CS/AR-2/2000-2001

WATER BALANCE STUDY OF KRISHNAI RIVER BASIN ACCORDING TO THORNTHWAITE'S CONCEPT OF POTENTIAL EVAPOTRANSPIRATION

NATIONAL INSTITUTE OF HYDROLOGY
JAL VIGYAN BHAWAN
ROORKEE - 247 667

PREFACE

The water balance method of determining water deficiency is a powerful tool for irrigation; it not only can indicate when moisture is needed but it also provides information on how much to apply in order to satisfy needs without profligate waste. In a region such as India where drought and water surplus are both great problems, where water conservation is urgent and the need for irrigation ubiquitous, the water balance method offers a firm basis for appraising the problems in the planning stage and it provides a sound means for determining proper practices on a day-to-day basis. One of the most important aspects in planning of a water resources development and irrigation planning project is to assess the availability of water and its time distribution. Water availability is the life line of any water resources project. The estimation of total quantity of available water and its variability on long term as well as short term basis are the major factors contributing to success of any water resources scheme. Therefore, accurate estimation of water balance is very much essential both for planning as well as operation of a water resources and irrigation development schemes. In order to ensure the success of a project, it is necessary to plan it such that desired quantity of water is available on most of the time.

The present study aims to determine the climatic water balance of Krishnai river basin according to most popular Thornthwaite's concept of Potential Evapotranspiration. The report has been prepared by Sh. S.R. Kumar, Scientist `B' from North Eastern Regional Centre, National Institute of Hydrology, Guwahati under the work programme of 2000-2001.

(Dr. K.S. Ramasastri)
Director

CONTENTS

Page No.

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

The estimation of water balance is necessary in water resources development not only for economic appraisal of the project but also for checking the reliability and general pattern of availability of water from month to month. The planning, development and operation of water resources projects is very much dependent upon the availability of water in required quantity. Study of water balance of a river basin is necessary for various water resources development activities. Water balance study is an essential part to be carried out before deciding an irrigation project. The current work involves the study to see the feasibility of available water for Krishnai river basin in Goalpara district, Assam. The catchment area under study is 953.88 square km and extends on both the banks of river Krishnai.

For the study of climatological water balance for Krishnai river basin, 9 years (1986-1994) of mean monthly required climatological data like temperature etc. have been collected from the state irrigation department, Assam and Indian Meteorological Department, Borjhar and used for the analysis of various components of water balance like prediction of water surplus, water deficit etc. Thornthwaite's method has been used to find out the required essential input data named potential evapotranspiration. Mean monthly rainfall data for different months over the basin were computed using Isohyetal method.

The study reveals that, on normal annual basis, the basin has a water need of 1476.56 mm, the rainfall is 1844.14 mm and actual evapotranspiration is 1406.13 mm. Water surplus is 388 mm, and deficit is 70.43 mm. Since annual water surplus is more then water deficit, Basin is free from drought.

1.0 INTRODUCTION

In order to ensure the success of a project, it is necessary to plan it such that desired quantity of water is available on most of the time. Of course some shortage may be permitted in order to make the project cost effective and to have optimum utilization of the water resources. Necessary analyses are therefore to be carried out for identifying the characteristics of the water balance which are essentially required in decision making process.

Water balance study of a river basin is an important component of project hydrology, on the basis of which development of water resources of a river basin for various beneficial uses is thought of. Due to uneven distribution of precipitation, catchment characteristics and predominant hydro-meteorological factors in the watershed, all taken as the input, there is wide degree of variation in the water surplus and deficit. Therefore, water balance study in different time periods and its dependability has to be carried out to conceive available water resources development projects and ascertain its success for long term operation for a particular purpose for which it was meant for.

From a hydrologic viewpoint, precipitation constitutes almost the entire water supply to any region; however, its water potential can never be assessed from precipitation alone. It is necessary to know whether the precipitation is greater or less than the water need as determined essentially by the maximum amount of evaporation and transpiration, or the evapotranspiration (Thornthwaite, 1948) as it is called. Where the precipitation is an excess of the potential evapotranspiration, the region is wet, while the precipitation is low in comparison with the water need, it is dry.

The mutual comparison of precipitation and potential evapotranspiration for the evaluation of water balance, i.e., for quantitatively assessing the adequacy of precipitation (as water supply) in relation to potential evapotranspiration (as water need) may be effectively performed employing a simple accounting procedure devised by Thornthwaite (1948). In this procedure, based on the universal hydrologic cycle, precipitation is treated as income, potential evapotranspiration as expenditure and the amount of moisture stored in the soil as a sort of a reserve available for use to a limited extent for purposes of evapotranspiration during rainless periods. Where the precipitation is exactly the same as the potential evapotranspiration all of the time and water is available for use just as needed, there is neither water deficiency nor excess; the climate of the station is neither wet nor dry. As water deficiency (precipitation less than potential evapotranspiration) becomes large with respect to water need, the climate becomes progressively drier or more arid. On the other hand, as the water surplus (precipitation greater than potential evapotranspiration) becomes larger, the climate becomes progressively wetter or more humid.

In agricultural planning, detailed information on soil moisture status, i.e. absolute moisture content, its seasonal variation, period, duration, and, magnitudes of moisture deficiency and surplus, etc. are very essential. The water balance approach is, thus, a very powerful tool for practicing scientific irrigation, for it not only indicates when moisture is needed but also recommends how much water to apply in order to satisfy fully the water requirements of crops without profligate waste, a point of utmost importance to a country like India where water conservation is urgent and need for irrigation is ubiquitous.

The water balance of an area is an itemised statement of all gains, losses, and change of storage of water occurring in a given field within specified boundaries during a specified period of time. The task of monitoring and controlling the field water balance is valuable to the efficient management of water and soil. A knowledge of water balance is necessary to evaluate the possible methods to minimise loss and to maximise gain and utilization of water which is so often the limiting factor in crop production. One of the approaches to study water balance of any region is the climatic water balance first enunciated by Thornthwaite (1948) and later modified by Thornthwaite and Mather (1955). This approach of computing the water balance was carried out by Subrahmanyam et al. (1970) for Godavari river basin. They computed water surplus, water deficit and actual evapotranspiration for the entire basin by utilising the precipitation and temperature data of 56 stations. Similar study was done by Nale and Correia (1983) for weekly water balance of Udaipur by employing Thornthwaite's book-keeping technique for individual years from 1977 to 1981. This method is widely accepted because it facilitates the quantitative assessment of all major parameters in connection with water balance.

In the present case the catchment of river Krishnai, the left bank tributary of Brahmaputra consisting of catchment area of about 950 sq km, has been selected for the water balance study because no information is available about climatic water balance.

2.0 REVIEW

2.1 THE WATER BUDGET OF A PLACE

Over the years, many scientists have worked on the problem of how to express the daily or seasonal water budget of a place or area. These studies were advanced significantly in the 1940s by the work of C. W. Thornthwaite in the United States, H. L. Penman in England, and M. I. Budyko in the USSR. The approaches of these three major contributors to water balance climatology are all quite different; the myriad of modifications of each of the schemes that these and other scientists produced later have resulted in innumerable variations on the basic techniques. Each of the many water budgeting schemes and models that have appeared in the last quarter century has something to contribute to the understanding of our environmental water relations.

Any water budget is limited in part by the actual data that are entered into it. Many of the scientists who worked in this field have produced their own methods to compute the evaporation or evapotranspiration of moisture from the surface to the air. Arguments abound as to which expression is less empirical or more physically sound or which provides values of evaporation under particular meteorological or time conditions with more accuracy.

It would appear that the emphasis has been somewhat misplaced. While precipitation is measured at a large number of places around the world, we still have only a rough idea of the actual totals of precipitation except at the measuring gage itself. (Even here, wind and other exposure problems result in certain errors.) Extrapolation of precipitation values even a short distance can result in appreciable errors. Yet precipitation along with evapotranspiration are the major inputs to any water-balance bookkeeping procedure. Errors in the precipitation values entered into any water budget may be as large as errors in evapotranspiration, and, of course, they will produce as significant errors in the results.

Realizing that one could not determine whether a climate was moist or arid without comparing the climatic moisture supply with the climatic moisture needs, Thornthwaite developed a climatic water budget utilizing a bookkeeping system of accounting for increments of water supply and loss on either a daily or a monthly basis. The climatic water budget developed during the early 1940s was modified by Thornthwaite and Mather (1955b) to make it more useful under a wide range of soil and vegetation conditions.

2.2 APPLICATION OF THE FACTORS OF THE WATER BUDGET

It is possible to determine the actual evapotranspiration or the actual loss of water from the plant and soil surfaces which, in almost all cases, is different from the potential water need. It is extremely difficult to measure actual evapotranspiration in practice because of the dependence of this quantity on such factors as soil type and method of land cultivation, type of plant cover, and moisture condition of the soil profile. Second, the difference between the potential and the actual evapotranspiration provides a measure of the moisture deficit of a place, the amount by which the available moisture fails to satisfy the demand for water. Knowledge of the moisture deficit is basic to any understanding of the economic feasibility of irrigation, for it provides information on the total volume of water needed at any time and gives a definitive measure of drought. When compared with the moisture surplus in other seasons it makes clear whether there is sufficient water accumulating during the year to permit large-scale irrigation during the dry period. At the same time, determination of the changes in soil moisture storage on a daily basis gives information on the state of the moisture in the ground at any time for use in the actual scheduling of the time and amount of supplemental irrigation.

Third, information on the water surplus, the amount by which the precipitation exceeds the water needs when the soil is at field capacity, is fundamental in any hydrologic studies which deal with the recharge of the groundwater table or with the runoff of water in streams and rivers. By definition, the water surplus is the water which does not remain in the surface soil layers but is available for deep percolation to the water table and overland or subsurface flow to the water courses. Thus information on water surplus, climatically determined from the water budget, provides a knowledge of stream flow which can only otherwise be obtained from extensive stream-gauging installations and data on flow to the groundwater table, which requires detailed well records.

In oceanographic work, the water surplus is important in determining the amount of freshwater flow from the land to the ocean. This is particularly significant in the case of bays, estuaries, and seas which are almost entirely landlocked, for the volume of freshwater runoff to the water body will be important in determining the salinity, density, and other characteristics of the water.

Fourth, the water budget provides information on the detention of moisture on and within the land areas of the earth through the year. The seasonal fluctuations in the amount of land storage are reflected in the worldwide change in ocean levels through the year, a subject of vital importance not only to oceanographers but to others who are concerned with problems of large-scale moisture flux between land and ocean.

Moisture storage in the land is also basic to any understanding of the movement of men and vehicles over off-road surfaces. On all but the most sandy soils, an increase in soil moisture content to or above the field capacity will result in a loss of bearing capacity and shearing strength and an increase in stickiness. This results in a lowered ability of men and vehicles to move over off-road surfaces. On sands, of course, the reverse is true; as the moisture content increases up to the point where quicksand conditions exist, the tractionability, or the ability of men and vehicles to traverse off-road surfaces, improves.

