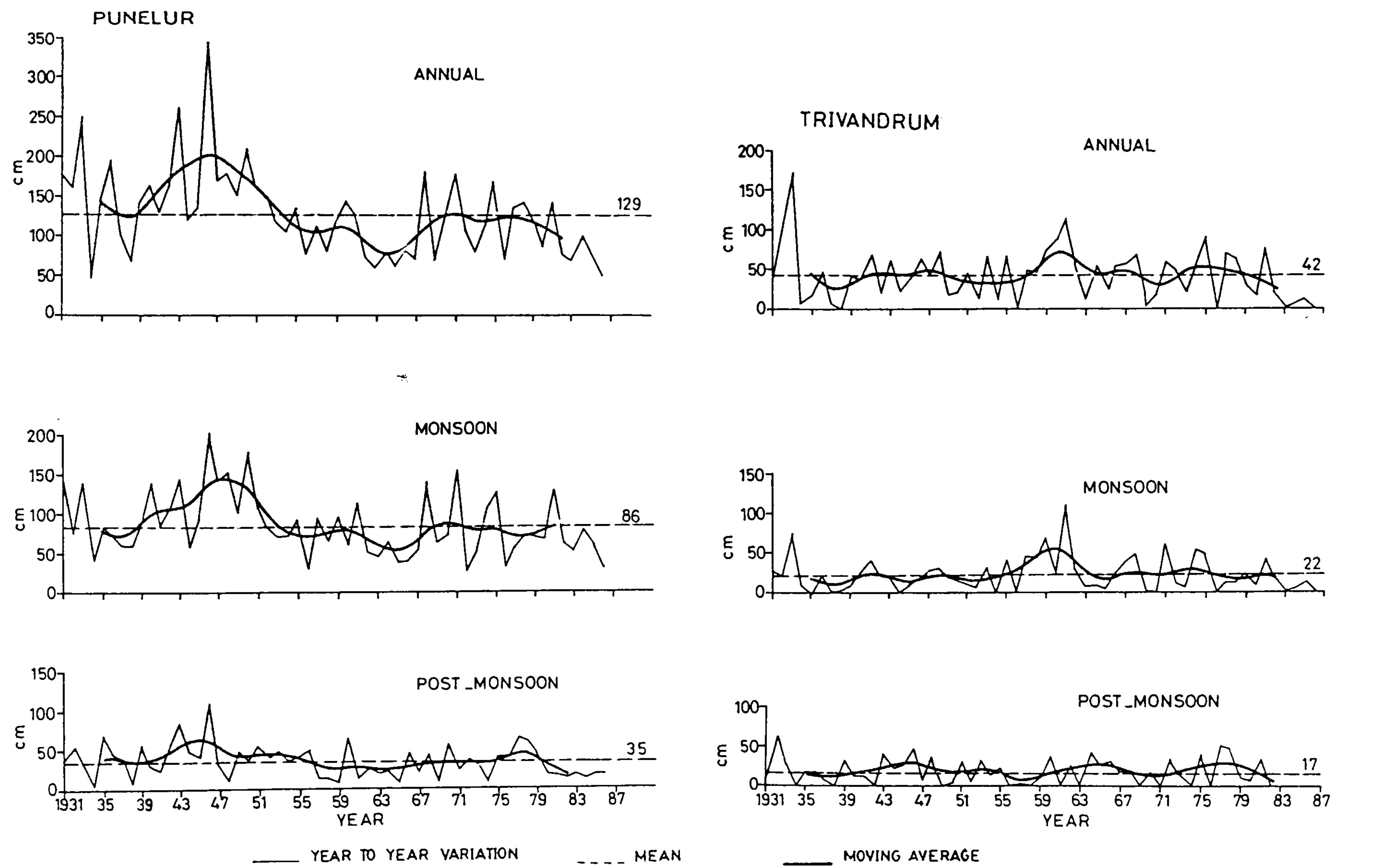


Fig. 5.17 Nine-point filtered series of water surplus

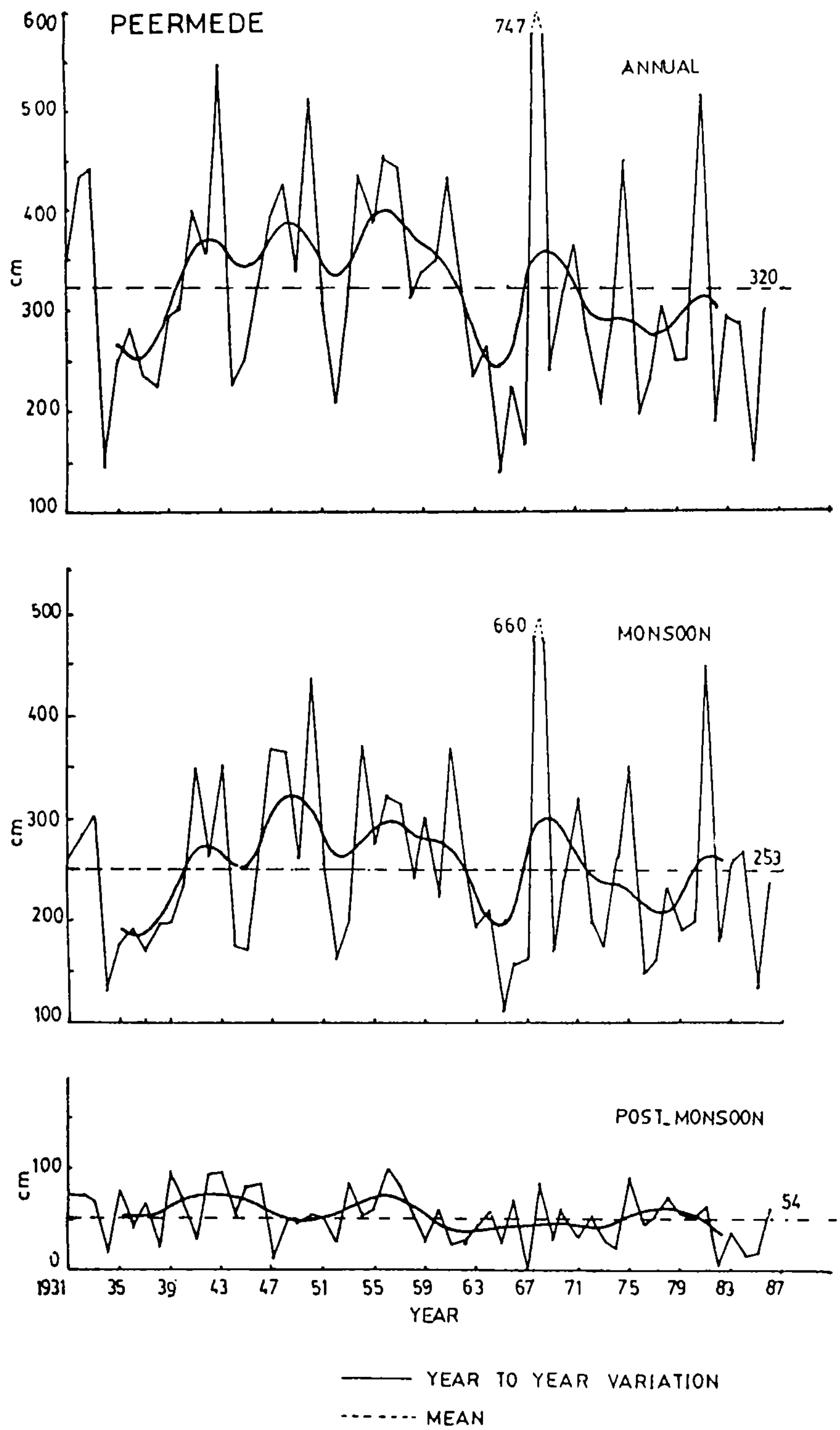


Fig. 5.18 Nine-point filtered series of water surplus

	Rainfall	A.E.	deficit	Surplus
KSD	-	***	@@@	-
HSD	-	*	@@@	-
PYR	-	-	-	-
IRK	***	*	@@@	*
CNR	-	-	@	-
MTY	-	*	@@@	-
KTD	-	-	-	-
VYT	**	-	@@@	**
NBR	-	**	@	-
CLT	-	**	@	-
PRM	-	-	**	-
MRT	-	-	-	-
OPM	-	-	-	-
PGT	-	**	-	-
PNI	-	-	-	-
ATR	-	*	@@	-
TCR	-	-	@@@	-
CGR	*	***	@@@	*
MYR	-	-	-	-
MTR	*	-	-	*
DVM	**	-	@	*
NMG	***	-	@	***
MTZ	-	-	@	-
CHN	-	-	@@	-
CIR	-	-	-	***
KKD	-	@@@	-	-
VMT	-	-	@@	-
STL	-	*	@@@	-
KTM	**	-	-	*
KMY	-	-	-	-
PMD	-	-	@@@	-
KJY	***	-	@@	***
ALP	-	-	@	-
TVL	***	***	@@@	***
KNI	**	-	-	**
KYM	**	***	@@@	**
PNL	***	*	@	***
AKV	*	-	-	*
QLN	***	***	@@@	*
ATL	*	***	@	*
NMD	***	***	@@@	***
TVM	-	-	-	-

* increasing trend at 90% level
** increasing trend at 95% level
*** increasing trend at 99% level

@ decreasing trend at 90% level
@@ decreasing trend at 95% level
@@@ decreasing trend at 99% level

Table 5.5 Trends in annual values of different parameters shown at different levels by all the stations

5.3 Power Spectrum Analysis:

Time series of annual values of rainfall, A.E., water deficit and water surplus for all stations have been subjected to power spectrum analysis. The analysis carried out earlier (Section 5.2) has shown that some stations exhibit significant trends in some of the series, which indicates that power is concentrated in a very narrow band. Since such bands can cause errors in spectral estimates where there is less power, the series have been subjected to a high-pass filter to improve the spectral estimates at these frequencies. For a clearer understanding of the results, the power spectrum analysis has been carried out for actual and filtered data.

To achieve satisfactory resolution, the maximum lag (m) has been chosen as 18 for most cases, but it has been taken as 16 or 14 for stations which have data for lesser number of years. Spectral analysis has been carried out separately for two different maximum lags, in order to reduce chances of picking up high power in certain harmonics.

Null hypotheses have been fixed depending on whether the series exhibits persistence or not. Some of the series have shown persistence, but none of these were Markov linear type. So, their spectral estimates in the first half have been tested with reference to red noise spectrum and the second half against white noise spectrum. Spectral estimates have been tested against white noise spectrum for the series which do not have any persistence.

5.3.1 **Rainfall:**

Lag 1 correlation coefficient (r_1) was significant for 19 stations, of which eight have shown significance at 99% level. About two thirds of the stations in the southern half of the State exhibited persistence, but in the northern half only one fourth of the stations exhibited this periodicity. However, none of these stations has shown Markov linear type persistence, which indicates the existence of some form of oscillation.

It is already seen from the trend analysis that 16 stations have shown a significant trend, atleast at 90% level for annual rainfall series. Time series of all these stations have been subjected to high-pass filtering. The observed significant periodicities at different levels in actual and filtered annual rainfall series have been summarised in Table 5.6.

Stations which have shown major quasi-periodicities are presented in Fig. 5.19. Punelur has shown a significant concentration of power for zero-lag corresponding to an infinite wavelength (trend). The analysis carried out earlier (Section 5.2) has also proved the presence of a trend in the annual rainfall series of Punelur. A major quasi-periodicity in the high wavelength region of 8.0-24.0 years has been observed for some stations. Palghat has shown a periodicity (at 95%) of 10.3-14.4 years, corresponding to the third harmonic; the neighbouring harmonics (second and fourth), corresponding to the wavelength ranges of 14.4-24.0 and 8.0-10.3 are also significant for this station at 90% level. Five other stations - Mannarghat, Alathur, Trichur, Vandenmettu, and Konni - also exhibited significant periodicities in atleast one of the above said harmonics. Of these, periodicity of 14.4-24.0 years is significant at 95% level for Alathur.

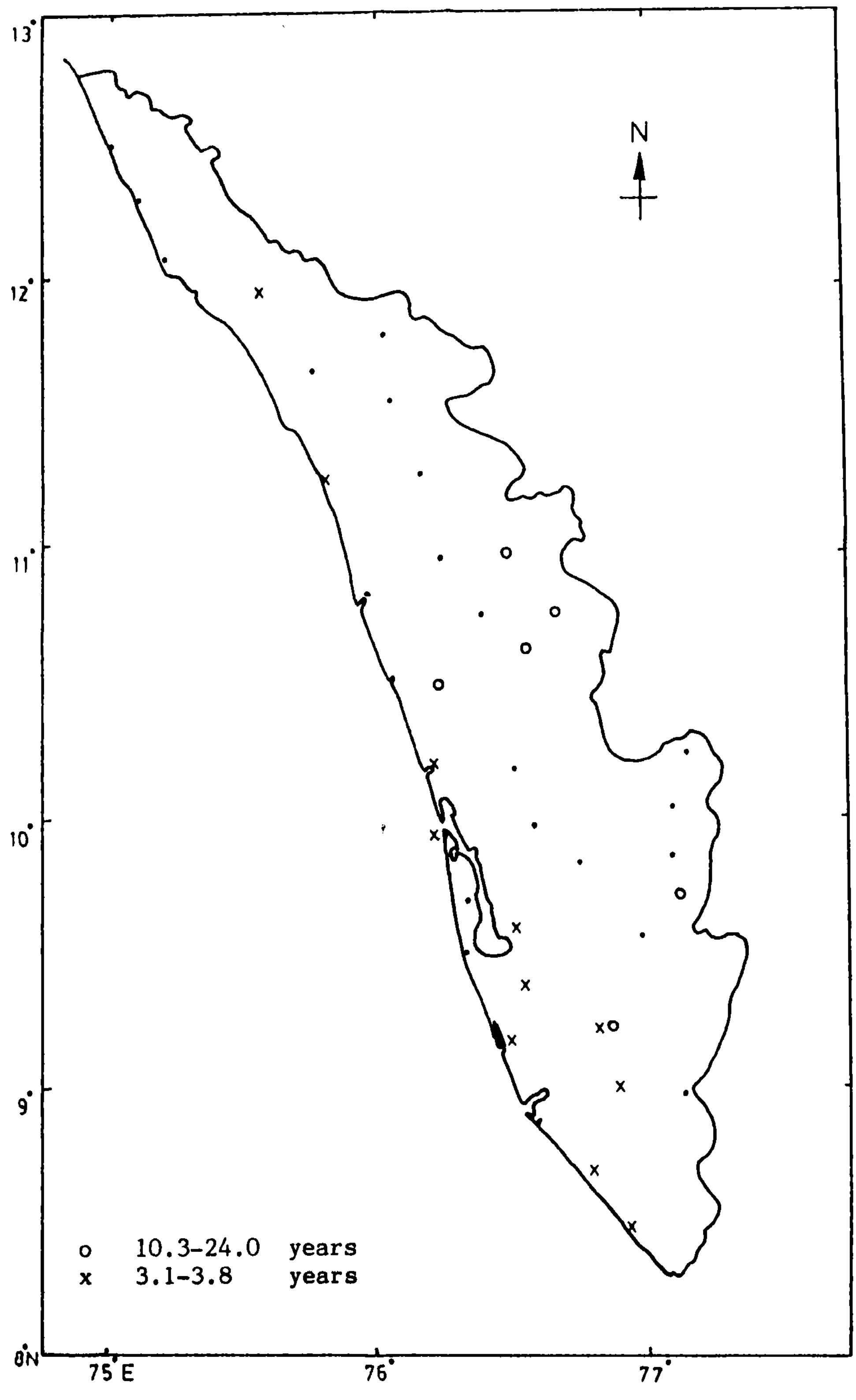


Fig. 5.19 Stations which exhibited major quasi-periodicities in annual rainfall

Station	Periodicities before filtering	Periodicities after filtering
KSD	-	
HSD	-	
PYR	-	
IRK	3.3-3.7,$^{\times\times}$ 3.7-4.3$^{\times}$	2.2-2.4,$^{\times}$ 2.9-3.3$^{\times\times}$
CNR	-	
MTY	-	
KTD	-	
VYT	-	2.3-2.5$^{\times}$
NBR	-	
CLT	3.1-3.4$^{\times}$	
PRM	-	
MRT	10.3-14.4$^{\times}$	
PGT	8.0-10.3,$^{\times}$ 10.3-14.4,$^{\times\times}$ 14.4-24.0$^{\times}$	
ATR	10.3-14.4,$^{\times}$ 14.4-24.0$^{\times\times}$	
TCR	10.3-14.4$^{\times}$	
CGR	3.1-3.4,$^{\times}$ 3.4-3.8$^{\times}$	2.2-2.3,$^{\times\times}$ 3.1-3.4,$^{\times\times}$ 3.4-3.8$^{\times\times}$
MYR	-	
MTR	-	2.1-2.2,$^{\times}$ 2.2-2.4,$^{\times\times}$ 3.0-3.4$^{\times\times}$ 4.3-4.9$^{\times}$
DVM	-	2.2-2.4,$^{\times}$ 2.4-2.6,$^{\times\times\times}$ 2.6-2.8$^{\times\times}$ 3.8-4.3,$^{\times\times}$ 3.4-3.8$^{\times\times}$
NMG	-	2.0-2.1,$^{\times}$ 3.7-4.4$^{\times\times}$
MTZ	4.3-4.5$^{\times}$	
CHN	3.1-3.4,$^{\times\times}$ 3.4-3.8,$^{\times}$ 8.0-10.3$^{\times}$	
CIR	-	
KKD	-	
VMT	12.8-21.3$^{\times}$	
STL	-	
KTM	3.1-3.4$^{\times\times}$	3.1-3.4,$^{\times\times}$ 3.4-3.8$^{\times\times}$
KMY	-	
PMD	3.1-3.4$^{\times}$	-
KJY	-	2.5-2.8,$^{\times\times}$ 2.8-3.2$^{\times\times}$
ALP	-	
TVL	-	3.1-3.4,$^{\times}$ 3.4-3.8$^{\times}$
KNI	3.1-3.4,$^{\times}$ 10.3-14.4$^{\times}$	3.1-3.4,$^{\times\times}$ 3.4-3.8$^{\times}$
KYM	3.1-3.4$^{\times}$	2.9-3.1,$^{\times\times}$ 3.1-3.4$^{\times}$
PNL	trend$^{\times}$	3.1-3.4,$^{\times\times}$ 3.4-3.8$^{\times\times}$
AKV	-	-
QLN	-	-
ATL	-	3.1-3.4$^{\times}$
NMD	-	2.3-2.5,$^{\times}$ 2.5-2.7$^{\times}$
TVM	3.1-3.4$^{\times\times}$	

××× significant at 99% level
× significant at 90% level
×× significant at 95% level

Table 5.6 - Significant periodicities in annual rainfall series (in years)

In the medium wavelength range, the major quasi-periodicity observed is 3.1-3.8 years, which corresponds to the harmonics of 11 and 10. Eleven stations have shown significant periodicities in one of these harmonics. Spectral estimates corresponding to wavelength of 3.1-3.4 years are significant for 11 stations; at Irikkur, Cochin, Kottayam, Konni, Punelur and Trivandrum, it is significant at 95% level. Seven stations which have shown periodicity of 3.1-3.4 years wavelength range have also shown a significant periodicity for the wavelength range 3.4-3.8 years. At Irikkur, Kottayam and Punelur, these two periodicities are significant at 95% level.

Some of the stations have shown periodicity in very short wavelength ranges, but it appears that these high frequency oscillations are very random and also none of them is significant at 99% or 95% levels. From Fig. 5.19 it is clear that many stations in the southern half of the State exhibit the quasi-periodicity of 3.1-3.8 years.

Pictorial representations of power spectra of annual rainfall series for three selected stations, Trivandrum, Punelur and Calicut are shown in Fig. 5.20.

It is important to note, that, none of the stations has shown any periodicity at 99% significant level. When the power spectrum analysis has been carried out for the filtered series, it is seen that the high frequency oscillations have become more prominent.

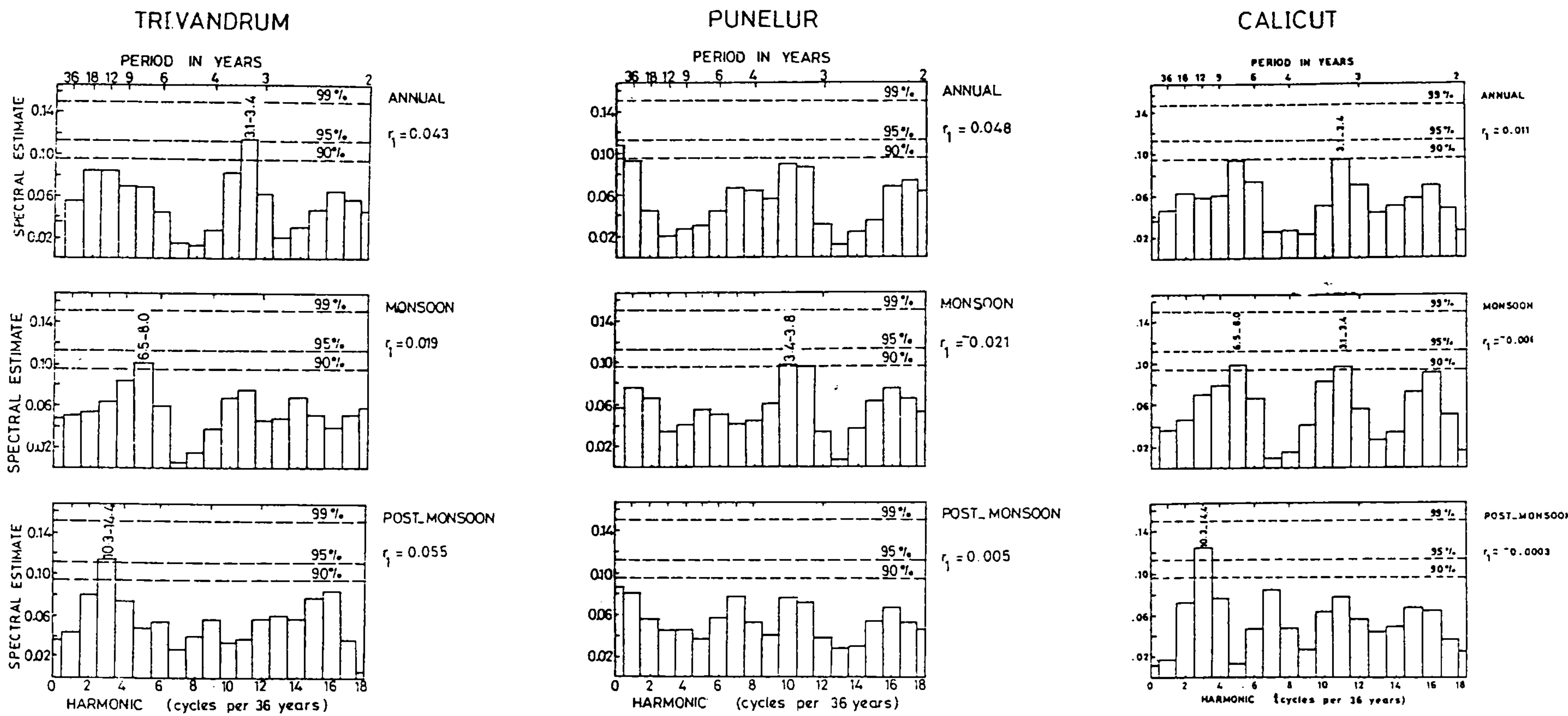


Fig. 5.20 Power spectrum of rainfall series for three selected stations

5.3.2 Actual Evapotranspiration:

Significance tests have already shown that 17 stations exhibit trends in annual A.E. series. The time series of these stations have been filtered and subjected to power spectrum analysis.

Following are some of the salient features brought out by the analysis of annual A.E. series. Various periodicities exhibited by different stations at different levels of significance are given in Table 5.7. Stations which have shown major quasi-periodicities are presented in Fig. 5.21. Fig. 5.22 gives the graphical representations of power spectra of A.E. for the three selected stations Trivandrum, Punelur and Calicut.

Significance of lag 1 correlation coefficient (r_1) highlights the presence of persistence in the time series of annual A.E. of ten stations: among these, for half of the stations, the persistence is significant at 99% level. But none of these cases reveal the Markov linear type persistence.

The spectral peak for zero harmonic corresponding to an infinite wavelength, is significant at 90% level for Kayamkulam. Significance tests have already shown that this series contains a trend at 99% level. Major quasi-periodicities observed in annual A.E series are

(a) high frequency waves with wavelength of 2.2-2.5 years: filtered series of Irikkur has shown significance at 99% level for this wavelength and Nilambur, Cranganore and Nedumangad have shown significance at 95% level. These periodicities are significant at four more stations at 90% level. This periodicity becomes evident only in the analysis of filtered series, except for Neriamangalam.