Fifth, the water budget will result in information not only on the periods of moisture surplus and deficit but will permit the magnitude of these quantities to be compared with one another and with the water need in order to provide climatic indices that can be used in classification and correlation studies. Precipitation and the climatically determined water need are truly active factors in climate, and, as such, they can serve as the basis for the classification of the climates of the earth. At the same time, a comparison of moisture surplus or deficit with the water need provides indices of humidity and aridity which can be correlated with the distribution of vegetation.

Sixth, probably more important than the use of the water budget in any one of these many lines of research is the fact that with the ability to secure information on all phases of the moisture relationships of an area from readily available climatic data comes the ability to determine values of these moisture parameters for many years. This is significant for it not only makes data available for periods when actual measurements of these parameters were not made but it also permits the accumulation of a record which can be utilized in statistical studies. Many problems, such as the determination of probabilities of the amount of surplus water available for stream flow, of the occurrence of soil moisture conditions affecting the movement of men or vehicles over off-road surfaces, or of drought, can only be solved in this manner at present since measured values of the necessary parameters are not available for a long enough period of time. Such statistical studies provide the basis for evaluating the economic feasibility of any program of action and aid in forecasting the outcome of the program.

2.3 ASSUMPTIONS AND LIMITATIONS IN THE BOOKKEEPING PROCESS

Many investigators have pointed out certain shortcomings in the Thornthwaite water-budget bookkeeping procedure especially if it is used in daily computations. The most significant objection is that the value of computed potential evapotranspiration is not reliable on a daily basis. Thornthwaite's formula does not directly include humidity, radiation, or wind; it provides reasonable monthly values based only on monthly temperature by assuming that the other factors that also affect evapotranspiration do not deviate greatly from normal over a period as long as a month. In areas in which the humidity or wind changes markedly from month to month or from one season to another, the formula may not work well. Pelton, King, and Tanner (1960) and Jensen and Haise (1963) have both pointed out the lack of relation between daily temperature (the key to the Thornthwaite expression for potential evapotranspiration) and daily water loss. Penman (1956a) feels that Thornthwaite's formula for evaporation should be used only for periods longer than 5 days. Pelton, King, and Tanner report a correlation of 0.92 between monthly estimates of potential evapotranspiration and net radiation. However, they find a correlation coefficient of only 0.47 between the daily Thornthwaite potential evapotranspiration value and estimates of daily water loss based on energy budget calculations.

If daily values of potential evapotranspiration are needed, as they are for the determination of daily soil moisture content or irrigation scheduling, one of the many combination methods should be used. Use of these daily values day-to-day changes in soil moisture content, of water surplus, and deficit to be evaluated for use with various scheduling operations.

A second question that many investigators have raised is the fact that total precipitation is entered directly into the budget although, for some purposes, the overland storm runoff should be subtracted and only the so-called "effective" precipitation used in the computation. This is especially true when values of water storage, or moisture surplus or deficit, are sought.

The Soil Conservation Service (SCS) has published information on the infiltration characteristics for most soil series and has provided procedures for estimating storm runoff from values of daily precipitation, ground cover, and hydrologic soil characteristics (Soil Conservation Service, 1964). Albrecht (1971), using the values of effective precipitation derived from the SCS procedure, has obtained values of actual evapotranspiration from the water budget. He then evaluated the ratio AE/PE and related it to crop yield in the Missouri Valley area. He found that the ratio AE/PE computed by using the values of "effective" precipitation provided correlation coefficients with corn, sorghum, and wheat yield that were 0.09 to 0.11 higher than those found by using the AE/PE ratio computed on the basis of total, uncorrected precipitation.

In computing the depth of water in a soil column, the gravitational water or moisture above field capacity and the capillary water or moisture below field capacity shouted be considered separately. At field capacity the soil contains no surplus of gravitational water and no deficit of capillary water. Thus this value becomes an important and useful point in the computational process. When the moisture content of the soil is at field capacity or above, the surplus water or water that is added by precipitation is lost slowly by downward percolation regardless of whether there is evapotranspiration or not. This gravitational water is only detained briefly, the period depending on the depth and permeability of the soil and the amount of gravitational water. For example, it has been empirically found that, in a 1-m thickness of loam, about 90 percent of the gravitational water in the soil on any given day is held over in the soil until the succeeding day. This percentage becomes smaller as the thickness of the soil layer decreases. Also, the greater the amount of sand in the soil, the smaller is the percentage of gravitational water held over from one day g the next. Thus, in computing the drying of a soil from an initial value of moisture above field capacity, it is necessary to determine separately both the loss of water by evapotranspiration and by gravitational flow.

The use of various empirical formulas to provide the starting value of potential evapotranspiration for comparison with precipitation, the use of somewhat different assumptions concerning the way water is stored in the soil or how it is made available to the plant roots during a drying period, or the use of other methods of accomplishing soil moisture recharge and initiating runoff may all be accepted. These modifications represent only variations in technique rather than fundamental differences in the overall approach. While we will utilize the Thornthwaite approach in the present instance, our major concern is for an understanding of the overall value of a water budget at a particular place, its usefulness and applicability, and its function in clarifying the water resources relationships of a place or an area.

3.0 STUDY AREA

3.1 KRISHNAI RIVER SYSTEM

The study area of Krishnai river catchment is in the north-eastern frontier of the country comprising seven states. The Krishnai river catchment belongs to the states of Meghalya and Assam. The physiography of the entire region is mainly divided into two divisions, namely the Meghalya plateau and the plains of river Brahmputra valley which falls into the state of Assam accounting for about 70% and 30% of the total area respectively. The Assam state mainly comprises of two main river valleys. The northern valley is called the Brahmaputra valley and the southern valley is known as Surama and Barak valley. The Brahmaputra valley is an alluvial plain in between the foot hills of Bhutan range on the north and two other hill tracts of Naga, Mikir, Khasiya, Jaintia, Garo hills etc. on the south. The Brahmaputra valley is nearly 720-km. long and 80-km. wide covering about 56339 Sq km. of riverine area between both banks of the Brahmaputra starting from Sodiya in the east and Dhubri in the West. The river Brahamputra receives number of tributaries and sub-tributaries throughout its course. The river Dudhnoi is one of such major south bank tributary. The river Krishnai is again a tributary of the river Dudhanoi. The river Krishnai originates in Meghalya from Garo hills at an elevation of about 280 m above mean sea level and meets with river Dudhnoi near Domuni at about 12 km north from Dudhnoi at an elevation of about 150 m above mean sea level and finally flows towards river Brahmaputra. A good number of streams originating from Garo hills having elevation between 500m to 300m above mean sea level fall to the Krishnai river in the Meghalya area which produces good discharges for Krishnai river. The Krishnai river catchment lying between 25°35' to 26°2' north latitude and 90°20' to 90°45' east longitude is in Garo hill district of Meghalya, in the northern slope of the state adjoining

Assam. The geographical area of the catchment is about 953.88 Sq Km up to the proposed head work site for construction of a barrage at Beltraghat. The area with elevation ranging from 500 to 250 m above m.s.l. is narrow and steep, forming deep river valleys. Major part of the sub-basin is a hilly terrain with a few isolated V shaped valleys developed along the course of river with undulating topography. Geo-morphologically the basin can be divided into three broad limits. The first one is hilly gneissic complex, the second one the foot hill zone consisting of unsorted mixture of boulders, clay and the third one i.e. flood plains is of alluvium deposits. The elevation of the basin decreases towards north.

3.2 HYDROMETEOROLOGY OF KRISHNAI SUB-BASIN

The North Eastern Region is divided into four meteorological sub divisions for acquiring the meteorological information of the region. Characteristics of rainfall in the different meteorological sub divisions are mainly affected by the forest density, elevation of the place, orientation of the hill slope with respect to wind flow, type of storms etc. The Krishnai sub-basin falls within the meteorological sub division no. 2 which comprises the states of Assam and Meghalaya. The sub-basin enjoys an average annual rainfall of 4000 mm. In this zone the bulk of the rainfall occurs during the month of May to September. Significant rainfall occurs in May and October too. The months from October to April are generally dry.

Tropical storms and depressions affect the weather in this zone during the months from June and September. Climatological situation prevailing in Krishnai sub-basin in different parts of the year is briefly outlined below. It is predominantly characterized by four distinct seasons in a year which are: (i) Winter, (ii) Pre-Monsoon, (iii) Monsoon and (iv) Post Monsoon seasons.

The Winter Season (Dec-Feb) is the driest season and the rainfall is generally light. The precipitation is in association with the passage of low pressure, originating in the Bay of Bengal and moving in a Westerly and North-Westerly direction. The sub-basin receives significant rain under the influence of Eastern bound tropical disturbances which may appear as low pressure area. However, this season is devoid of flood in the valley due to low rainfall.

The Pre-Monsoon Season (March-May) is the season of thunder storms. The rainfall is in association with thunder storms. The precipitation due to tropical storms developed over the Bay of Bengal sometimes cause extensive rain and floods in the month of May.

The Monsoon Season (June-Sept) is the principal rainy season for the entire region and accounts for 65% of the rainfall. The orographic influence is dominant in the distribution of rainfall during this season as the prevailing winds blow almost at right angles against Khasi-Jayantia hills. The south-west monsoon sets in the first week of June and starts withdrawing by the end of September or beginning of October.

The Post Monsoon Season (Oct.-Nov.) is the season when the catchment receives generally light to moderate rainfall. The rainfall during this season is due to the cyclonic storms which form in the Bay of Bengal. Sometimes, western disturbances appear in the sub-basin mainly in second half of the October and cause light precipitation. However, floods are rare during this season.

The area is in the highest rainfall zone of the country. The rains are of long duration and occur mostly between March and October. During March and April the rainfall is sporadic, but it is steady and heavy or very heavy during May and October. Average annual rainfall in the Krishnai basin is about 1850 mm.

3.3 LOCATION OF COMMAND AREA

The proposed command area of the scheme extends on both the banks of the river Krishnai. The whole command area falls under Matia development block under Goalpara Civil Sub-Division in the district of Goalpara. The entire command area is bounded between latitude 26°-0' to 26°-5' N and longitude 90°-35' to 90°-45' E. The index map of the area is shown in figure 3.1.

3.4 HYDROLOGY OF THE AREA

The catchment area of the river up to the proposed head work site is about 953.88 Sq km., a major portion of which falls in Meghalya state. Average monthly rainfall in the Krishnai basin is given in Table 3.1. Mean monthly pan evaporation data for the basin is given in Table 3.2. Daily discharge of river Krishnai is available from 1972 to 1997. Yearly peak discharge of river Krishani as collected from Flood Control Department is given in Table 3.3.