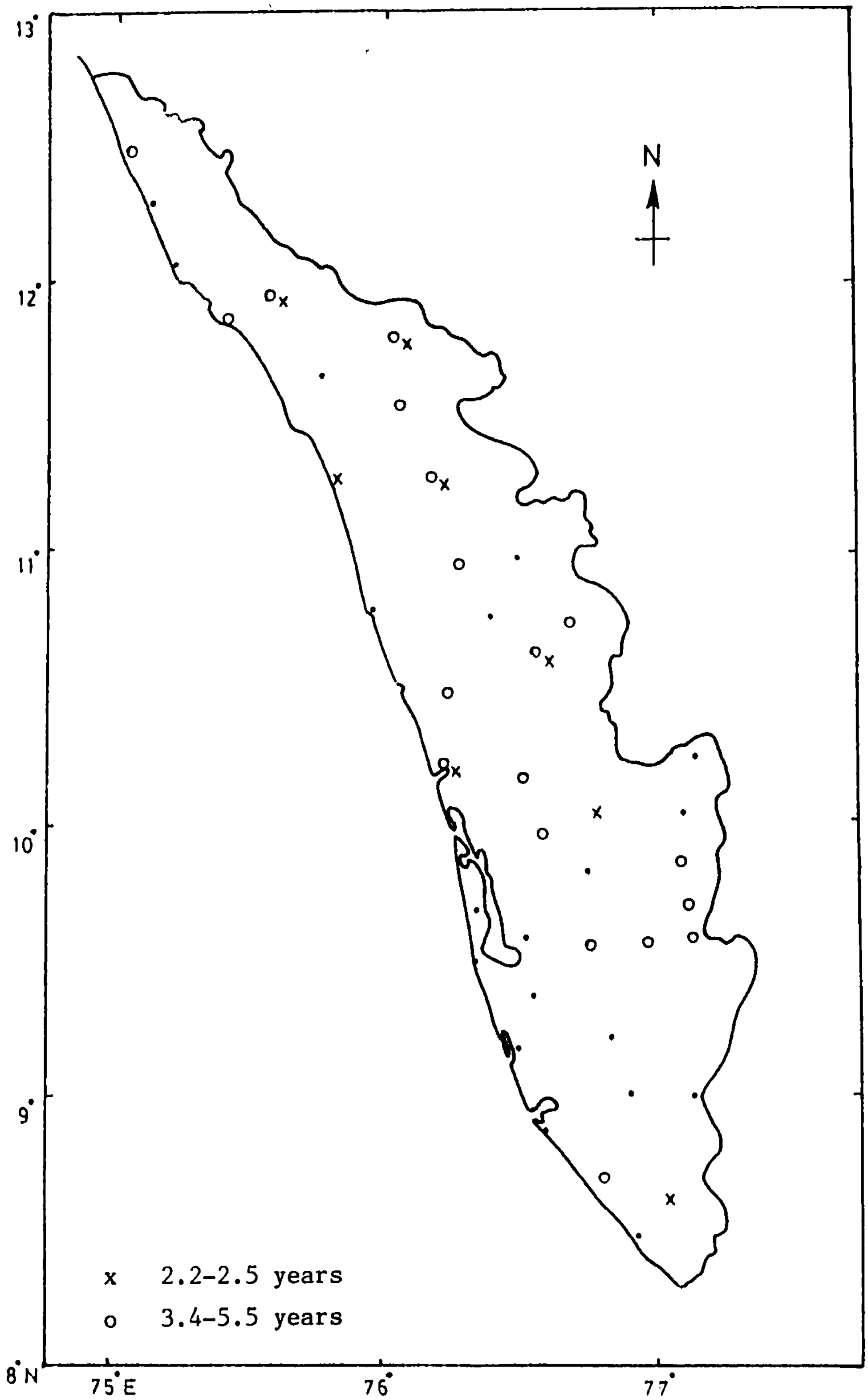


Fig. 5.21 Stations which exhibited major-periodicities in annual A.E. series

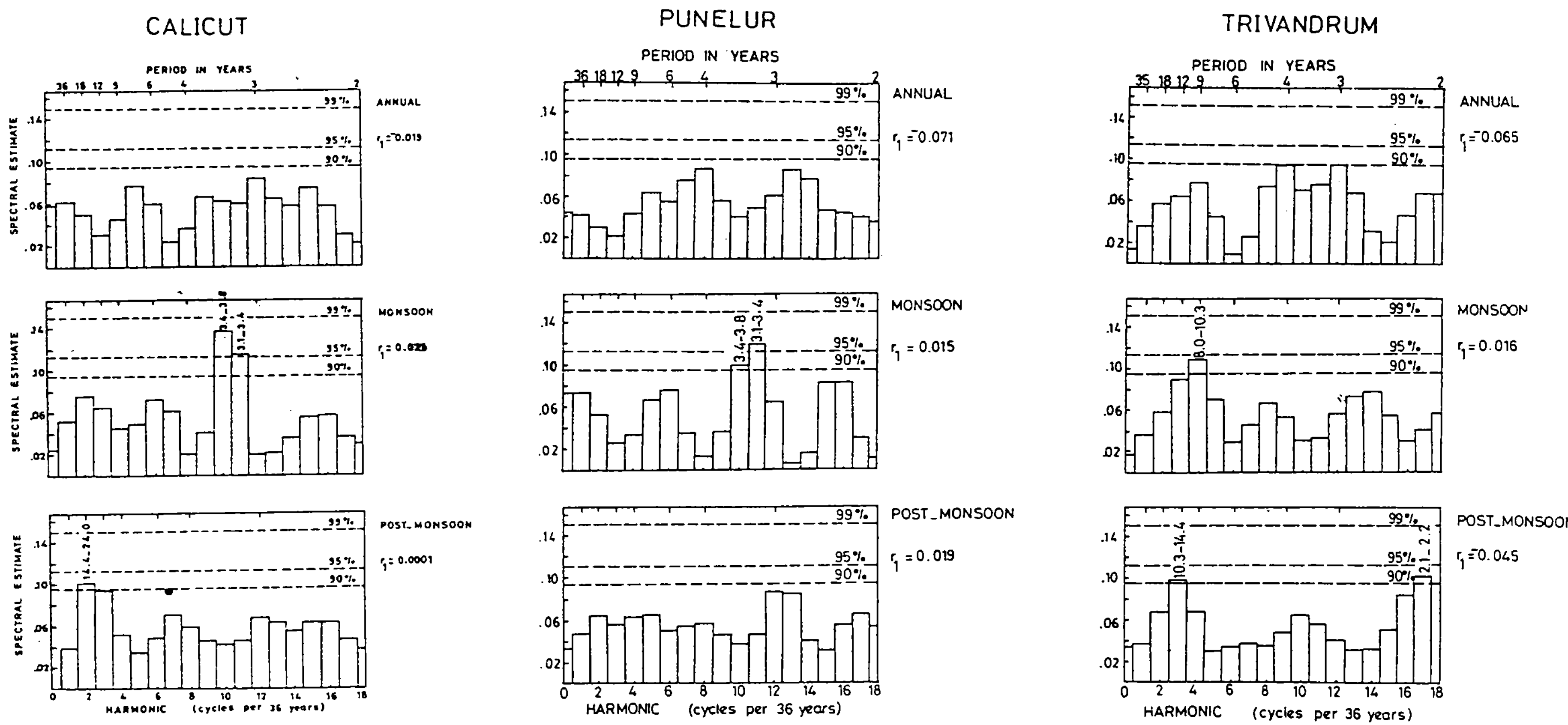


Fig. 5.22 Power spectrum of A.E. series for three selected stations

Station	Periodicities before filtering	Periodicities after filtering
KSD	3.4-3.8 $^{\times\times}$	3.4-3.8 $^{\times\times}$
HSD	-	2.7-2.9, $^{\times}$ 2.9-3.1 $^{\times\times}$
PYR	-	
IRK	-	2.1-2.2, $^{\times}$ 2.2-2.4, $^{\times\times\times}$ 2.4-2.7 $^{\times}$ 3.7-4.3, $^{\times}$ 4.3-5.1, $^{\times\times}$ 5.1-6.2 $^{\times}$
CNR	3.4-3.8, $^{\times\times}$ 3.8-4.2 $^{\times}$	
MTY	3.4-3.8 $^{\times}$	2.2-2.3, $^{\times}$ 2.3-2.5, $^{\times}$ 3.4-3.8 $^{\times\times}$
KTD	-	
VYT	3.4-3.8 $^{\times\times}$	
NBR	-	2.2-2.3, $^{\times}$ 2.3-2.5, $^{\times\times}$ 3.4-3.8 $^{\times}$
CLT	-	2.3-2.5 $^{\times}$
PRM	3.4-3.8, $^{\times\times\times}$ 3.8-4.3 $^{\times\times}$	
MRT	-	
PGT	14.4-24.0 $^{\times}$	3.4-3.8 $^{\times}$
ATR	4.8-5.5 $^{\times}$	2.3-2.5, $^{\times}$ 3.1-3.4 $^{\times}$
TCR	4.8-5.5, $^{\times}$ 10.4-14.4, $^{\times}$ 14.4-24.0 $^{\times}$	
CGR	4.2-4.8, $^{\times\times}$ 4.8-5.5 $^{\times}$	2.3-2.5, $^{\times\times}$ 4.2-4.8 $^{\times}$
MYR	-	
MTR	4.3-4.9, $^{\times\times}$ 4.9-5.8, $^{\times\times}$ 5.8-7.1 $^{\times\times}$	
DVM	-	-
NMG	2.3-2.5 $^{\times}$	
MTZ	4.3-5.1, $^{\times}$ 5.1-6.2 $^{\times\times}$	
CHN	-	
CIR	3.7-4.4 $^{\times\times}$	
KKD	-	-
VMT	3.8-4.3, $^{\times}$ 12.8-21.3 $^{\times}$	
STL	-	-
KTM	8.0-10.3 $^{\times}$	
KMY	3.7-4.4 $^{\times}$	
PMD	3.8-4.3 $^{\times}$	
KJY	2.8-3.2, $^{\times\times}$ 3.2-3.7 $^{\times\times}$	
ALP	4.2-4.8 $^{\times}$	
TVL	-	-
KNI	-	
KYM	trend $^{\times}$	2.9-3.1 $^{\times}$
PNL	-	2.7-2.9 $^{\times}$
AKV	-	
QLN	-	-
ATL	3.8-4.2, $^{\times\times}$ 4.2-4.8, $^{\times\times}$ 4.8-5.5 $^{\times\times}$ 5.5-6.5, $^{\times\times}$ 6.5-8.7 $^{\times}$	5.8-7.1, $^{\times}$ 7.1-9.1 $^{\times}$
NMD	-	2.1-2.2, $^{\times}$ 2.2-2.3 $^{\times\times}$
TVM	-	

$\times\times\times$ significant at 99% level $\times\times$ significant at 95% level
$\times$ significant at 90% level

Table 5.7 - Significant periodicities in annual A.E series
(in years)

(b) the other significant quasi-periodicity is 3.4-5.5 years (seventh to tenth harmonics). About half of the stations have shown periodicity in one or more harmonics in this wavelength range. Perintalmanna has shown significance at 99% level for the wavelength range of 3.4-3.8 years, while for the harmonic corresponding to wavelength range of 3.8-4.3 years, it was significant at 95% level. Attingal has shown a high significance over a wide spectrum: it is significant at 95% level for 5^{th} to 9^{th} harmonics and for the 4^{th} harmonic, at 90% level. The wavelength range corresponding to these harmonics is 3.8-10.3 years. Similarly, Malayattur has shown a comparatively high concentration of spectral estimates (95% level) for 3 consecutive harmonics, corresponding to a wavelength range of 4.3-6.5 years. Irikkur has shown significant periodicity for 5 harmonics, but, they were not continuous ones.

Five stations have shown both the major quasi-periodicities. None of the stations has shown significance for 1^{st} harmonic, but, three stations Palghat, Trichur and Vandanmettu have shown a periodicity, significant at 90% level for a wavelength of 14.4-24.0 years.

By comparing with the rainfall series it becomes obvious, that, there exists no relationship between periodicities of these two series. In general, rainfall series have shown a quasi-periodicity of 3.1-3.8 years, but at the same time, A.E. series have shown a quasi-periodicity of 3.4-4.3 years, but only a few stations have shown both these periodicities. The number of stations which exhibit significant periodicities in A.E. series in comparison with rainfall series decreases in the southern half of the State, while it increases in the northern half.

5.3.3 Water Deficit:

Trend analysis of water deficit series have already shown that 27 stations exhibit significant trends. To avoid concentration of power in high wavelength ranges, these series have been subjected to digital difference technique and then spectral analysis.

Significance of lag 1 correlation coefficient (r_1) for 15 stations indicates that there is persistence in these series and 6 of these stations have shown persistence at 99% level. Absence of Markov linear type persistence reveals the presence of some form of oscillation in all series. This validates the results obtained from the low pass filtering technique.

Various significant periodicities observed for all stations at different levels of significance have been put together in Table 5.8. Fig. 5.23 shows the stations which exhibit major quasi-periodicities in annual water deficit series. Power spectra of annual water deficit for three stations have been presented in Fig. 5.24.

The spectral estimates have shown that there is a concentration of power for infinite wavelength for Kayamkulam (95% level) and Cranganore. This trend has been already identified by significance tests even at 99% level.

Except at 5 stations, water deficit series do not show any significant periodicities beyond 6.5 years. Major quasi-periodicities observed are 2.2-2.9 years and 3.1-4.8 years. More than half of the stations have shown significant periodicities in one or more harmonics in

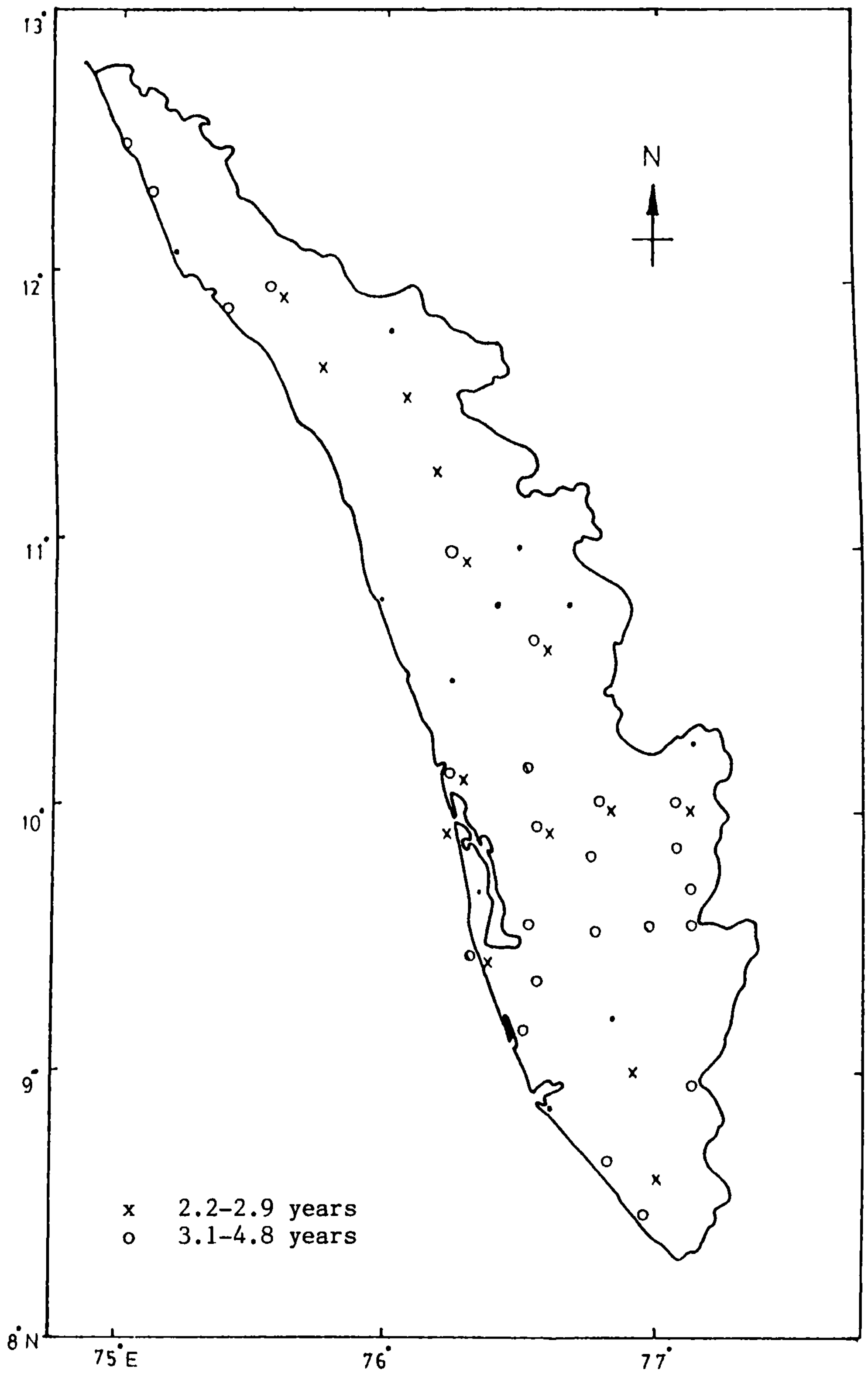


Fig. 5.23 Stations which exhibited major quasi-periodicities in annual water deficit.

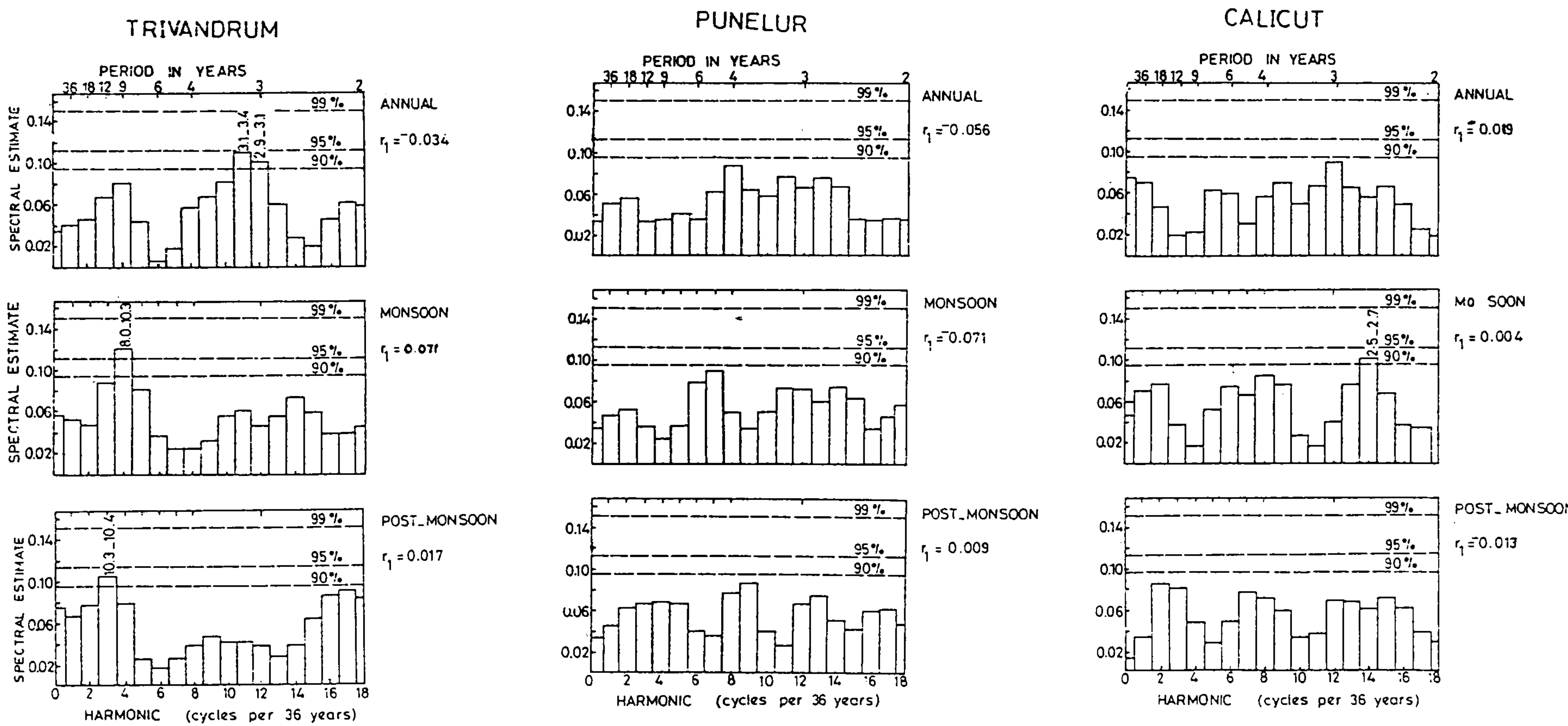


Fig. 5.21 Power spectrum of water deficit series for three selected stations

Station	Periodicities before filtering	periodicities after filtering
KSD	3.1-3.4,$^{\times}$ 3.4-3.8$^{\times\times}$	3.1-3.4,$^{\times}$ 3.4-3.8$^{\times\times}$
HSD	4.2-4.8$^{\times}$	2.9-3.1$^{\times\times}$
PYR	-	
IRK	-	2.2-2.4,$^{\times\times\times}$ 2.4-2.7,$^{\times}$ 3.7-4.3$^{\times\times}$ 4.3-5.1,$^{\times\times}$ 5.1-6.2$^{\times}$
CNR	3.4-3.8$^{\times}$	3.4-3.8$^{\times}$
MTY	-	-
KTD	2.2-2.4$^{\times}$	
VYT	2.3-2.5$^{\times}$	2.2-2.3,$^{\times\times}$ 2.3-2.5,$^{\times\times\times}$ 2.5-2.7$^{\times}$
NBR	-	2.2-2.3,$^{\times}$ 2.3-2.5$^{\times\times}$
CLT	-	-
PRM	3.4-3.8,$^{\times\times}$ 3.8-4.3$^{\times\times}$	2.6-2.8,$^{\times}$ 3.4-3.8,$^{\times\times\times}$ 3.8-4.3$^{\times\times\times}$ 4.3-4.9$^{\times}$
MRT	-	
PGT	14.4-24.0$^{\times\times}$	
ATR	4.8-5.5$^{\times}$	2.3-2.5,$^{\times}$ 3.1-3.5,$^{\times}$ 4.8-5.5$^{\times}$
TCR	-	-
CGR	4.2-4.8,$^{\times\times}$ trend$^{\times}$	2.3-2.5$^{\times}$
MYR	-	
MTR	4.3-4.9,$^{\times\times}$ 4.9-5.8,$^{\times\times}$ 5.8-7.1$^{\times\times}$	
DVM	-	2.6-2.8,$^{\times}$ 3.8-4.3$^{\times\times}$
NMG	2.3-2.5$^{\times}$	2.1-2.3,$^{\times\times}$ 2.3-2.5,$^{\times\times\times}$ 2.5-2.8$^{\times\times}$
MTZ	4.3-5.1$^{\times\times}$	2.2-2.4,$^{\times}$ 2.4-2.7,$^{\times\times}$ 2.7-2.9,$^{\times}$ 3.7-4.3,$^{\times}$ 4.3-5.1,$^{\times\times\times}$ 5.1-6.2$^{\times\times}$
CHN	-	2.3-2.5,$^{\times\times}$ 2.5-2.7$^{\times}$
CIR	3.7-4.4,$^{\times\times}$ 6.9-9.6$^{\times}$	
KKD	4.2-4.8$^{\times}$	
VMT	3.8-4.3$^{\times}$	3.4-3.8,$^{\times\times}$ 3.8-4.3$^{\times\times\times}$
STI	-	-
KTM	3.4-3.8$^{\times}$	
KMY	3.7-4.4$^{\times\times}$	
PMD	3.8-4.2,$^{\times}$ 4.2-4.8$^{\times}$	3.8-4.2$^{\times}$
KJY	3.2-3.7$^{\times\times}$	2.8-3.2,$^{\times\times}$ 3.2-3.7$^{\times\times\times}$
ALP	-	2.2-2.3,$^{\times\times}$ 4.2-4.8$^{\times}$
TVL	3.8,4.2,$^{\times}$ 4.2-4.8$^{\times}$	-
KNI	-	
KYM	4.8-5.5,$^{\times}$ trend$^{\times\times}$	2.9-3.1,$^{\times\times}$ 3.1-3.4$^{\times\times}$
PNL	-	2.7-2.9$^{\times}$
AKV	3.1-3.4$^{\times}$	
QLN	-	2.7-2.9$^{\times}$
ATL	3.8-4.2,$^{\times\times}$ 4.2-4.8,$^{\times\times}$ 4.8-5.5$^{\times}$	3.1-3.4,$^{\times}$ 3.4-3.8,$^{\times}$ 6.5-8.0$^{\times}$
NMD	-	2.1-2.2,$^{\times\times}$ 2.2-2.3$^{\times}$
TVM	2.9-3.1,$^{\times}$ 3.1-3.4$^{\times}$	

$\times\times\times$ significant at 99% level $\times\times$ significant at 95% level
$\times$ significant at 90% level

Table 5.8 - Significant periodicities (in years) in annual water deficit series

the wavelength range of 3.1-4.8 years. As many as 10 stations have shown quasi-periodicity for 8^{th} and 9^{th} harmonics corresponding to 4.3-4.8 years and 3.8-4.3 years. Periodicities of 3.4 -3.8 and 3.8-4.3 are significant at 99% level for Perintalmanna. Muvattupuzha has shown a strong periodicity (99% level) of 4.8-5.5 years. Fourteen stations have shown significant periodicities in one or more harmonics in the wavelength range of 2.2-2.9 years. The 15^{th} harmonic corresponding to the wavelength range of 2.3-2.5 years is significant for 9 stations and for Irikkur and Vythiri this periodicity is significant at 99% level. Neriamangalam has shown 99% significant periodicity of a wave length range of 2.5-2.7 years. It is found that three stations - Irikkur, Muvattupuzha and Attingal -have shown periodicity for 5 or more harmonics. It is interesting to note that the periodicities observed for rainfall series and that of water deficit series are not correlated.