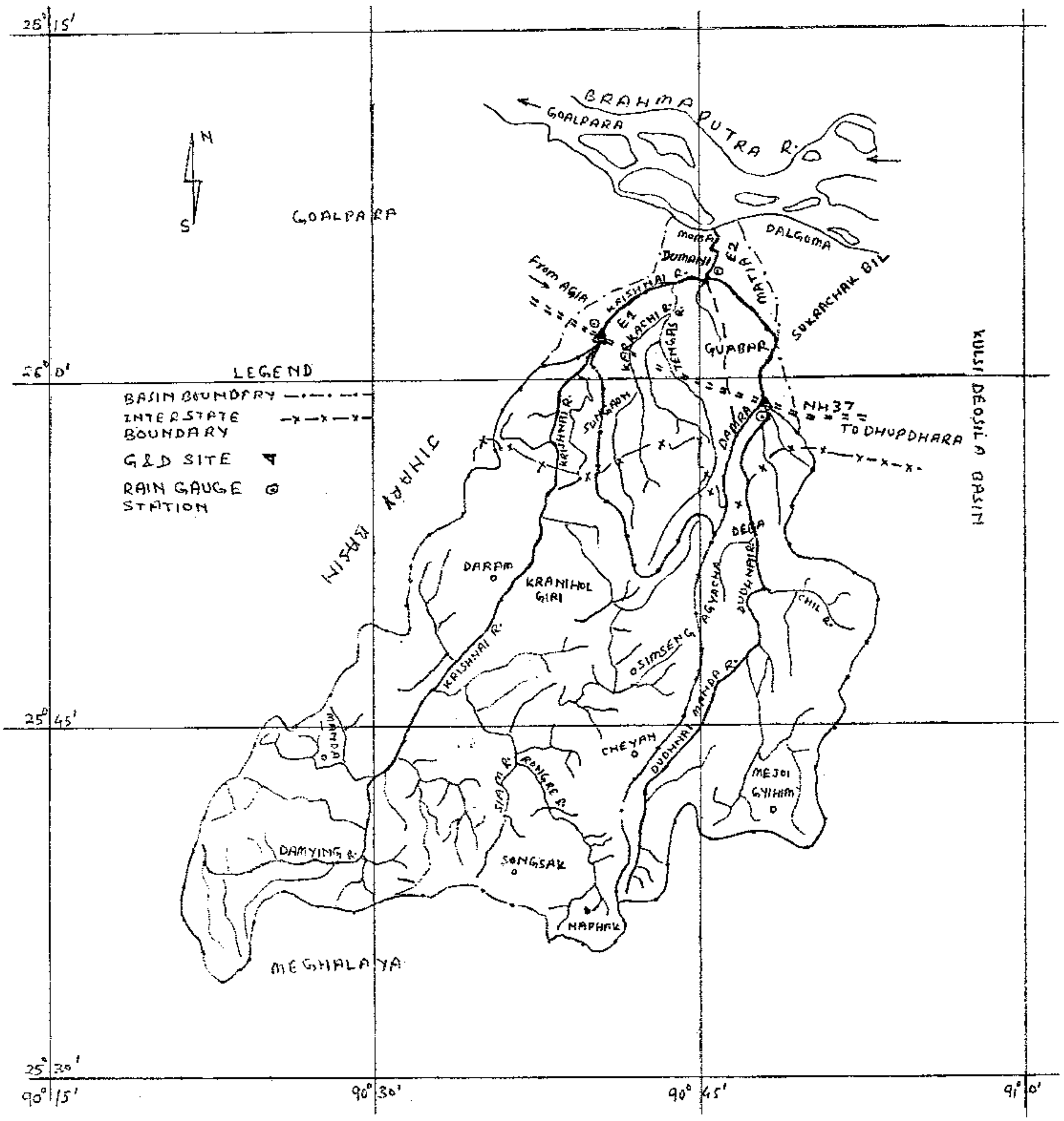

Fig. 3.1 : Map of Krishnai River Basin

Table 3.1 - Average Monthly Rainfall in Krishani Basin

Month	Average Rainfall (mm)
January	16.38
February	26.28
March	64.28
April	180.57
May	264.37
June	294.49
July	356.18
August	277.60
September	206.78
Octoberr	136.58
November	14.66
December	6.01

Table 3.2 – Mean Monthly Evaporation Data for Krishani Basin

Month	Pan Evaporation (mm/day)
January	2.10
February	3.30
March	4.90
April	5.70
May	5.00
June	4.30
July	4.40
August	4.20
September	3.90
October	3.30
November	2.70
December	2.00

Table 3.3 - Annual Peak Discharge of River Krishani at Beltraghat

Year	Peak Discharge (cumecs)
1972	519.10
1973	833.99
1974	646.19
1975	284.93
1976	376.63
1977	610.60
1978	339.21
1979	567.98
1980	345.54
1981	296.77
1982	553.80
1983	419.53
1984	596.43
1985	334.60
1986	622.54
1987	376.28
1988	559.82
1989	724.20
1990	222.02
1991	345.36
1992	641.81
1993	697.51
1994	191.17
1995	833.60
1996	302.93
1997	158.22

3.5 EXISTING DATA NETWORK FOR KRISHNAI BASIN

Rainfall in the catchment occurs during May to October. There are also some pre-monsoon and post monsoon showers. The average annual rainfall in the catchment is in the order of 4000 mm. Daily rainfall records are available from three different rain gauge stations namely, Dudhanoi, Damara, Wagasi on the eastern side of the catchment for the period 1988 to 1993, one rain gauge station namely Bajendoba on the western side of the catchment for the period 1978 to 1988 and one rain gauge station namely Goalpara on the northern side of the catchment for the period 1992 to 1995. Further rainfall data of Goalpara station are available with the Indian Meteorological Department for substantial period. Hourly rainfall records of rain gauge station at Dudhanoi, near the proposed barrage site is available for the period 1983 to 1993, for rain gauge station at Damara, about 5 km. south-east of the proposed site for the period 1983 to 1991 and rain gauge station at Goalpara, about 20 km. north west of the proposed site for the period 1992-1993 are available. The location of these stations are shown in figure 3.1.

Gauge And Discharge data at Beltraghat G&D site is available from 1972 to 1997. This discharge site is maintained by Goalpara Investigation Division of Irrigation Department of Govt. of Assam. Hourly gauge data along with water level is available only for the year 1992 (June to October) and 1993 (September to October). The basin has a low runoff ratio of about 0.22 in the year 1990 and as high as 0.75 in the year 1983. The 90% dependable year has been identified as 1990-91. Inventory of data for the Krishani Basin is given in Table 3.4.

3.6 SCOPE OF THE SCHEME

The population of the area are mainly Bodo, Rava, and other community in general. Agriculture is the only main source of their livelihood. The people of this localities are very active and laborious. The principal crop of this region is paddy. Due to the irregular and uneven distribution of rainfall, the crops of the locality suffer from short fall of water. The irregular rainfall can't meet up the timely requirement of water for the crops. This is evident from the statement of water requirement of different crops as worked out by Irrigation Department of Govt. of Assam. The soil in the command area is sandy loam and very fertile. If timely supply of water can be made available to the crops as per requirement by providing irrigation facilities, the yield of the different crops will sufficiently increase as well as uplift the economic condition of the locality. Hence the scheme to construct a Barrage on river Krishnai at Beltraghat is proposed to tap water for Irrigation to the proposed command area.

The object of the project is aimed to supply the controlled water to a vast cultivable area in the Goalpara Civil Sub-Division under the district Goalpara and to improve the existing cropping pattern and also to ensure irrigation to the paddy field against vagaries of rain fall. This will promote practice of multiple cropping which has not been practiced at present by the local people of the locality for want of ensured irrigation. The location of the Head work is situated within the revenue village Beltraghat under Matia Development Block. There will be a diversion barrage on river Krishani with two numbers of head regulator on both the banks.

Table 3.4 - Inventory of data for Krishnai Basin

Particular of Data	Availability	Remarks
(A) Daily Rainfall		
Rain gauge Stations at		
(i) Dudhnoi	Available	1978-1992 (May-Oct.)
(ii) Damara	Available	1978-1992 (May-Oct.)
(iii) Wagasi	Available	1978-1988 (May-Oct.)
(iv) Balabala	Available	1978-1988 (Jan.-Dec.)
(v) Bajendoba	Not available	
(vi) Goalpara	Available	1990-1995 (Jan-Dec.)
(B) Hourly Rainfall		
(i) Dudhnoi	Available	1983-1992 (May-Oct.)
(ii) Damara	Available	1983-1991 (May-Oct.)
(iii) Goalpara	Available	1992-1993 (Jan.-Dec.)
(C) Discharge Data for river Krishnai at Beltraghat G&D Site		
(i) Daily	Available	1988-1995
(ii) Hourly	Available	1992 (Jun-Oct.)
		1993 (Oct.)

4.0 METHODOLOGY

4.1 CONCEPT AND MEASUREMENT OF POTENTIAL EVAPOTRANSPIRATION

Consumptive water use is the amount of water entering plant roots to build plant tissues, water retained by plant body, transpired by the leaves to the atmosphere and the amount evaporated from adjacent soil and water surfaces. Since the water used in the actual metabolic processes is insignificant, the term consumptive use is generally taken equivalent to evapotranspiration. Evapotranspiration is the evaporation of water from all surfaces of water, soil, snow, ice, vegetative and other surfaces plus transpiration.

The concept of evaporation and consumptive use of natural water available from rainfall has been of concern to the mankind from time immemorial. On the basis of experimental evidence available, it was earlier believed that the type and form of vegetation cover on the earth's surface had little effect on the rate of natural evaporation . Evaporation was limited by the heat supplied to the surface and not by the surface water. So a term potential evapotranspiration (PET) was conceived.

Thornthwaite (1948) suggested that soil moisture may have considerable effect on evapotranspiration and potential evapotranspiration was equal to actual evapotranspiration that would occur when there was an adequate supply of soil moisture at all the times. Penman(1956) defined potential evapotranspiration as the amount of water transpired in unit time by a short green crop, completely shading the ground, of uniform height and never short of water. Van Bavel (1966) defined potential evapotranspiration as the evapotranspiration that occurs when the vapour pressure at the evaporating surface is at the saturation point. Gangopadhyaya et. al. (1970) defined potential evapotranspiration as the maximum quantity of water capable of being lost as water vapour in a given climate by a continuous, extensive stretch of vegetation covering the whole ground when the soil is kept saturated. Jensen (1973) defined potential evapotranspiration as the rate at which water, if available, would be removed from the soil and plant surfaces, expressed as the latent heat transfer per unit area or its equivalent depth of water per unit area.