5.3.4 Water surplus:

Trend analysis of water surplus has shown that 17 stations exhibit significant trends. The filtered series of annual water surplus and the actual series were subjected to power spectrum analysis. It is confirmed that Punelur exhibits the decreasing trend which has already been observed from statistical significance tests.

Significance of r_1 has shown that only 8 stations have persistence in the series, but the fluctuations are oscillatory.

Various periodicities identified for all the stations at different levels of significance are given in Table 5.9. Stations which have shown major quasi-periodicities are presented in Fig. 2.25,and Fig. 5.26 gives

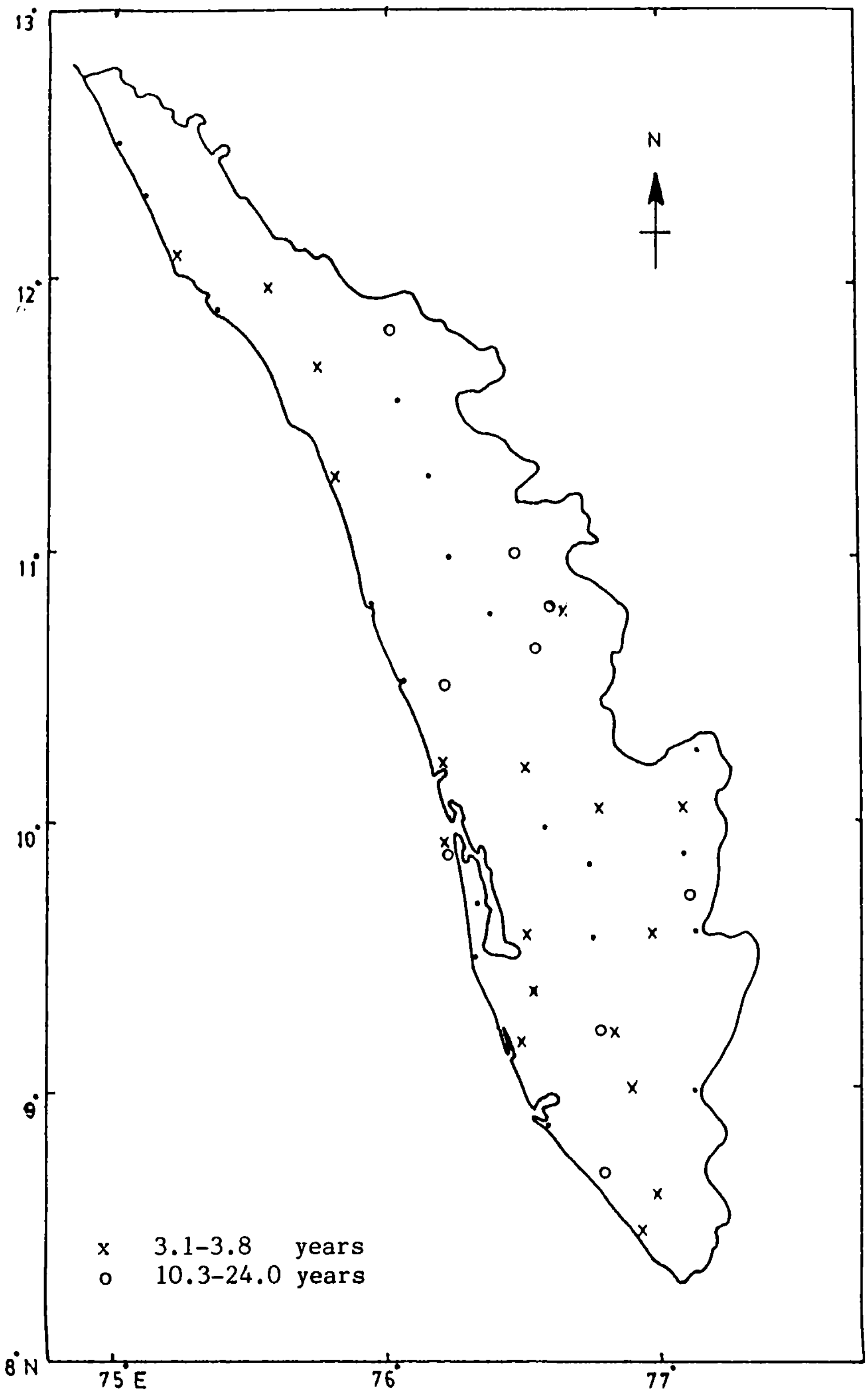


Fig. 5.25 Stations which exhibited major quasi-periodicities in annual surplus series

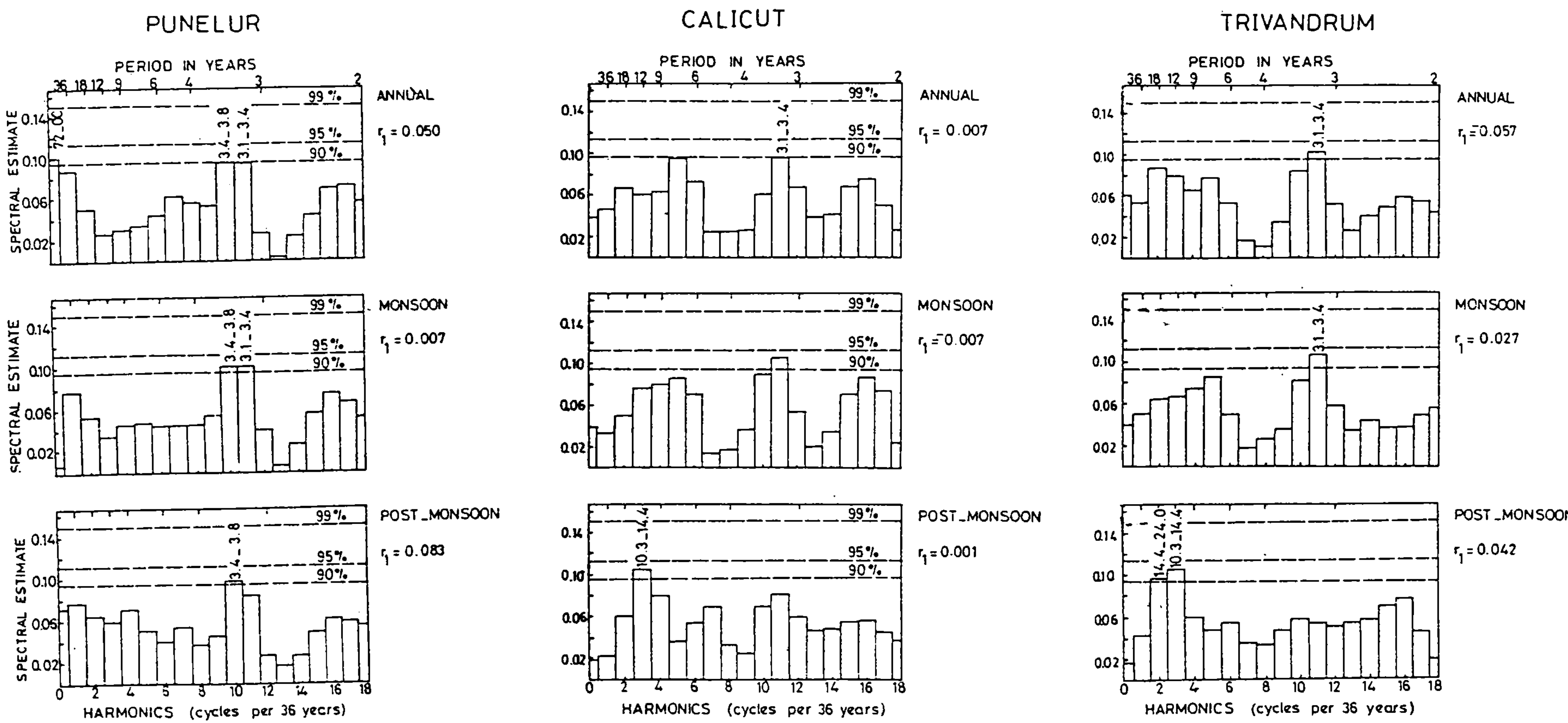


Fig. 5.26 Power spectrum of water surplus series for three selected stations

the graphical representation of power spectra of annual water surplus series for the three selected stations.

The presence of a quasi-periodicity of wavelength 3.1-3.8 years has been revealed by spectral analysis of many stations. Fifteen stations have shown a concentration of spectral peaks for 11th harmonic corresponding to a wavelength range 3.1-3.4 years. At Kottayam, Konni and Punelur, this periodicity was significant at 99% level. Spectral estimates for a wavelength range of 3.4-3.8 years are significant for 11 stations. Another major quasi-periodicity observed is 10.3-24.0 years, corresponding to 3rd and 2nd harmonics. None of the stations has shown significance at 99% level for this high wavelength periodicity. A few of the stations have shown periodicities in very short wavelengths too. Periodicities of 2.2-2.3 years for Malayattur and 2.5-2.7 years for Devikulam are significant at 99% level. Stations in the Palghat Gap show a tendency for 10.3-24.0 years quasi-periodicity and more than half of the stations in the southern half show a quasi-periodicity of 3.1-3.8 years. All stations (except Attingal) which have shown periodicity for 3.1-3.8 years in rainfall series also exhibit the same periodicity in water surplus. But, time series of water surplus of 8 more stations also exhibit this periodicity. Similarly, all stations which have shown periodicity for 8.3-24.0 years in rainfall series also exhibit the same periodicity in surplus series also. In addition to these, three more stations also exhibit this periodicity in water surplus series.

Station	Periodicities before filtering	Periodicities after filtering
KSD	-	
HSD	-	
PYR	3.4-3.8$^{\times}$	
IRK	3.3-3.7,$^{\times\times}$ 3.7-4.3$^{\times}$	2.2-2.4,$^{\times}$ 2.9-3.3,$^{\times\times}$ 3.3-3.7$^{\times}$ 3.7-4.3$^{\times\times}$
CNR	-	
MTY	14.4-24.0$^{\times}$	
KTD	3.4-3.8$^{\times}$	
VYT	-	2.3-2.5$^{\times}$
NBR	-	
CLT	3.1-3.4$^{\times}$	
PRM	-	
MRT	10.3-14.4,$^{\times\times}$ 14.4-24.0$^{\times\times}$	
PGT	3.1-3.4,$^{\times}$ 10.3-14.4$^{\times\times}$	
ATR	10.3-14.4,$^{\times}$ 14.4-24.0$^{\times}$	
TCR	10.3-14.4$^{\times}$	
CGR	3.1-3.4,$^{\times}$ 3.4-3.8$^{\times}$	2.2-2.3,$^{\times\times}$ 3.1-3.4,$^{\times\times}$ 3.4-3.8$^{\times\times}$
MYR	-	
MTR	-	2.1-2.2,$^{\times\times}$ 2.2-2.4,$^{\times\times\times}$ 3.0-3.4$^{\times\times}$ 3.4-3.8$^{\times}$
DVM	-	2.2-2.4,$^{\times}$ 2.4-2.6,$^{\times\times\times}$ 2.6-2.8$^{\times\times}$ 3.4-3.8,$^{\times\times}$ 3.8-4.3$^{\times\times}$
NMG	-	2.0-2.1,$^{\times}$ 3.2-3.7,$^{\times}$ 3.7-4.4$^{\times\times\times}$
MTZ	-	
CHN	3.1-3.4,$^{\times\times}$ 3.4-3.8,$^{\times}$ 8.0-10.3$^{\times}$ 10.3-14.4$^{\times}$	
CIR	-	2.0-2.1,$^{\times}$ 2.1-2.3,$^{\times}$ 3.7-4.4$^{\times\times}$
KKD	-	
VMT	12.8-21.3$^{\times\times}$	
STI	-	
KTM	3.1-3.4$^{\times}$	3.1-3.4,$^{\times\times\times}$ 3.4-3.8$^{\times\times}$
KMY	-	
PMD	3.1-3.4$^{\times}$	
KJY	-	2.5-2.8,$^{\times\times}$ 2.8-3.2$^{\times\times}$
ALP	-	
TVL	-	3.1-3.4,$^{\times\times}$ 3.4-3.8$^{\times\times}$
KNI	3.1-3.4,$^{\times}$ 10.3-14.4$^{\times}$	3.1-3.4,$^{\times\times\times}$ 3.4-3.8$^{\times}$
KYM	3.1-3.4$^{\times}$	2.9-3.1,$^{\times\times}$ 3.1-3.4$^{\times\times}$
PNL	3.1-3.4,$^{\times}$ 3.4-3.8,$^{\times}$ trend$^{\times}$	3.1-3.4,$^{\times\times\times}$ 3.4-3.8$^{\times\times}$
AKV	-	-
QLN	-	-
ATL	10.3-14.4,$^{\times\times}$ 14.4-24.0$^{\times\times}$	2.3-2.5$^{\times}$
NMD	-	3.1-3.4$^{\times}$
TVM	3.1-3.4$^{\times}$	

$\times\times\times$ significant at 99% level $\times\times$ significant at 95% level
$\times$ significant at 90% level

Table 5.9 - Significant periodicities in annual water surplus series (in years)

Different harmonics which have significant periodicities in series of various parameters for all stations have been summarised in Table 5.10

From the table it is evident that the 10^{th} harmonic corresponding to the wavelength range of 3.4-3.8 years has shown significant periodicities for comparatively higher number of stations for all parameter. High quasi-periodicities are observed for 10^{th} and 11^{th} harmonics for rainfall and water surplus series. Large wavelength periodicities are more for rainfall and surplus series. Similarly, a quasi-periodicity with wavelength of 3.4-5.5 years and 2.2-2.5 years are more for A.E and water deficit series. It is clear that different harmonics which have exhibited significant periodicities in rainfall series exhibit significant periodicities in surplus series also. Similarly, a relationship between the periodicities of A.E. series and water deficit series has been observed for some stations.

5.3.5 Periodicity for Seasonal values:

Nine stations have been selected for the periodicity analysis of series of seasonal values:- Kasargode, Cannanore, Vythiri, Calicut, Palghat, Cochin, Peermede, Punelur and Trivandrum. Seasonal studies are confined to the monsoon and post-monsoon series, since they are the major rainfall seasons. As in the case of annual series, all the time series which exhibited some form of trend have been subjected to high pass filtering.

For the sake of comparison, the periodicities observed in the time series of various parameters for all the nine stations for annual, monsoon and post-monsoon seasons are given in Table 5.11.

Station	Rainfall	A.E.	Water Deficit	Water Surplus
KSD	-	10	11,10	-
HSD	-	13,12	12,8	-
PYR	-	-	-	10
IRK	16,11,10,9	15,14,9,8,7	15,14,9,8,7	15,11,10,9
CNR	-	10,9	9	-
MTY	-	16,15,10	-	2
KTD	-	-	15	10
VYT	15	10	16,15,14	15
NBR	-	16,15,10	16,15	-
CLT	11	15	-	11
PRM	-	10,9	13,10,9,8	-
MRT	3	-	-	2
PGT	4,3,2	10,2	2	11,3
ATR	3,2	15,11,7	15,11,7	3,2
TCR	3	7,3,2	-	3
CGR	16,11,10	15,8,7	15,8,0	16,11,10
MYR	-	-	-	-
MTR	-	8,7,6	8,7,6	17,16,11,10
DVM	-	-	13,9	16,14,13,10,9
NMG	18,9	15	15,14,13	11,9,1
MTZ	-	8,6	15,14,13,9,8,7,6	-
CHN	11,10,4	-	15,14	11,10,4,3
CIR	-	9	9,4	18,17,9
KKD	-	-	8	-
VMT	2	9,2	10,9	2
STL	-	-	-	-
KTM	11,10	5,4	10,	11,10
KMY	-	9	9	-
PMD	-	9	9,8	11
KJY	13,12	12,10	12,11	13,12
ALP	-	8	16,8	-
TVL	11,10	-	9,8	11,10
KNI	11,10,3	-	-	11,10,3
KYM	12,11	12,0	12,11,7,0	12,11
PNL	11,10,0	13	13	11,10,0
AKV	-	-	-	-
QLN	-	-	-	-
ATL	11	9,8,7,6,5,4	11,10,9,8,7,5	15,3,2
NMD	15,14	17,16	17,16	11
TVM	11	-	12,11	11

Periodicity in years corresponding to each harmonics

0	72- ∞	1	24-72	2	14.4-24	3	10.3-14.4
4	8.-10.3	5	6.5-8.0	6	5.5-6.5	7	4.8-5.5
8	4.3-4.8	9	3.8-4.3	10	3.4-3.8	11	3.1-3.4
12	2.9-3.1	13	2.7-2.9	14	2.5-2.7	15	2.3-2.5
16	2.2-2.3	17	2.1-2.2	18	2.0-2.1		

Table 5.10 - Significant harmonics for different parameters

Stn.	Annual	Monsoon	Post-monsoon
		Rainfall	
KSD	-	2.2-2.3	2.7-2.9
CNR	-	-	-
VYT	2.3-2.5	-	2.7-2.9, 2.9-3.1, 5.5-6.5
CLT	3.1-3.4	3.1-3.4, 6.5-8.0	10.3-14.4
PGT	8.0-10.3, 10.3-14.4, 14.4-24.0	3.1-3.4, 8.0-10.3, 10.3-14.4	14.4-24.0
CHN	3.1-3.4, 3.4-3.8 8.0-10.3	3.1-3.4, 8.0-10.3 10.3-14.4	10.3-14.4
PMD	-	3.1-3.4, 6.5-8.0	10.3-14.4
PNL	3.1-3.4, 3.4-3.8, trend	3.1-3.4, 3.4-3.8	-
TVM	3.1-3.4	6.5-8.0	10.3-14.4
		A.E	
KSD	3.4-3.8	3.1-3.4, 3.4-3.8	2.5-2.7
CNR	3.4-3.8, 3.8-4.3	3.1-3.4, 3.4-3.8	-
VYT	3.4-3.8	3.1-3.4, 3.4-3.8	3.1-3.4, 3.4-3.8
CLT	2.3-2.5	3.1-3.4, 3.4-3.8	14.4-24.0
PGT	3.4-3.8, 14.4-24.0	2.8-3.0, 3.1-3.4	14.4-24.0
CHN	-	-	-
PMD	3.8-4.3	-	2.1-2.2, trend
PNL	2.7-2.9	3.1-3.4, 3.4-3.8	-
TVM	-	8.0-10.3	2.1-2.2, 10.3-14.4
		Water Deficit	
KSD	3.1-3.4, 3.4-3.8	2.7-2.9	2.3-2.5, 2.5-2.7
CNR	3.4-3.8	4.2-4.8	-
VYT	2.2-2.3, 2.3-2.5 2.5-2.7	-	2.5-2.7, 2.7-2.9 2.9-3.1, 5.5-6.5
CLT	-	2.5-2.7, 4.2-4.8	-
PGT	14.4-24.0	2.5-2.7, 2.7-2.9 4.3-4.8, 4.8-5.5	2,1-2.2
CHN	2.3-2.5, 2.5-2.7	-	-
PMD	3.8-4.3, 4.3-4.8	-	2.0-2.1
PNL	2.7-2.9	2.5-2.7, 2.9-3.1	-
TVM	2.9-3.1, 3.1-3.4	8-10.3, 10.3-14.4	2.0-2.1, 2.1-2.2 2.2-2.3, 10.3-14.4
		Water surplus	
KSD	-	2.2-2.4	-
CNR	-	-	2.2-2.3
VYT	2.3-2.5	-	2.8-3.0
CLT	3.1-3.4	3.1-3.4	10.3-14.4
PGT	3.1-3.4, 10.3-14.4	3.1-3.4, 8.0-10.3 10.3-14.4	-
CHN	3.1-3.4, 3.4-3.8 8.0-10.4, 10.4-14.4	3.1-3.4, 3.4-3.8 8.0-10.3, 10.3-14.4	10.3-14.4
PMD	3.1-3.4	-	10.3-14.4
PNL	3.1-3.4, 3.4-3.8 trend	3.1-3.4, 3.4-3.8	3.1-3.4, 3.4-3.8
TVM	3.1-3.4	3.1-3.4	2.2-2.3, 10.3-14.4 14.4-24.0

Table 5.11 - Periodicities observed for different parameters in annual and in the monsoon and post-monsoon seasons (in years)

From the trend analysis carried out earlier for the monsoon season (Section 5.2), it was found that Punelur shows a significant trend in rainfall and water surplus, Cochin and Peermede in A.E. and Kasargode, Cannanore, Calicut, Palghat, Cochin and Punelur in water deficit series. Significance of lag 1 correlation coefficient has shown that Calicut and Trivandrum exhibit persistence in rainfall, Cochin and Trivandrum in A.E., and Trivandrum in water deficit and surplus series. The non-existence of Markov linear-type persistence for all the series indicates that the variations are oscillatory.

Analysis of monsoon values have shown that two major quasi-periodicities are present in time series of rainfall, A.E. and water surplus (3.1-3.8 years and 6.5-14.4 years) for most stations. None of the stations has shown any periodicity higher than 14.4 years in time series of any parameter. A periodicity of 8.0-10.3 years has been observed in rainfall series of 2 stations and water surplus series of one station. Three stations have shown a periodicity of 6.5-8.0 years for monsoon rainfall, but this periodicity has not been seen in any other parameter. Quasi-periodicity for the wavelength 3.1-3.8 years for monsoon A.E. is highly significant (at 95%). The major quasi-periodicity observed for deficit series is 2.5-3.1 and 4.2-4.8 years. Periodicities observed in monsoon rainfall series are reflected in monsoon season surplus.

Time series of rainfall, deficit and surplus for post-monsoon season have shown that the series do not have any persistence. Calicut and Trivandrum have, however, shown persistence for post-monsoon A.E. series only.

Spectral analysis of time series of all hydrometeorological parameters for all the 9 stations for the post-monsoon season have shown that only the A.E. series of Peermede is significant at 90% level for 0^{th} harmonic corresponding to a trend. It is observed that periodicities seen in post-monsoon seasons are random in nature. High frequency oscillations are observed in all parameters over Kasargode and Vythiri. Four stations have shown significances corresponding to a wavelength of 10.3-14.4 years in rainfall and surplus series.

A comparison of periodicities of annual, monsoon and post-monsoon series has shown that there exists a common periodicity for monsoon and annual time series of rainfall, A.E. and water surplus for some stations. The harmonics which have shown significant periodicities for monsoon season series are reflected in annual series also. The 11^{th} harmonic (3.1-3.4 years) is significant for the series of monsoon and annual values for rainfall and surplus. But, for A.E. series, there is a common periodicity for 10^{th} harmonic corresponding to 3.4-3.8 years. This feature is not observed for the series of water deficit. It is already seen that periodicity for the series of post-monsoon season is highly randomized and also not reflected in monsoon or annual series of the same parameter.

Koteswaram and Alvi (1970) observed a negative relationship between rainfall and sunspot in west coast stations particularly Cochin and Trivandrum. Ananthakrishnan and Parthasarathy (1984) observed a negative relationship between sunspot and rainfall in south eastern parts of the Indian Peninsula and a positive relationship in other parts of Peninsula.

CHAPTER VI

SUMMARY AND CONCLUSIONS

The State of Kerala lies in the southwestern part of the country, along the west coast. The diverse physiographic features of the State are very significant in influencing the climate, vegetation and land-use of the region. Within a short distance of 120 km from the coastline to the Western Ghats, a variety of climates is observed due to the diversity of physical features. The most conspicuous feature of the climate of Kerala is the heavy rainfall due to the southwest monsoon. The vagaries of the monsoon - its onset and withdrawal, active and break conditions, space and time variations - are all very complex.

The State has a well-distributed drainage network consisting of 44 rivers. Due to effluent seepage, rivers of the State are perennial and they possess high potential for hydel-power generation, irrigation and transportation.

A knowledge of what happens to the large amount of the water that reaches the earth surface as rainfall is a pre-requisite for the study of many surface and subsurface water problems and for the efficient control and management of water resources. For a State such as Kerala, whose welfare depends very much on agriculture, a quantitative knowledge of water requirements of the region and the availability of water for plant growth and supplemental irrigation, etc. on a monthly or seasonal basis is an essential requirement for agricultural development. Increasing population in recent decades and the resultant higher demands for food have led to many attempts aimed at optimal exploitation of water resources. Since the power generation of the State depends totally on hydel projects, a quantitative measure of the water surpluses of the region is a very useful parameter, since it provides a rough estimate of the utilisable water for the power projects.

In this context, a study of the water balance of the State has been found to be very relevant and useful. The derived parameters of water balance, especially water surplus and water deficit, on a seasonal basis give very essential information useful for various agricultural activities, such as choosing the variety of crops, adjusting the farming operations, assessing the irrigation potential of the region and scheduling the irrigation operations. Study of water surplus is especially important for the development of river basins for water supply, power generation, irrigation, flood control and drainage, among other things.

The spatial distributions together with seasonal variations of the water balance parameters help us to delineate the optimal regions for the development of agriculture and hydel-power projects and to assess the economic feasibility of different activities connected to water resources management.

Studies on large scale temporal changes in the hydrometeorological parameters, especially rainfall and temperature are important for planning the development of a country's natural resources. There is also a general opinion that rainfall of Kerala is decreasing and temperature is increasing.