It has been found that evapotranspiration depends on the density of vegetation cover and its stages of development. Therefore, potential evapotranspiration needs to be defined with reference to a particular surface cover. Doorenbos and Pruitt (1977) stated that the climate was the most important factor to be taken into account and the effect of which on crop water requirements was given by the reference crop evapotranspiration (ETo) which is defined as "*the rate of evapotranspiration from an extensive surface of 8 to 15 cm tall, green grass cover of uniform height, actively growing, completely shading the ground and not short of water.*"

4.2 THORNTHWAITE 'S Method

Various research workers defined and discussed many ways for measurement of potential evapotranspiration. Thornthwaite (1948) assumed that an exponential relationship exists between mean monthly temperature and mean monthly consumptive use. The relationship was based largely on experience in the central and eastern United States. No allowance was made for different crops on varying land uses. The formula was originally developed for the purpose of a rational classification of the broad climatic patterns of the world. Suitable coefficients should therefore be developed locally for reliable estimation of crop ET values. Thornthwaite proposed the following formula:

$$ET = 1.6\,La(10\,T/I)^{a} \qquad ..(4.1)$$

Where,

ET = Monthly PET in cm.

La = Adjustment for the number of hours of daylight and days in the month, related to the latitude of the place.

T = Mean monthly air temperature in degree Celsius.

I = Total of 12 monthly values of heat index i

$$= \sum_{n=1}^{12} i_n$$

where,

$$I = (T/5)^{1.514}$$

a = an empirical constant = $6.75\text{x}10^{-7}\,I^{3}-7.71\text{x}10^{-5}\,I^{2}+1.792\text{x}10^{-2}\,I+0.49239$

The Thornthwaite formula gives a reasonable estimate of PET in the temperate, continental climate of North America where the formula was originally derived, because there the temperature and radiation are strongly correlated. In other parts of the world this approach has been less successful.

4.3 PROCESSING OF RAINFALL DATA

Rainfall either in the form of precipitation or snow-melt is the process of driving the model. Surface runoff is the direct consequences of the excess rainfall. Rainfall can be described either in the following forms : intensity, duration, depth, frequency, temporal distribution, spatial distribution with aerial corrections etc.

The intensity of rainfall varies widely in time and space. For small sized catchments the average rainfall of a duration equal to the concentration time is usually the primary rainfall parameter. Therefore, a rainfall description relying exclusively on constant rainfall intensity is limited to small catchments. The duration of a rainfall event or storm varies widely, ranging from a few minutes to several days. The runoff concentration properly indicates that all catchments, regardless of size, eventually reach an equilibrium runoff condition subjected to constant effective rainfall. In practice, it implies that small catchments are likely to reach runoff equilibrium conditions much more readily than middle sized and large catchments. An increase in storm duration does not necessarily lead to a higher runoff peak.

The temporal distribution of a storm has a leading role in the hydrologic response of middle size catchments. For a given storm depth and duration, the choice of dimensionless temporal rainfall distribution allows the development of a design storm hyetograph. In practice, however a judicious choice of temporal distribution of a design storm is necessary for the accurate calculation of peak flows using catchment modeling techniques. A design temporal distribution can be either locally or regionally derived. Dimensionless temporal rainfall distribution are expressed as percent of rainfall duration in the abscissa and percent of rainfall depth as ordinates. Alternatively, the duration can be fixed at a set value and only the ordinates are expressed as percent of rainfall depth.

For large catchments, the modeling hinges upon the assessment of the storm's spatial distribution. Storms that cover large areas tend to have elliptical shapes, with an eye of higher intensity located in the middle of the ellipse, surrounded by decreasing rainfall intensities and depth. Furthermore, the eye of the storm tends to move in a direction parallel to prevailing wind.

Daily rainfall data available for rain gauge stations at Dudhanoi, Damara, Wagasi, Balabala, and Goalpara under and adjacent to Krishnai basin were used to draw the isohytes for each day. The area between each isohytes were measured by the plannimeter and the average basin rainfall was determined. Knowing the basin rainfall for each day, weightage of each rainfall station for that day was determined. With the help of the drawn isohytes, rainfall pattern over Krishnai basin was ascertained

4.4 ESTIMATION OF MEAN AERIAL RAINFALL USING ISOHYETAL METHOD

An isohyetal map is first prepared using monthly station rainfall to interpolate aerial rainfall values. Identical depths from each interpolation is joined to develop a isohyet. The areas between adjacent isohytes are determined by a digital plannimeter. The mean aerial rainfall on the watershed is determined using the following equation :

$$P_{ave} = (A_i P_i / A) \qquad ...(4.2)$$

where A_i is basin area lying between isohytes A_i and A_{i+1} and P_i is the mean of A_i and A_{i+1}.

For deriving daily mean rainfall from the above monthly values, the following assumptions are used :

1. The ratio of monthly rainfall over an individual station to the mean monthly rainfall is equal to the ratio of daily rainfall over an individual station to the mean daily rainfall of the basin.
2. The temporal distribution of rainfall is uniform over the basin.

First the monthly isohyetal mean of the basin is calculated for the available period. In the next step the weightage of each individual rain gauge station (Wm.) are estimated using the following relation :

$$W_{m.} = P_{mean}/P_i$$

...(4.3)

where P_{mean} is the monthly isohyetal mean and P_i represents the monthly rainfall for an individual station. Daily mean rainfall for the basin is estimated as follows :

$$\text{Daily } P_{mean} = (W_{mi}\, P_i /n) \qquad ...(4.4)$$

Where W_{mi} is the weightage factor for an individual station and P_i is their corresponding monthly rainfall values, n is the total number of rain gauge stations in the basin. The above procedure is adopted to avoid the process of drawing daily isohyetal maps to reach at the mean. The method is checked for accuracy after comparing with the results obtained with daily isohyetal maps.

Isohyetal maps prepared using monthly station rainfall are used to interpolate aerial rainfall values. A total number of about 60 isohyetal maps were prepared for ascertaining the rainfall pattern over the Krishnai basin and then about 20 isohyetal maps were drawn to cover the available rainfall series. The areas between adjacent isohyets were measured with digital plannimeter for determining the average monthly rainfall of the basin. The estimates of weightage of each individual rain gauge (Wm1) station using the relation (as in 4.3) are given in table 4.1. Daily mean rainfall for the basin is estimated using the above weightage values as per the procedure described earlier. For checking the validity of the method few random daily observations were analyzed. In the analysis the daily mean values of rainfall were obtained using the daily isohyetal map.

Table - 4.1 : Estimates of weightage of rainfall stations in Krishani basin

		Rainfall Stations	
Event No.	Date	Goalpara	Dudhnai
1	25.6.92	0.87	1.91
	26.6.92	0.98	0.8
	27.6.92	2.2	1.55
	28.6.92	0.18	0
2	15.7.92	1.15	2.15
	16.7.92	251.8	6.3
	17.7.92	0.09	0.41
	18.7.92	4.2	0.97
	19.7.92	0.6	1.65
	20.7.92	0.45	0.3
	21.7.92	6	0.41
	22.7.92	0.55	0.2
	23.7.92	0	32.33
3	30.8.92	0	1.4
	31.8.92	0.44	0.33
4	28.9.92	0.79	0.7
	29.9.92	0	17.2
	30.9.92	0	0
	1.10.92	0	0.5
	2.10.92	0	0
	3.10.92	0.45	2.12
5	22.9.93	0	0
	23.9.93	0.09	0.33
	24.9.93	0	0
	25.9.93	0	1.5

5.0 RESULTS AND ANALYSIS

In the present study the normal water balance of krishnai basin has been computed. Rainfall and mean monthly temperature data were collected for a period of 9 year from 1986 to 1994 from the Indian Meteorological Centre, Borjhar and State Irrigation Department of Assam. The monthly water balance computations were done using the procedure of Thornthawaite (1948) to estimate the elements of water balance; viz. : actual evapotranspiration (AE), water deficit (WD) and water surplus (WS).

For the water balance calculation, rainfall data and potential evapotranspiration estimated with the help of temperature data as suggested by Thornthwaite (1948) were considered as input parameters. Mean monthly maximum and minimum temperature data for different months under the observed period are shown in Fig. 5.1. Computed PET by Thornthwaite has been presented in Fig. 5.2. Field capacity for the soil was assumed as 100 mm for Krishnai basin. Fig. 5.3 shows the variation of rainfall over the basin under the observation period. Following the Thornthwaite's method (1948), values of various parameters of average water balance were computed. Table 5.1 shows the climatic water balance of Krishnai basin.

Various statistical methods are employed to summarize the vast amount of accumulated climatic data for the purpose of condensing the data into a digestible form. However, the judicious use of such data is necessary, as otherwise the information may have little actual meaning and, indeed, may be very misleading. Variation diagram of certain climatic factors is often a more satisfactory representation then is a mean value. Fig. 5.4, 5.5 and 5.6 show the variation diagrams for the mean monthly temperature, PET and rainfall respectively. The heavy horizontal line represents the mean or average value. The top triangle and bottom reverse triangle represents the highest and lowest observation during the period. The mean value of the monthly precipitation gives no indication of the variability of the precipitation, nor of the large departures from the mean. The diagram for the monthly temperature variation diagram shows that there is less variability of temperature. Such diagram for a locality will often reveal interesting facts concerning the behavior of various climatic factors. On the basis of observed mean monthly PET and rainfall data for Krishnai basin normal values of PET and rainfall for different month are plotted in the Figs. 5.7 and 5.8 respectively.

It is observed that highest mean monthly rainfall is 356.18 mm in the month of July and the water surplus in the month is 148.96 mm, which is the highest water surplus in any month. Again it is revealed that PE exceeds P for 5 months and the total deficit during that period comes to 70.43 mm. For the rest of the period, i.e. April to November the value of P exceeds PE (541 mm). Out of this amount 388 mm appears as water surplus and remaining 153 mm adds to soil moisture as recharge. Out of 12 months, six are water surplus months. In four months there is water deficit and the surplus month of April recharges the moisture deficit of the soil mass. On an annual basis the basin has a water need of 1476.56 mm, where as the rainfall is 1844.14 mm; still 388 mm of water appears as surplus on account of the relative marches of rainfall from April to October being in excess of water need by an amount 541 mm. (Fig. 5.9).