In Kerala, whose economy is very much dependent on water availability, fluctuations in rainfall affect human welfare, through their effects on agriculture, power generation and industrial activities. Power cuts and load shedding have become a common feature in the State during the last decade, due to the deficiency of power. This again affects agricultural and industrial production and thereby the economy. Even though well-developed irrigation facilities reduce the risk in agricultural activities, prolonged drought conditions will affect the irrigation system itself. Salt water intrusion through the rivers is another problem in Kerala, especially during pre-monsoon months, which indirectly affect agriculture. Since the population density is very high, and is further increasing, the water requirements for domestic purposes too, would be increasing.

In the present context, a detailed study of time series of rainfall and other water balance parameters such as actual evapotranspiration, water surplus and water deficit to detect the trends and periodicities in the series, seems to be very relevant. Therefore, the spatial and temporal variabilities of some important hydrometeorological parameters over the State have been analysed in the present study. The thesis consists of six Chapters with a general introduction as the first one. The first Section of the Second Chapter explains the concepts of hydrologic cycle and water balance, various methods of estimation of potential evapotranspiration, the book-keeping procedure of water balance of Thornthwaite (1948) and various applications of water balance techniques. The second Section of this Chapter is mainly concerned with the applications of time series analysis in climatology. Various techniques such as power spectrum analysis, Mann-Kendall statistic test, Student's t-test and filtering methods which are employed to reveal the temporal variations in time series have been discussed. An exhaustive and relevant review of various hydrometeorological studies are cited in this Chapter.

The third Chapter consists of a discussion of the important physico-climatic features of Kerala State. The location and extent, physiography, drainage, soil types, agricultural pattern and land-use systems over the State are explained in the first Section, while details about temperature, wind and humidity which form the climatological features are discussed in the second.

The seasonal and annual distributions of important water balance parameters namely rainfall, potential evapotranspiration, actual evapotranspiration, water surplus, water deficit, surface flow, underground flow and total discharge over the State have been mapped and discussed to present a broad picture of hydro-climatic background of the region in the fourth Chapter. The spatial distributions of various indices derived from the water balance procedure, such as Moisture Adequacy Index, Aridity Index, Humidity Index, and Moisture Index have also been presented. A classification of climates of Kerala, based on Thornthwaite's scheme has also been depicted in this Chapter. The salient results of the study are given below.

The average annual rainfall for the State as a whole is 294 cm, of which 45% (131 cm) is utilised for evapotranspiration and the remaining 55% (163 cm) is available for utilisation. By segregating the exploitable water, it is found that about 97 cm (33% of rainfall) is available as surface flow and the remaining as underground flow. For the State as a single unit, the average annual surface flow is greater than underground flow.

Average annual water need for the State is 160 cm.. The actual evapotranspiration (A.E.) is 133 cm which is about 83% of the water need, and therefore a deficit (P.E.- A.E.) of 27 cm (17% of the need) is experienced. This indicates that the State as a whole, experiences heavy rainfall and a large water surplus, but water deficits are not altogether absent. The average annual water surplus is about 6 times higher than that of deficit: also water deficit is only about one third of the surface flow. So, by a proper management of the surplus water, the deficit now experienced over the State can be mitigated, even without much exploitation of groundwater.

There are two pockets of very heavy rainfall over the State, having average annual rainfall of more than 500 cm: one in the south and the other in the north. Among the stations selected for the study, the highest mean annual rainfall has been recorded at Neriamangalam (507 cm) and the lowest at Chinnar (60 cm). An interesting feature to be noted is, that, these two stations are only about 35 km apart. The rainfall varies from about 175 cm in the extreme south to about 350 cm in the extreme north. The highest annual point rainfall (842.5 cm) has been recorded at Peermede, in 1968 and the lowest (12.3 cm) at Chinnar in 1939.

The seasonal contributions to average annual rainfall are 1%, 15%, 66% and 18% for the winter, pre-monsoon, monsoon and post-monsoon seasons respectively. The rainfall pattern in the monsoon season also exhibits two regions of very heavy rainfall. The northern pocket has comparatively higher monsoonal rainfall, though in the case of annual rainfall, the higher value is in the south. The maximum rainfall in the monsoon season occurs at Vythiri (347 cm), which is about 80% of its annual value, and the lowest at Chinnar (17 cm), where it is only 28% of the annual rainfall. The percentage contribution of monsoon rainfall to the annual is more than 80% in the northern parts, and gradually decreases to about 45% in the extreme south, where post-monsoon rainfall is comparatively higher (about 30% of annual). The heavy rainfall pockets observed in the annual and monsoon rainfall patterns in the north are not seen in the post-monsoon rainfall pattern. The north-south gradient of monsoon season rainfall is in a direction opposite to that of annual values and that of the other three seasons.

The mean annual rainfall over the State is about two and a half times the rainfall of India. The rainfall over Kerala in pre-monsoon, monsoon and post-monsoon seasons are more than twice the national average. Only in the winter months, the seasonal value over the State is less than that of the rainfall over the country. The percentage contribution of the monsoon season to the annual total is less for the State than for the country. The years of extremes of rainfall over the State and the country are not identical.

Stations in the southern parts of the State have their highest monthly rainfall in June, but over the northern parts, the maximum occurs in July. The heaviest mean monthly rainfall of 140 cm occurs at Vythiri, followed by Kuttiyadi (130 cm), both in July and in the northern heavy rainfall pocket. In the northern parts, the major contributions to annual rainfall are in the months of June, July and August, but in the southern parts, the rainfall is more widely distributed among the months. A double maximum exists in the monthly rainfall pattern all over the State, except in the extreme north. Here, the variability pattern of monthly rainfall shows a trimodal structure for most of the stations.

The highest weekly rainfall (35 cm) occurs at Vythiri during the 29th week. This station experiences weekly rainfall of more than 30 cm over four consecutive weeks, and more than 25 cm each during six consecutive weeks. Almost all stations have shown a secondary maximum corresponding to the post-monsoon season, a fact which is not evident from the monthly distribution pattern over northern parts of the State.

Isolines of potential evapotranspiration are nearly parallel to the Ghats, but there exist a few pockets of low annual values (less than 90 cm) corresponding to hill stations. The average annual P.E. for the State as a whole is 160 cm, 15% of which is in winter, 29% in pre-monsoon, 32% in the monsoon and 24% in the post-monsoon seasons. The distribution of annual P.E. for different seasons are more uniform compared to the rainfall distributions, and it is this factor that determines the water balance of the State.

The spatial distribution pattern of mean annual A.E. has a resemblance to that of P.E. distribution. But, an increasing trend towards the south in annual A.E. has been observed, in contrast to the annual P.E. pattern. The highest value of annual A.E. of 165 cm (more than 95% of annual P.E.) is at Kanjirapally. During winter and pre-monsoon seasons, the distribution patterns of A.E. are quite different from that of P.E., but have a similarity to the corresponding rainfall patterns.

A salient feature of the seasonal distribution of A.E. is that during monsoon season it equals P.E. all over the State except over a very small area surrounding Chinnar.

The moisture adequacy index for most parts of the State is very high - more than 70% - indicating that almost all parts of the State are suitable for a wide variety of agricultural crops.

The mean annual water deficit increases from 24 cm in the south-west to about 47 cm in the north-western parts of the State, with certain ares having higher values. This may appear to be paradoxical, considering the fact that the mean annual rainfall also increases in the same direction. The highest value of annual deficit of about 77 cm occurs over Chinnar region, while Devikulam region experiences the lowest value of only 2 cm. The winter and pre-monsoon seasons each contribute about 45% of the annual deficit. During monsoon season, there are no deficits over the State, except over Chinnar region. A general decrease of deficit towards south and east is observed in all the seasons.

The mean annual water surplus varies from 0 cm at Chinnar to 358 cm at Neriamangalam. During winter season no station has any surplus. Furthermore, almost all stations, except those in the southern heavy rainfall pocket do not have any surplus during pre-monsoon season too. Even though 15% of the State's average annual rainfall is contributed by pre-monsoon season, it adds only about 1% of the surplus to the annual value. About 85% of the surplus is during the monsoon season, though the percentage contribution of the monsoon rainfall to the annual is only 66%.

Even though rainfall is widely distributed over the year, surplus is observed only between June and November. The highest monthly surplus over the extreme south of the State occurs in October, though the heaviest monthly rainfall is in the month of June.

Annual surpluses are very high for all stations compared to annual deficits, except at Chinnar, where there is no surplus, but exists the highest annual deficit. In general, both annual surplus and deficit decrease towards south, with the exception of a few isolated pockets. All stations north of Cranganore (except high altitude stations) have annual deficits more than the average for the State: stations south of Cranganore except Chinnar have deficits less than the State average.

Climatic classification shows that there is no arid climate over the State, while a small area surrounding Chinnar belongs to the semi-arid type, and most parts of the State have humid type of climate. Northeast Kerala and an area surrounding southern pocket of heavy rainfall enjoy perhumid type of climate. The thermal regime of classification shows that, except the eastern high altitude stations, the State has megathermal type of climate, and can support the most luxuriant forms of vegetation.

The spatial distribution patterns of surface flow on an annual and seasonal basis are similar to that of surplus. The monsoon and post-monsoon seasons contribute about 99% of the surface flow.

The State average annual groundwater flow is distributed as 11%, 8%, 50% and 31% respectively among four seasons. Even though there is no significant surplus in winter and pre-monsoon seasons, there is underground flow. Rainfall is least in winter, but the underground flow is least in the pre-monsoon months: also, the winter season groundwater flow is more than that of rainfall for that season. The spatial distribution patterns of groundwater flow on both annual and seasonal bases are very much different from that of surplus pattern, with high values being observed in the northwestern part of the State. The western parts of the State have comparatively high values of groundwater flow than the eastern parts. Chinnar region does not have any groundwater flow in any season, on a climatic basis. For the State as a whole, annual surface flow is about one and a half times the groundwater flow. But, on a seasonal basis, underground flow is more than surface flow, except in the monsoon season.

On a monthly basis, even though there is no surplus till June, there is groundwater flow (which is more than monthly rainfall) during the months of January and February. Rainfall and surplus are maximum in June or July, but the highest monthly groundwater flow occurs in August for most of the stations, indicating a lag of atleast one month. The secondary maximum observed in the monthly rainfall and surplus values are not much pronounced in the case of groundwater flow.

On a climatic basis, total discharge is the same as that of total annual water surplus, but surplus is concentrated in monsoon and post-monsoon seasons, while the total discharge is distributed among all seasons. On a monthly basis, the least total discharge occurs in May as does groundwater flow, but the highest values are observed in June or July as in the case of surface flow.

The fifth Chapter deals with the time series analysis of rainfall, actual evapotranspiration, water deficit and water surplus over the State as revealed by power spectrum analysis and trend aspects as indicated by Mann-Kendall statistic, Student's t-test and low pass filtering techniques. The analysis has been carried out on a seasonal basis for nine selected stations.

Trend analysis of annual rainfall has shown that some stations in the southern half of the State exhibit a significant decreasing trend, but only two stations in the northern half of the State have shown such a trend. None of the stations in the State has shown any significant increasing trend. The stations which have shown significant decreasing trends appear to be randomly distributed. The departures of half-period averages vary from +21 cm at Perintalmanna to -165 cm at Neriamangalam. A conspicuous feature is that the region of maximum decrease in annual rainfall corresponds to the region of heaviest annual rainfall for the State. Three pockets have shown a decrease of more than 50 cm. It is worth noting that a slight increasing tendency in half-period averages has been observed over Palghat Gap, and an area extending to the north through the coastal tracts of the State and the leeward side of the Western Ghats in the southern half. The percentage ratio of departure is maximum over Neriamangalam (-28%). Marayur, a station on the leeward side of the Ghats has shown a positive departure of more than 15%.

For the monsoon season, only Punelur has shown a significant decreasing trend in rainfall. Half period averages have shown that both stations in the high ranges - Peermede and Vythiri - also exhibit a decreasing tendency. It is interesting to note that all the other six stations show a slight increasing tendency in monsoon rainfall. For the post-monsoon season, all stations except Palghat have shown a decreasing tendency. Punelur, Peermede and Vythiri have shown a decreasing tendency in monsoon, post-monsoon and annual rainfall. On the other hand, Palghat has shown an increasing tendency in all the three cases. For all coastal stations, the departure of means for monsoon rainfall is much more than the annual rainfall.

Filtered series of rainfall have shown that variations are oscillatory with peaks and dips. Although Punelur has shown a significant decreasing trend, the filtered series does not indicate a continuous decrease. The filtered series of rainfall of various stations do not exhibit many common features. But, it is observed that the annual rainfall of all stations were near normal during 1978-1979: after that, a sharp decrease has begun. This feature has been observed to a certain extent in monsoon rainfall also. This decreasing trend ceases by 1986-1987 and then onwards an increasing trend is noted and the rainfall becomes above normal by about 1988.

About one third of the stations have shown a significant decreasing trend in annual A.E.. Almost all stations which have shown a significant decreasing trend in rainfall, have shown a decreasing trend in A.E. too. Many of the stations which do not exhibit any significant decreasing trend in annual rainfall or even some stations which have shown an increasing tendency have shown very significant decreasing tendencies in annual A.E.. Only Karikode has shown a significantly increasing trend in A.E. values.

Stations in the northern half of the State which do not exhibit any significant decrease in annual rainfall or increase in P.E., exhibit a significant decreasing trend in annual A.E.. This implies that seasonal distributions of both rainfall and P.E. play a major role in these cases. It is to be noted that a small decreasing trend in winter or pre-monsoon rainfall will certainly affect the A.E. values, but need not have much effect on annual rainfall. Similarly, a decreasing trend in annual or post-monsoon rainfall need not have much effect on annual A.E. values.

Cochin and Peermede have shown an increasing trend in A.E. of monsoon period, but do not show any significant change in annual A.E.. All the other seven stations do not show any significant trend in monsoon, post-monsoon and annual A.E. series.

Trend analysis of annual deficits has shown that two-third of the stations exhibit significant increasing trends and none of the stations except Perintalmanna shows any significant decreasing trend. It is to be remembered that, for a third of the stations the decreasing trend is significant at 99% level. Stations which exhibit significant trends appear to be distributed at random. A few of the stations which do not exhibit any decreasing trend either in rainfall or in A.E. show an increasing trend in annual deficit. Similarly, some of the stations in the southern half of the State which exhibit significant decreasing trends in rainfall have not shown any increasing trend in annual deficit.

Departure of half-period means have revealed that most of the areas in the State show an increasing tendency with comparatively higher values in the southwestern parts of the State, with a maximum of 22 cm at

Nedumangad. Neriamangalam which shows the maximum decrease in annual rainfall (165 cm) has shown a departure of only 4 cm in annual deficit. The northwestern parts of the State which experience a decreasing tendency in annual rainfall do not show a corresponding increasing tendency in annual deficit. Stations on the leeward side of the Western Ghats show a slight decreasing tendency in deficits.

The percentage departure of annual deficit is maximum around Nedumangad region (more than 90%). It is to be noted that the increase in the percentage ratio of annual deficit is more than twice the decrease in the percentage ratio of annual rainfall for most of the stations. The area of increasing tendency of annual deficit is much more than the area of decreasing tendency of annual rainfall.

Deficits in the monsoon season for many stations have shown statistically significant decreases by Mann-Kendall statistic test, though this is not of much practical significance, since actual values themselves are very low. But, none of the stations has shown any increasing trend in this season. It is interesting to note that, during post-monsoon season, Peermede, and Vythiri have shown a decreasing tendency in water deficits.

For all stations, high values of annual deficits occurred in 1982 or 1983: at the same time the filtered values were above normal from 1975 onwards, except at Palghat. The series of annual values of rainfall and deficit do not appear to be correlated for Calicut and Trivandrum. This seems to be paradoxical, since one expect an increase in deficit as the rainfall decreases. This again implies that changes in the distribution pattern of rainfall are important.

All stations which exhibit significant trends in annual rainfall have shown trends in annual surplus too. Many stations in the southern half of the State reveal the presence of highly significant decreasing trends. None of the stations has shown any increasing trend. This indicates reduction in hydrologically available water and also the reduction of flood severity over the State especially in the southern half.

Many stations in the southern half of the State exhibit significant trends, both in annual surpluses and annual deficits. But, in the northern half, many stations have shown significant increasing trends in annual deficits, but only two stations have shown significant decreasing trends in annual surplus.

The percentage departures of annual surplus are very high compared to that of annual rainfall for almost all stations, and it varies from -49% at Chinnar to +12% over Palghat Gap, with three pockets of more than 20%. This gives a very important conclusion that the hydrologically available water is getting reduced much faster than actual rainfall itself.

During the monsoon season, only one station has shown a significant decreasing trend in surplus values, but, for post-monsoon season, six out of nine stations have shown a decreasing trend. It is to be noted that for all coastal stations, increase in monsoon surplus during the second half over the first half is more than the corresponding increase in annual values. This implies that coastal stations have shown an increase in rainfall during the monsoon season and a decrease in other seasons.

Time series of annual values of rainfall, A.E., water deficit and water surplus for all stations have been subjected to power spectrum analysis, to find out significant periodicities present in the series. It is found that none of the time series of different parameters of any stations exhibits Markov linear type persistence. High-frequency oscillations become more prominent in the case of filtered series of all parameters.

About half of the stations have shown persistence in rainfall series, significant at 99% level for about one fifth of the stations. About two third of the stations in the southern half of the State have shown persistence, while in the northern half, only a few stations have done so.

A periodicity of infinite wavelength has been observed at Punelur. Six stations shown a quasi-periodicity in one or more harmonics in the wavelength range 10.3-24.0 years. Thirteen stations, mostly in the southern half of the State, have shown a quasi-periodicity in the medium wavelength range of 2.9-4.3 years and in this, a periodicity of 3.1-3.4 years was significant for 11 stations. Another salient feature of the time series of rainfall is that none of the stations exhibit any periodicity at 99% significant level.

Persistence has been observed in the time series of annual A.E. for 10 stations, in which half of them are significant at 99% level. Significant spectral concentration corresponding to an infinite wave length has been observed at Kayamkulam. About half of the stations exhibit a quasi-periodicity of 3.4-5.5 years. Another quasi-periodicity observed in the time series is 2.2-2.5 years (8 stations). Significant periodicities at 99% level have been observed for 2.2-2.5 years at Irrikur and 3.4-3.8 years at Perintalmanna. A.E. series of Attingal has shown significance for a wide spectrum of wavelength corresponding to 4^{th} and 9^{th} harmonic (3.8-10.3 years). It is observed that the periodicities observed in the annual rainfall series are not reflected in A.E. series.

More than one third of the stations have shown significant persistence in the case of annual water deficits. Deficit series of Cranganore and Kayamkulam have shown the presence of significant trends in the series, but only 5 stations have exhibited periodicities beyond 6.5 years. Major quasi-periodicities observed are 2.2-2.9 and 3.1-4.8 years. About one third of the stations have shown periodicity in one or more harmonics in the wavelength range of 2.2-2.9 years; more than half of the stations exhibit periodicity in one or more harmonics in the wavelength range of 3.1-4.8 years. Periodicities of 3.4-3.8 years and 3.8-4.3 years are significant at 99% level for Perintalmanna, 2.3-2.5 year at 99% level for Irikkur and Vythiri, and 2.5-2.7 and 4.8-5.5 years (99% level) over Neriamangalam and Muvattupuzha respectively. Periodicities observed for rainfall series and that of deficit series are not correlated.

Analysis of annual water surplus has shown that Punelur exhibits significant trend or long term periodicity. Major quasi-periodicities observed in annual water surplus series are 3.1-3.8 years and 10.3-24.0 years. One third of the stations exhibit periodicities in the 3.1-3.4 year wavelength range and about one fourth of the stations show periodicity in 3.4-3.8 year wavelength. A few stations have shown periodicities in very short wavelengths too. High significance (99% level) has been observed at

Malayattur (2.2-2.3 years) and Devikulam (2.5-2.7 years). Most of the periodicities observed in annual rainfall series are reflected in annual water surplus series. Almost all stations which have shown quasi-periodicities for 3.1-3.8 years and 8.3-24.0 years in rainfall series have shown the periodicity in annual water surplus series too. However, some stations exhibit these periodicities in annual water surplus but not in rainfall series.

A comparison of the periodicities observed for different parameters shows that the 10^{th} harmonic corresponding to a wavelength of 3.4-3.8 years has shown significant periodicities for comparatively larger number of stations for all parameters. Large wavelength periodicities are more for rainfall and surplus series. A correlation between the periodicities of A.E. series and water deficit series has been observed for some stations.

Periodicity analysis carried out for 9 selected stations have shown that during the monsoon season, two major quasi-periodicities of 3.1-3.8 and 6.5-14.4 years are observed in time series of rainfall, A.E. and water surplus. None of the stations has shown any periodicity higher than 14.4 years for any parameter. The quasi-periodicity of 3.1-3.8 years is observed at 6 out of 9 stations. The major quasi-periodicities observed in deficit series are 2.5-3.1 and 4.2-4.8 years.

It is clear from all the above results that the State as a whole experiences heavy rainfall and large water surpluses, but water deficits are not altogether absent. The average annual water surplus is about 6 times the water deficit, which is only about one third of the surface flow.

There are regions having large surpluses as also regions without any surplus. Water surplus occurs only in a few months: about 85% of the surplus occurs in the monsoon season and during winter there is no surplus anywhere in the State. The annual water deficit over the State varies from 2 cm to more than 75 cm. The winter and pre-monsoon seasons experience about 45% of the annual deficit. The co-existence of both water surplus and water deficit at different times of the year in different parts of the State is an important aspect of the hydrometeorology of the State.

By a proper management of the surplus water, the deficit now experienced over the State can be mitigated. A large quantity of the surplus water flows to the Arabian Sea unexploited; sometimes such flow causes damage to the river banks by flooding. This can be avoided to a large extent by the construction of dams and reservoirs at proper sites. Since the State is densely populated, construction of large dams will give rise to rehabilitation problems, cause environmental degradation and also affect the stability of the Ghats. Since the State is narrow, being confined to the area between the coast and the Ghats, all rivers in the State are very short in length and have steep flows. It is, therefore advisable to plan comparatively smaller projects at suitable locations for conserving the valuable surface flow. Since rainfall in the northern parts of the State, is concentrated in the monsoon season, it is imperative to impound as much water as possible in these areas, by comparatively bigger dams, if necessary. The present study clearly indicates the regions, periods of the year of large surplus and deficits.

In order to get the maximum utility of the hydel-projects, siltation in the rivers has to be reduced. Intense soil erosion will result in the reduction of the capacity of rivers and reservoirs. Therefore soil conservation is an important aspect of water conservation. Because of the rugged and steep topography of the State, the soil erosion will be naturally very high, augment by unwise human activities. Terracing, contour bunding and afforestation are some of the usually suggested techniques for soil conservation. Judicious agricultural and other land-use practices are very important for the proper management of the soil.

The study points out that, apart from surface flow, the State has large groundwater resources. For the State as a whole, underground flow is about 1.5 times the surface flow. Even though on an annual basis, surface flow is more than the underground flow, on a seasonal basis, underground flow exceeds surface flow, except in the monsoon season. In order to avoid lowering of the water table and intrusion of saline water it is necessary to recharge the groundwater during the monsoon months. For this, percolation ponds and wells can be planned. Highland regions of the State are comparatively steep, and so the infiltration rates are less. This can be solved to a certain extent by bunding and terracing of the slopes. Afforestation of the slopes is also a method suggested to reduce the runoff and thereby increase the infiltration rate.

By judicious management of water resources - both surface and subsurface water - and optimum utilisation of the available water, it is possible to convert large areas of cultivable wasteland into productive agricultural lands. Agricultural development can then be achieved by increasing the area of cropping, increasing the number of crops, and employing multiple cropping methods.

It is well recognised that, climate is always varying, and that climatic variability influences man's natural environment and his welfare. However, the practical importance of climatic changes may not always be revealed by statistical significance tests. This does not mean that the study of climatic variability is without practical applications. If it is true that a practically significant change of climate need not be a statistically significant change, the converse, that a statistically significant change of climate may be of practical importance is much less likely to be true. The practical value of any study of variability is in its potential applicability to future planning. Climatic variations are very important because they affect human beings in myriad ways and touch upon the most fundamental aspects of life. Interannual climatic variability can have radical effects on agricultural productivity and food supply, and also profound impact on water resources.

In the time series analysis carried out, it has been seen that some series contain statistically significant trends or cycles in relatively brief periods of time. But, if longer periods of observations are considered, these trends or periodicities may become less distinct. Similarly, relatively larger trends or cycles that did in fact exist in the climate may not be indicated in short-period analysis. It should be remembered that a fluctuation which lacks statistical significance during the period of study may be continuing in the same direction, so as to acquire statistical significance in the near future.

It is observed that rainfall over the State is decreasing, and the water surplus is getting reduced at a much faster rate than rainfall, while at the same time water deficit over the State is increasing. From the agricultural point of view, the irrigation potential is getting reduced along with the actual available water. Water conservation is therefore becoming more important, critical and urgent.

From the spectral analysis, it is seen that some series exhibit periodicity, but we do not have any idea about the phase of the oscillation. This phase difference of oscillation between different pairs of stations or of the different parameters of the same station can be obtained from co-spectrum and quadrature spectrum of the time series.

Water resources do not have political or administrative boundaries and should be considered as a national resource. A regional water grid as a part of national grid has to be developed, in order to fully exploit the natural wealth for the development of the State and the country.

In conclusion it may be said, the development of the State is linked to the conservation of surplus water during the monsoon season through appropriate storages and the utilisation through regulated release during the drier part of year for irrigation, power generation, navigation, fish culture and tourism. Coordination of the various needs and uses of the available water has to be secured through an integrated approach to the management of the precious natural resource.

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