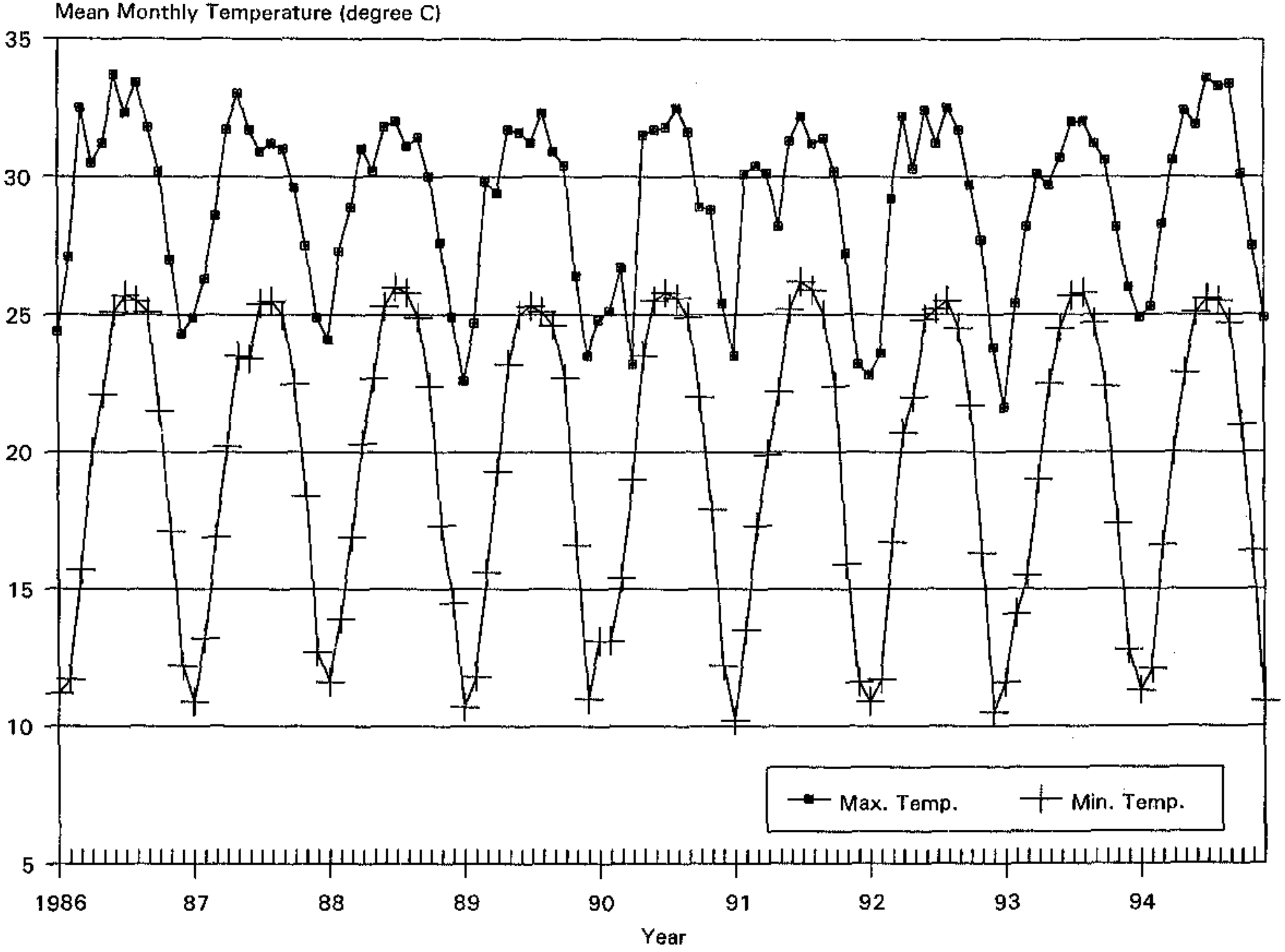

Fig. 5.1: Variation of max. & min. temp. in Krishnai basin

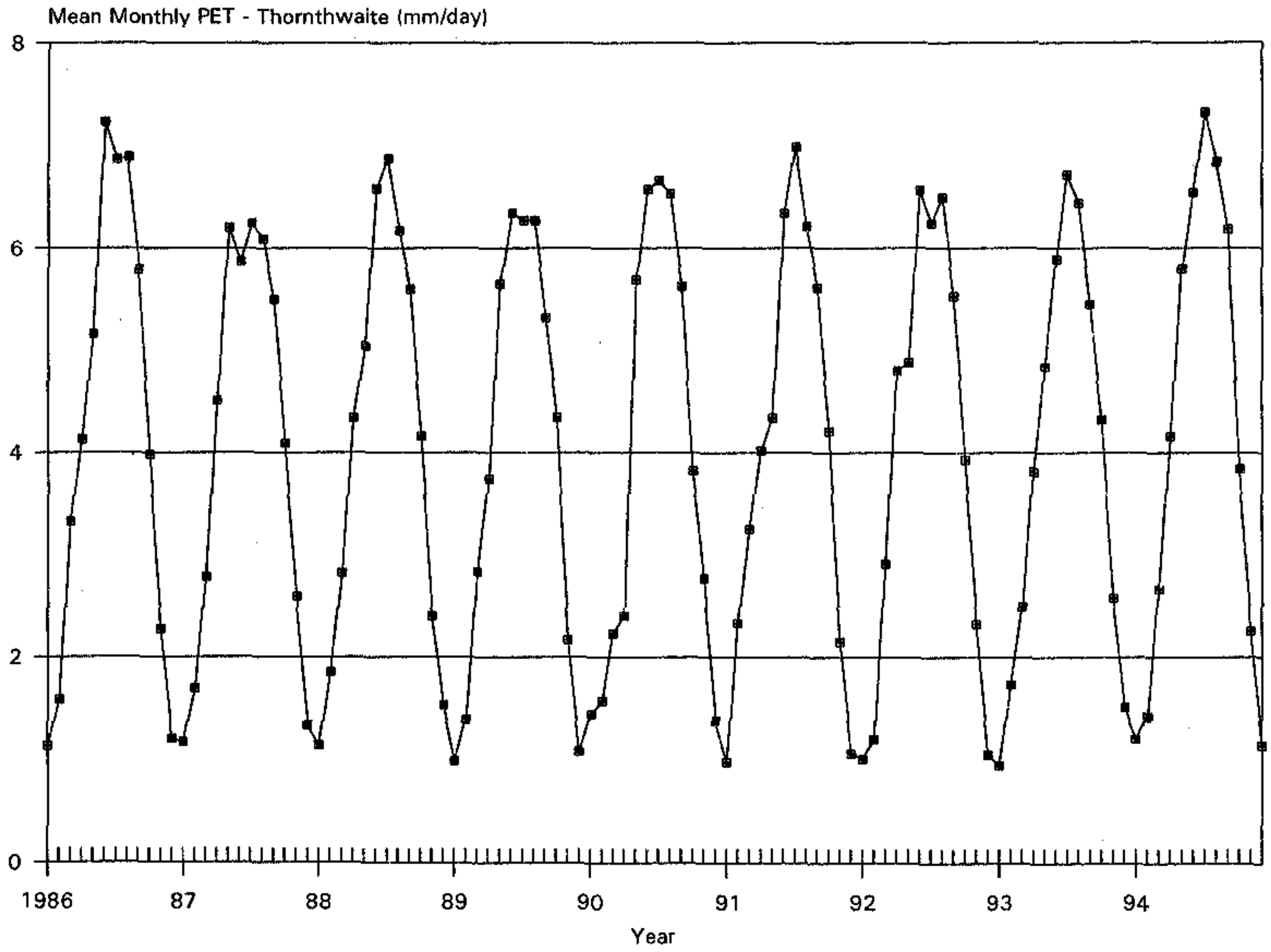

Fig. 5.2 : PET by Thornthwaite's method for Krishnai basin

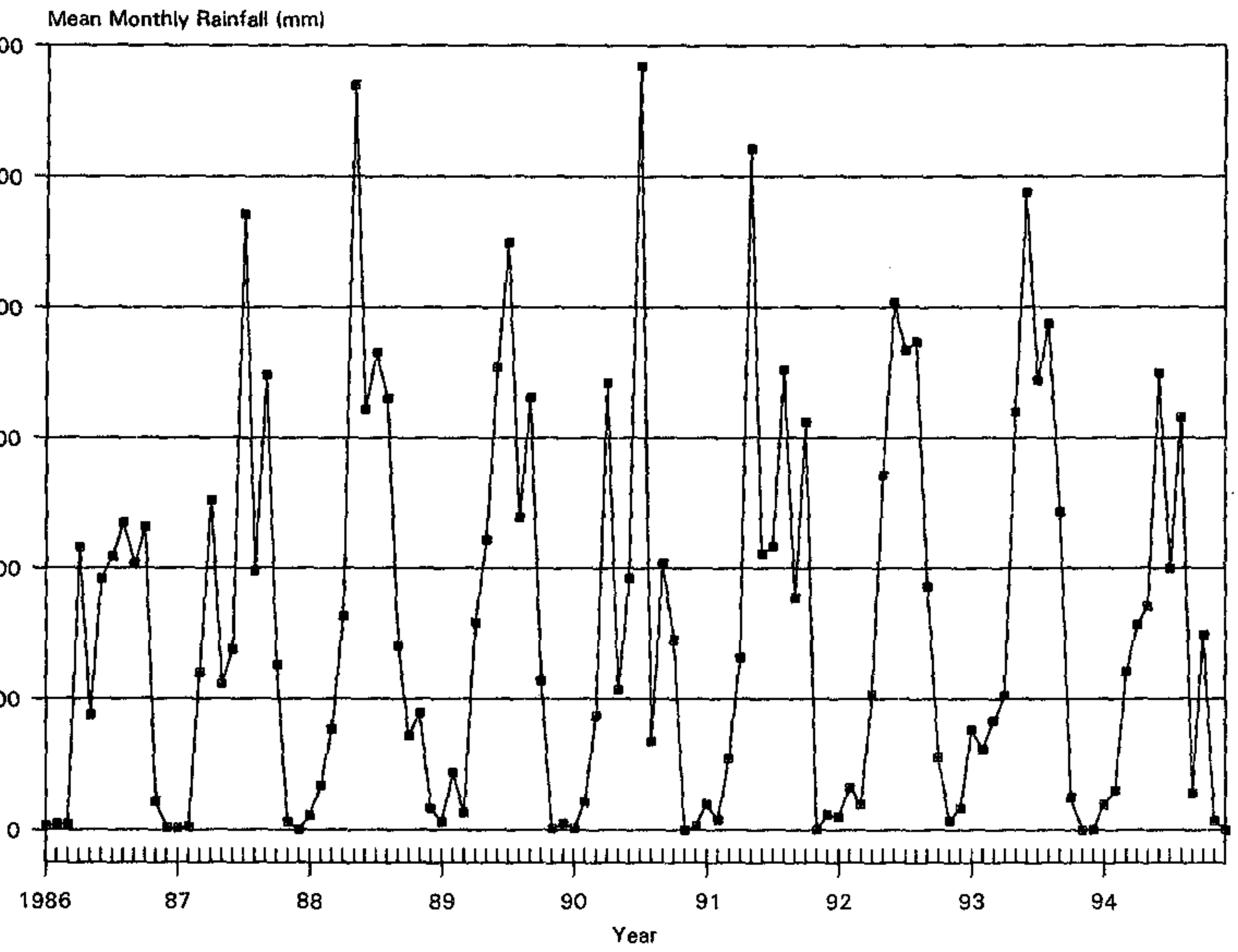

Fig. 5.3 : Variation of Rainfall over Krishnai basin

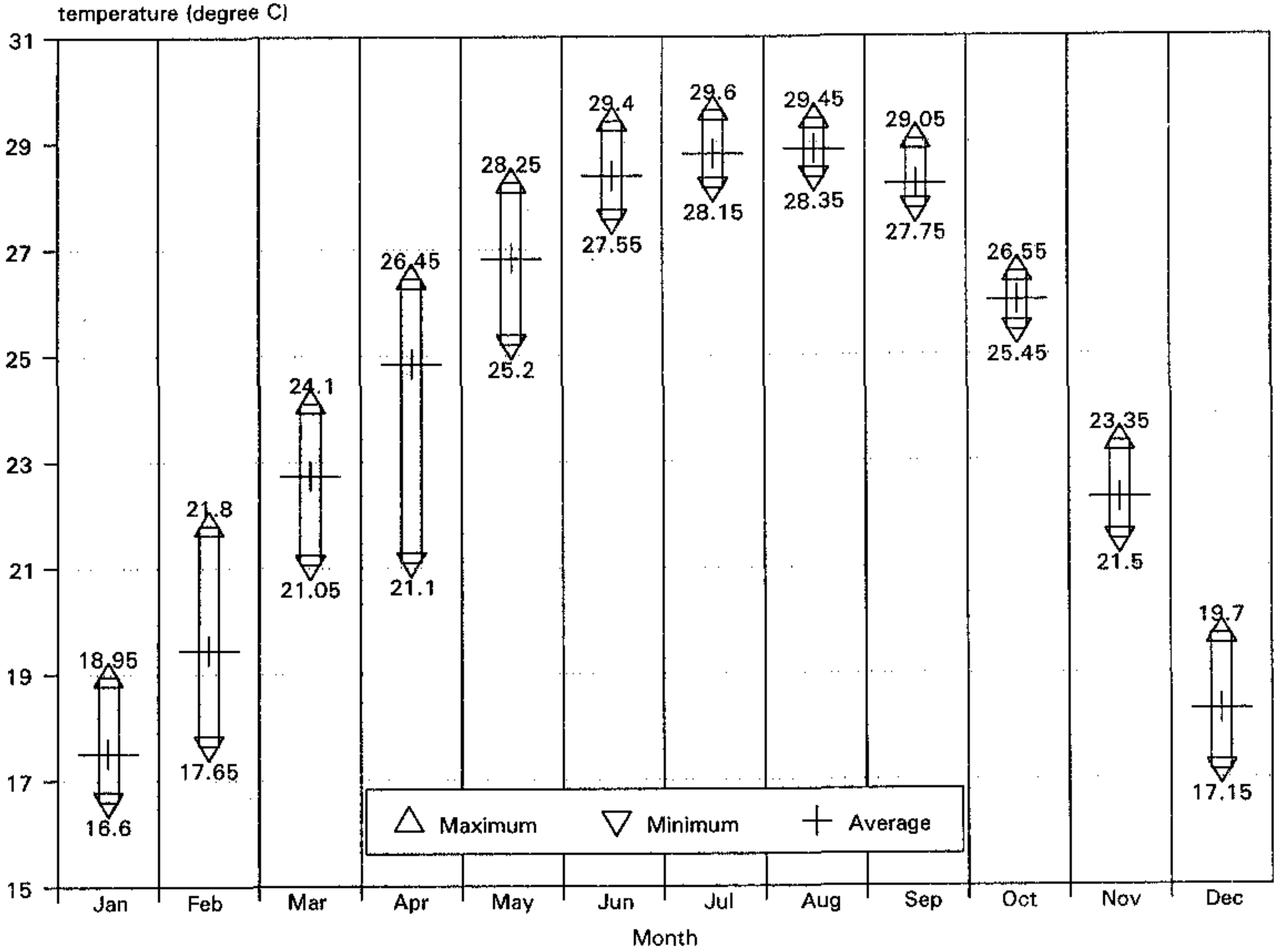

Fig. 5.4 : Variation of temperature (max & min) with average

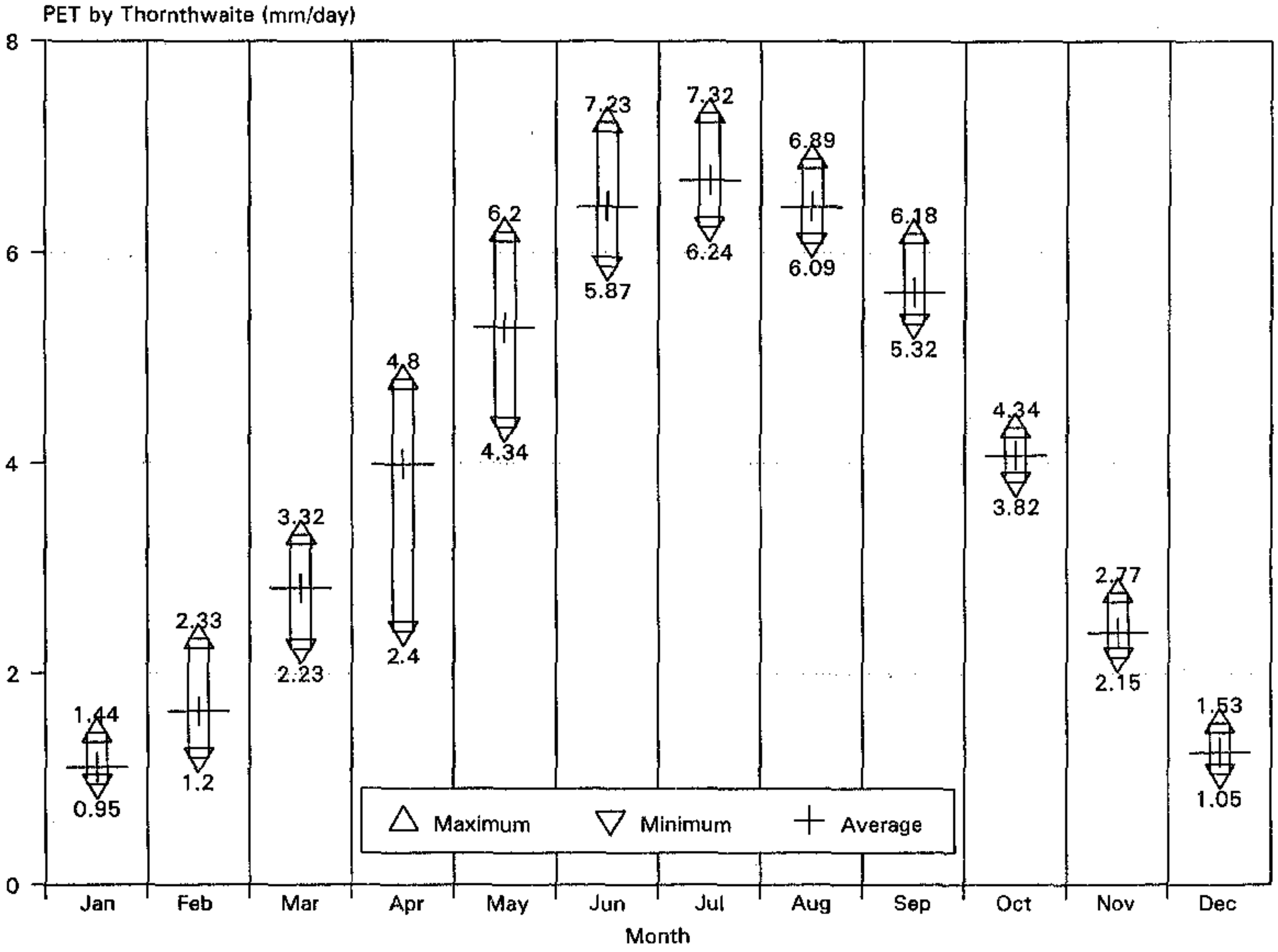

Fig. 5.5 : Variation of PET (max & min) with average

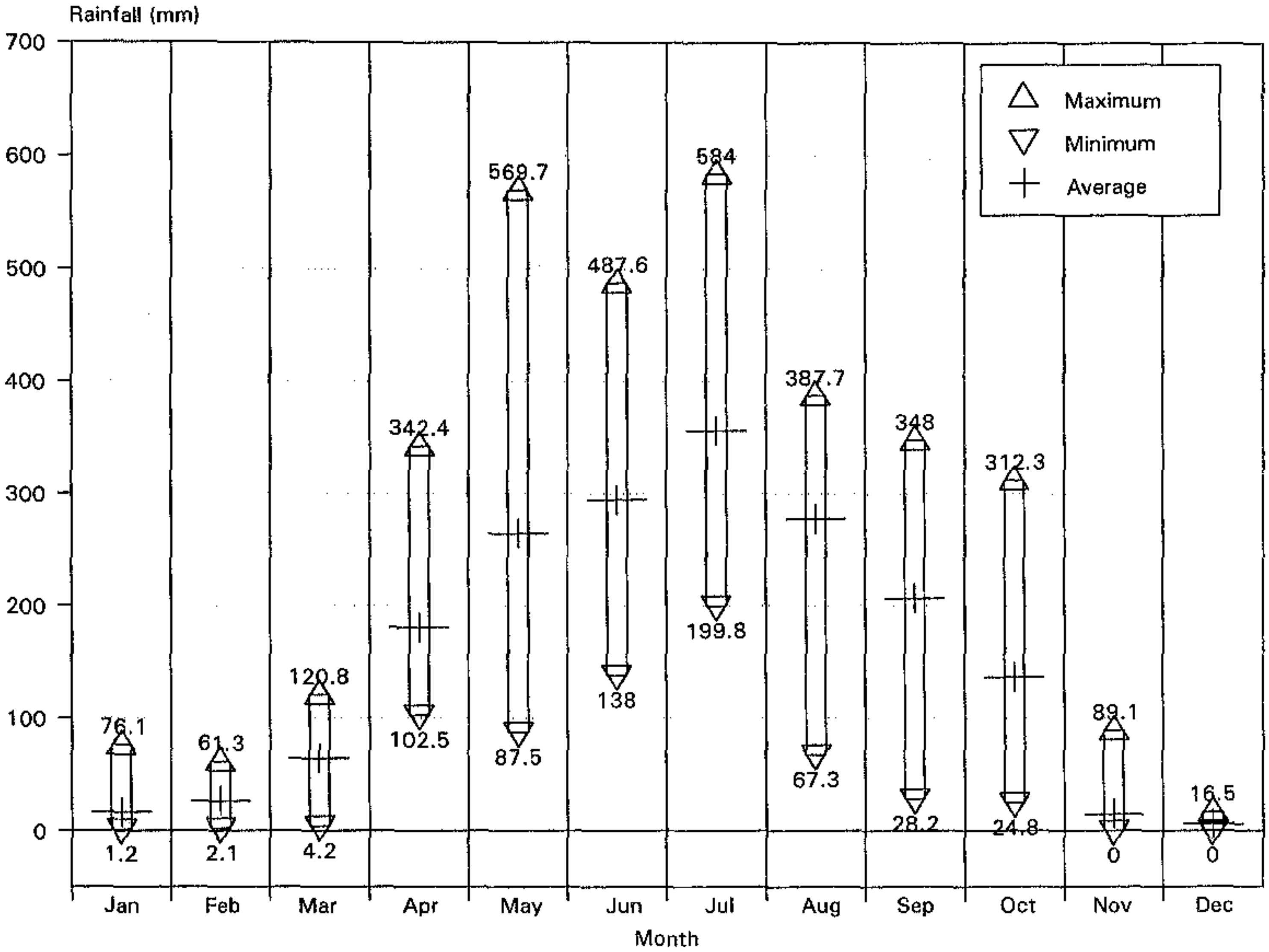

Fig. 5.6 : Variation of rainfall (max & min) with average

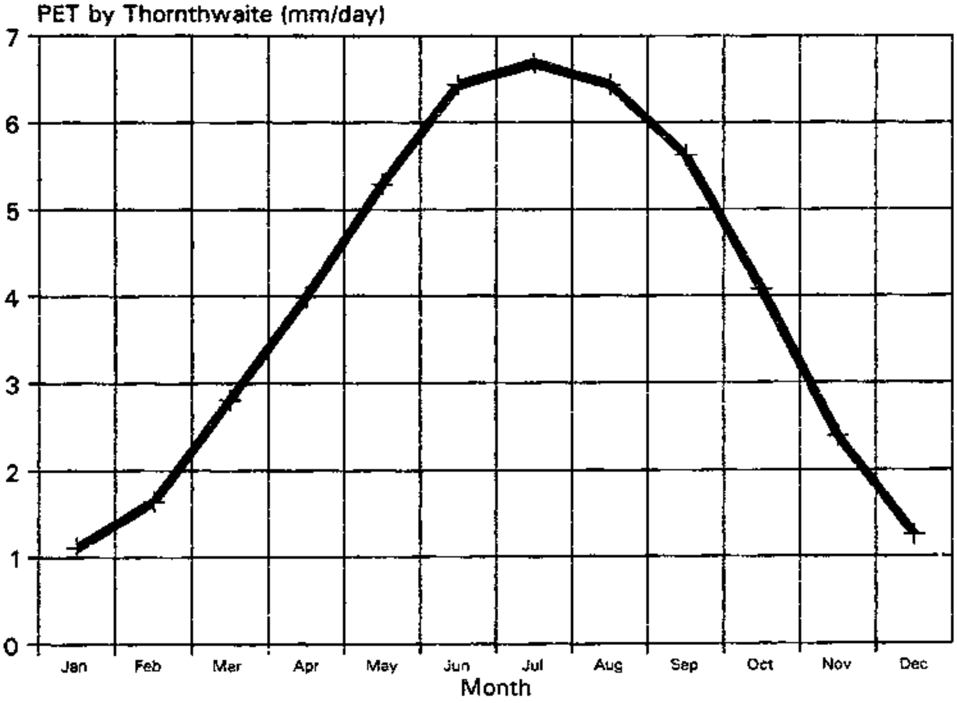

Fig. 5.7 : Normal value of PET for different months

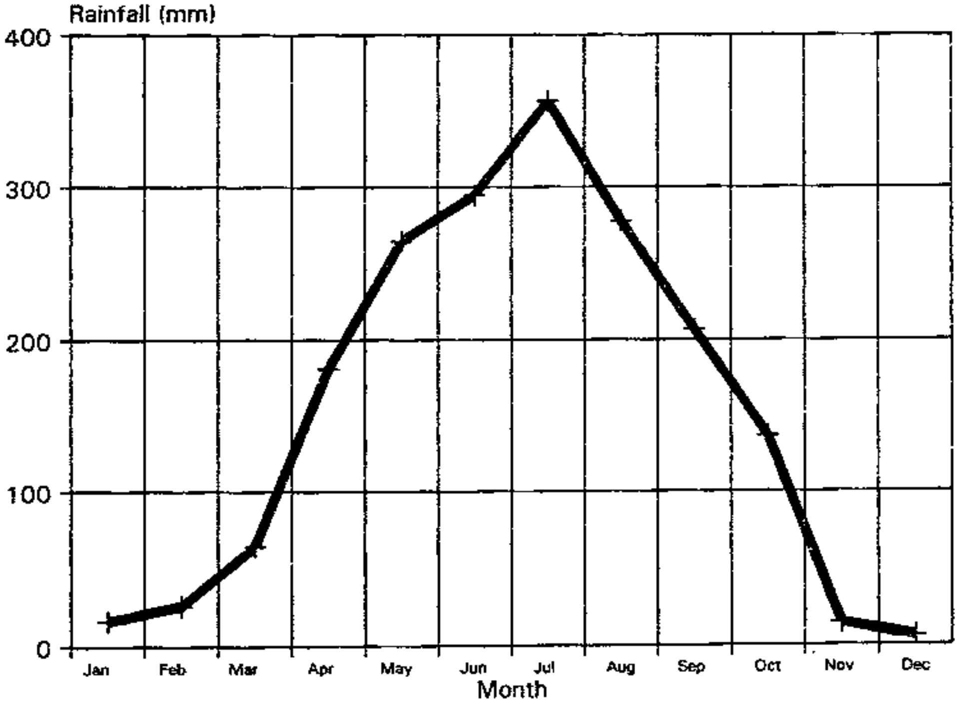

Fig. 5.8 : Normal value of rainfall for different months

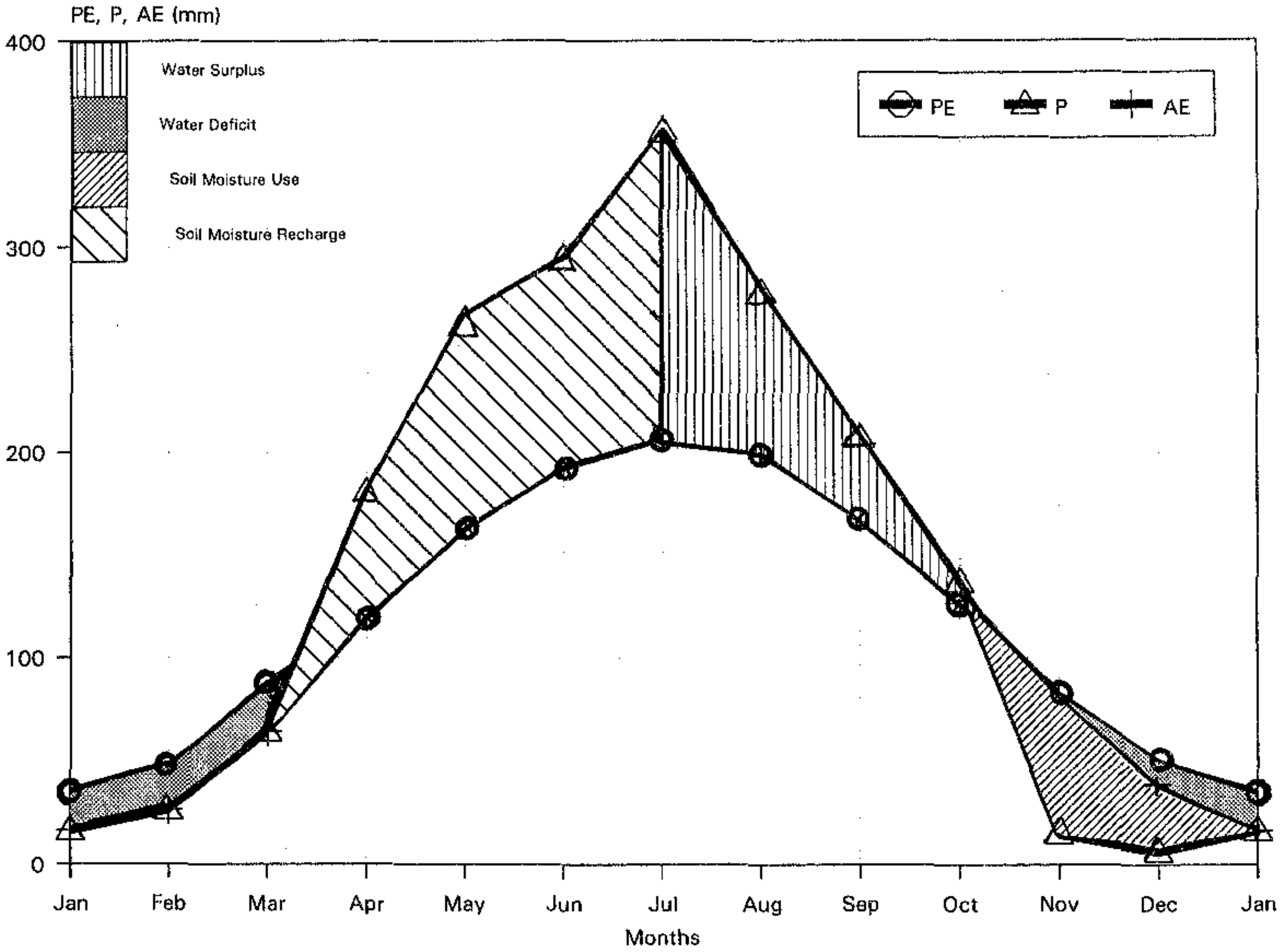

Fig. 5.9 : Normal Water Balance for Krishnai Basin

Table - 5.1 : Normal Climatic Water Balance Values for Krishnai Basin

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Pot. Evapt.(PE)	34.48	45.92	87.11	119.70	163.96	193.07	207.22	199.54	168.70	126.38	81.63	48.85	1476.56
Precipitation(P)	16.38	26.24	64.28	180.57	264.37	294.49	356.18	277.60	206.78	136.58	14.66	6.01	1844.14
P-PE (δ)	-18.10	-19.68	-22.83	60.87	100.41	101.42	148.96	78.06	38.08	10.20	-66.97	-42.84	
Change Storage* (δSt)	0.00	0.00	0.00	60.87	39.13	0.00	0.00	0.00	0.00	0.00	-66.97	-33.02	
Storage (St)	0.00	0.00	0.00	60.87	100.00	100.00	100.00	100.00	100.00	100.00	33.02	0.00	
Act. Evapt.(AE)	16.38	26.24	64.28	119.70	163.96	193.07	207.22	199.54	168.70	126.38	81.63	39.03	1406.13
Water Deficit (WD) (PE-AE)	18.10	19.68	22.83	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	9.82	70.43
Water Surplus (WS) (δ-δSt)	0.00	0.00	0.00	0.00	11.28	101.42	148.96	78.06	38.08	10.20	0.00	0.00	388.00

* Storage capacity in soil is 100 mm; All values are given in mm.

Since the water surplus is excess of precipitation over the water needs of the atmosphere and the soil, it must find its way through rivers and streams. Thus determination of water surplus enables the estimation of yields from river basin. Such an information can be used in designing water harvesting structures. In the same way, water deficit is the shortage of precipitation for satisfying the full demands of evapotranspiration. This has great impact on agriculture especially for scheduling irrigation water to cropped fields.

6.0 CONCLUDING REMARKS

As man increases his demands for water on this planet, through population growth, intensified industrialization, and increased application of water-using devices, and as usable supplies of water decrease through pollution, we are faced with a water crisis of growing seriousness. We will not run out of water as some predict although we may run out of free or inexpensive water. Technology will be able to supply us with enough to satisfy most of our needs or will provide us with alternate ways of using water more effectively.

Man, at present, is working diligently at the task of providing additional supplies of water or using water with greater efficiencies. This work is directed toward (1) increasing precipitation through cloud seeding, (2) reducing evaporation through the use of films or mulches, (3) desalination of ocean or brackish water, (4) storage and inter-basin transfers of excess water, and (5) tapping new underground sources of water. But consideration of any of these sources of water-how they occur, how they can be increased or decreased, what controls them, what their increased use will do to other aspects of the water economy over a large region-must ultimately focus back on the water budget or water balance.

Just the effects of vegetation changes, by grazing, cropping, substitution of species, or clearing, on the amount of water which enters or is retained in the soil, and hence on the water economy of the area, are illustrative of the interrelationships of water in all parts of the budget. The elimination of transpiration by stopping plant growth will result in additional water for soil moisture storage and for runoff. Uncontrolled runoff might result in harmful erosion and, hence, further change soil structure and the soil moisture relationships. Similarly, burning of vegetation destroys the above-ground parts of the plants as well as much of the surface organic material. Such action can also lead to increased runoff and decreased soil moisture storage. Grazing or overgrazing will result in two changes in environmental conditions: (1) the removal of vegetation will reduce transpiration and make more moisture available for soil storage or runoff, and (2) the compaction of soil by animals' hoofs will reduce the capacity of the soil to absorb water and hence make it less able to store water. Thus the additional water made available through reduced transpiration will probably run off with the possibility of erosion damage. Replacing a grassland or cropped vegetation surface with forest (allowing farmland to be reforested) will result in the retention of more moisture in the upper soil layers and increase actual evapotranspiration. This is in turn, will make less water available for stream runoff.

The water budget is an important area of human influence because knowledge of the water budget provide quantitative information on the periods of moisture surplus and deficit, and permits the determination of the amounts of moisture stored in the soil or lost through runoff at any time it becomes a basic tool in many aspects of applied climatology.

The water balance method of determining water deficiency is a powerful tool for irrigation; it not only can indicate when moisture is needed but it also provides information on how much to apply in order to satisfy needs without profligate waste. One of the most important aspects in planning of a water resources development and irrigation planning project is to assess the availability of water and its time distribution.

The estimation of water balance is necessary in water resources development not only for economic appraisal of the project but also for checking the reliability and general pattern of availability of water from month to month. The planning, development and operation of water resources projects is very much dependent upon the availability of water in required quantity. Study of water balance of a river basin is necessary for various water resources development activities. Water balance study is an essential part to be carried out before deciding an irrigation project.

The study reveals that, on normal annual basis, the basin has a water need of 1476.56 mm, the rainfall is 1844.14 mm and actual evapotranspiration is 1406.13 mm. Water surplus is 388 mm, and deficit is 70.43 mm. Since annual water surplus is more then water deficit, Basin is free from drought.

7.0 REFERENCES

Angstrom, A. (1936). A coefficient of humidity of general applicability. Geografiska Annaler, Vol. 18, pp. 245-254.

Carter, D.B. (1954). Climates of Africa and India according to Thornthwaite's 1948 classification. Pub. in Climatology. Johns Hopkins Univ. Lab. of Climatology. Vol 7, No. 4, pp. 453-474.

Champion, H.G. (1938). A preliminary survey of the forest types of India. Indian Forest Records (NS). Forest Research Institute, Dehra Dun.

Chow, V.T. (1964). Handbook of Applied Hydrology. McGraw Hill, New York.

Foley, J.C. (1957). Droughts in Australia. Bulletin No 43. Bureau of Meteorology, Commonwealth of Australia.

I.W.R.A. (1975). Water For Human Needs (Vol-V). Technology & Ecology.

Massaru Isozaki (1993). Thornthwaite's new classification of climate and its application to the climate of Japan. Jr. of Geogr., Tokyo Geographical Society, Vol. 45 (1933), pp.234-245.

Master Plan Report of Dudhnai-Krishnai Catchment, Vol-1 (1992). Brahmaputra Board.

Mather, J.R. (ed.) (1954). The measurement of potential evapotranspiration. Publications in Climatology. Johns Hopkins University. Laboratory of Climatology, Vol. 7, No. I, p. 225.

Mather, J.R. (1964). The climatic water balance. Climatology XIV (3).

Mather, J.R. (1974). Climatology : Fundamentals and Applications. Mc Graw Hill Book Co.

Meyer, A.F. (1915). Computing Runoff from Rainfall and other Physical data. Trans, Am. Soc., Civil Engrs.

Nale, S.M. and J.F. Correa (1985). Water balance of Udaipur. Jr. of Agril. Engg., ISAE, Vol. 22, No. 3, pp. 31-41.

Paul, J.C. et al. (1999). Studies on water balance and incidence of drought at Bhubneswar. Jr. of Appl. Hydr., Vol. XII, No. 2&3, pp. 8-14.

Patwary, B.C. and K.K.S. Bhatia (1996). Rainfall Distribution & Associated Meteorological Situations Contributing to Worlds Highest Rainfall in N.E. India. Souvenir, H.P.Baruah Memorial Lecture, IEI, Guwahati.

Penman, H.L. (1956). Estimating evaporation. Trans, Amer. Geophys. Un., Vol. 37, No. 1, pp. 43-56.

Puri. G.S. (1950). Forest ecology and evaporation measurement in India. Science and Culture, Vol. 15, pp. 465-467.

Raman, P.K. and V. Satakopan (1934). Evaporation in India - calculated from other meteorological factors. Sci. Note of the Ind. Met. Dept., Vol. 6, No. 61.

Ramdas, L.A. (1951). Evaporation and potential evapotranspiration over the Indian subcontinent. Ind. Jr. Agri. Sci., Vol 27, Pt. II, pp. 137-149.

Rohwer, C. (1931). Evaporation from free water surfaces. U.S Dept. of Agri. Tech. Bull. No. 271.

Schulz, E.F. (1974). Problems in Applied Hydrology. Water Resources Publications. Fort Collins, Colorado, USA.

Subramanya, K. (1991). Engineering Hydrology. Tata McGraw Hill.

Subrahmanyam, V.P. (1956). Climatic types of India according to the rational classification of Thornthwaite. Ind. Jour. Met. and Geophys., Vol, 7, No 3, pp. 253-264.

Subrahmanyam, V.P. (1958). Droughts and aridity in India - a climatic study. Proc. Symp. on Met. and Hydrol. Aspects of Floods and Droughts in India, New Delhi. pp. 171-177.

Subrahmanyam, V.P. (1958). The climates of India in relation to the distribution of natural vegetation. Ind. Geogr., Vols. 2 and 3; Nos. 1 and 2, pp. 1-12.

Subrahmanyam, V.P. (1967). The problem of incidence and spread of continental drought. World Met. Org., Rep. No. WMO/IHD - 2, p.52.

Subrahmanyam, V.P. (1969). Nature and classification of tropical climates with special reference to India. The Ind. Forester, Vol. 95, No. 10, pp. 659-670.

Subrahmanyam, V.P. and C.V.S. Sastry (1969). A study of aridity and droughts at Visakhapatnam. Annals of the Arid Zone. Vol. 8, No. 1, pp. 18-22.

Subrahmanyam, V.P., B. Subba Rao and A.R. Subramaniam (1963). Moisture adequacy in relation to the distribution of a few crops in India. Proc. Berkeley (California) Symp. of the Internat. Assn. Sci. Hydrol. (IUGG), pp. 462-467.

Subrahmanyam, V.P., B. Subba Rao and A.R Subramaniam, (1965). Koppen and Thornthwaite systems of climatic classification applied to India. Annals of the Arid Zone, Vol. 4, No 1, pp. 46-55.

Subrahmanyam, V.P., B. Subba Rao and Murthy Ch. V.S.N. (1970). The water balance of Godavari river basin. Jr. of Inst. of Engrs. (I), Vol. 50, No. 2, pp. 108-114.

Subrahmanyam, V.P. and A.R. Subramaniam (1964). Application of water balance concepts for a climatic study of droughts in South India. Ind. Jour. Met. and Geophs. Vol. 15, No. 3, pp. 394-402.

Subrahmanyam, V.P. and A.R Subramaniam (1965). Some characteristics and frequencies of occurrence of droughts in the dry climatic zones of India. Bull. Internat. Assn. Sci. Hydrol., Xe, Annec., No. 3, pp. 31-37.

Thomas Russel (1988). Depth of evaporation in United States. Monthly Weather Review, Vol 16, pp.235-239.

Thornthwaite, C.W. (1931). The climates of North America according to a new classification. Geographical Review, Vol. 21, pp. 633-655.

Thornthwaite, C.W., H.G. Wilm, and others (1944). Report of the Committee on evaporation and transpiration. Transactions, American Geophysical Union, Part V, p. 687.

Thornthwaite, C.W. (1947). Climate and moisture conservation. Annals of the Assn. Amer. Geogrs., Vol 37, No 2, pp. 87-100.

Thornthwaite, C.W, (1948). An approach toward a rational classification of Climate. Geogr. Rev., Vol. 38, No. 1, pp. 55-94.

Thornthwaite, C.W and J.R. Mather (1955). The water balance. Pub. in Climate., Lab. of Climate., Vol. 8, No. 1, 104 pp.

Thornthwaite, C.W. (1952). The water balance in arid and semi-arid climates. Proceedings International Symposium on Desert Research, Jerusalem.

Thornthwaite, C.W. and J.R. Mather (1955). The water budget and its use in irrigation. Yearbook of Agriculture, USDA.

Transeau, E.N., (1905). Forest centers of America. American Naturalist, Vol. 39, pp. 875-889.

Ponce, V.M. (1989). Engineering Hydrology - Principles and Practices. Prentice Hall Inc.

Wasif Abdul (1978). Study of Water Availability for Ramganga Basin upto Kalagarh (an M.E. dissertation of Roorkee University).

REPORTING GROUP

Director : Dr. K S Ramasastri

Co-Ordinator : Dr. K K S Bhatia (Scientist 'F')

Divisional Head : Sh. B C Patwary (Scientist 'E')

Study Group

Sh. S R Kumar (Scientist 'B')