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APPLICATION OF CATCHMENT WATER BALANCE MODEL TO THE MALAPRABHA BASIN, KARNATAKA

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PREFACE

A catchment water yield is a fundamental problem in hydrology, referring to the volume of water available at the catchment outlet over a specified period of time. The yield is expressed for monthly, seasonal or annual periods.

Several approaches are available for the computation of water yield. These vary in complexity from the simple empirical formulae to the complex models based on continuous simulation. While the empirical formulae have limited applicability and the continuous simulation models require large amount of data for their successful operation. A practical alternative is represented by the conceptual models, which use the water balance equation to separate precipitation into its various components.

In this report, conceptual model of water balance is used which is suitable for application to a wide range of climatic conditions. The model separates annual precipitation into its major components: surface runoff, baseflow and vaporization.

The report has been prepared by Mr. A. V. Shetty, Scientist 'B', HRRC Belgaum under the guidance of Prof. V. M. Ponce, San Diego State University, California, U. S. A., during his training in connection with ongoing UNDP project IND/90/03 entitled 'Developing Capabilities in Hydrological Studies' at San Diego State University, California U. S. A. from January 20, 1994 to May 20, 1994.

(S. M. Seth)
DDIRECTOR

ABSTRACT

The conceptual model of a catchment water balance is based on the sequential two step separation of annual precipitation into surface runoff and wetting, and wetting into baseflow and vaporization. A given set of model parameters, the model can separate annual precipitation into three major components: surface runoff, baseflow, and vaporization. It is also used to characterize baseflow and runoff coefficients as a function of climate. The runoff and baseflow functions are derived and analyzed : (1) runoff and baseflow coefficients vs annual precipitation and (2) baseflow and runoff gains vs annual precipitation. The conceptual model of water balance is also used to simulate changes in baseflow and runoff with annual precipitation.

The conceptual water balance model is applied to the Malaprabha river basin upstream of Khanapur, Karnataka. The wetting and Vaporization potentials, and surface runoff and baseflow initial abstraction coefficients have been calibrated. For a given annual precipitation, a set of surface flow and baseflow initial abstraction coefficients, and wetting and vaporization potentials are used to separate precipitation into surface runoff, wetting, vaporization, runoff coefficients, baseflow coefficients, and runoff gains and baseflow gains have been simulated by the model.

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INTRODUCTION

A catchment's water yield is a fundamental problem in hydrology, referring to the volume of water available at the catchment outlet over a specified period of time. The yield is expressed for monthly, seasonal or annual periods.

A catchment water budgeting is one of the tools to estimate the water yield from the basin. The catchment water balance can be described by a set of equations (L'vovich 1979).

Precipitation can be separated into two components:

$$P = S + W \tag{1}$$

in which P = annual precipitation, S = surface runoff, i.e., the fraction of runoff originating on the land surface; and W = catchment wetting(L'vovich 1979), the fraction of precipitation not contributing to surface runoff.

Likewise, wetting consists two components:

$$W = U + V \tag{2}$$

in which U = baseflow, i.e., the fraction of wetting which exfiltrates as the dry-weather flow of rivers, and V = vaporization, the fraction of wetting returned to the atmosphere as water vapor. Deep percolation, i.e., the portion of wetting not contributing to either baseflow or vaporization, is a very small fraction of precipitation and is usually neglected on practical grounds.

Vaporization, which comprises all moisture returned to the atmosphere, has two components:

$$V = E + T \tag{3}$$

in which E = nonproductive evaporation, and T = productive evaporation, i.e., that resulting from plant transpiration.

From Eqs. 1 to 3, runoff consists of two components;

$$R = S + U \qquad (4)$$

in which R = runoff. Likewise, precipitation consists of two components:

$$P = R + V \qquad (5)$$

Equations 1 to 5 constitute a set of water balance equations. Combining 4 and 5 leads to:

$$P = S + U + V \qquad (6)$$

that is, annual precipitation is separated into its three major components, surface runoff, baseflow, and vaporization.

Equations 2 and 5 enable the definition of water balance coefficients. The baseflow coefficient is (L'vovich 1979)

$$K_u = U/W = U/(U+V) \qquad (7)$$

the runoff coefficient is

$$K_r = R/P = R/(R+V) \qquad (8)$$

and the vaporization coefficient is

$$K_v = V/P = 1 - K_r \qquad (9)$$

The runoff gain is defined as the change in runoff coefficient per unit change of precipitation. In other words, it is the derivative of the runoff coefficient with respect to precipitation (Ponce and Shetty 1994). The runoff gain is

$$K_r' = dK_r/dP \qquad (10)$$

The baseflow gain is defined as the change in baseflow coefficient per unit change of precipitation. In other words, it is the derivative of the baseflow coefficient with respect to precipitation (Ponce and Shetty 1994). The baseflow gain is

$$K_u' = dK_u/dP \tag{11}$$

The vaporization loss is defined as the change in vaporization coefficient per unit change of precipitation. In other words, it is the derivative of the vaporization coefficient with respect to precipitation (Ponce and Shetty 1994). The vaporization loss is

$$K_v' = dK_v/dP = -K_r' \tag{12}$$

MODEL REVIEW

The conceptual model of water balance (L'vovich, 1979; Ponce and Shetty 1994) is suitable for wide range of climatic conditions. The model separates annual precipitation into its three major components: surface runoff, baseflow, and vaporization. It is based on the two-step sequential application of a proportional relation linking two variables such as precipitation and surface runoff, and wetting and baseflow.

The significant feature of the water balance equations, is that they all have the same structure, in which a quantity X is expressed as the sum of two components Y and Z:

$$X = Y + Z$$

L'vovich (1979) has shown that wetting reaches an upper bound asymptotically ($W \rightarrow Wp$) as precipitation and surface runoff increase unbounded($P \rightarrow \infty$; $S \rightarrow \infty$) and that vaporization reaches an upper bound asymptotically($V \rightarrow Vp$) as wetting and baseflow increase unbounded ($W \rightarrow \infty$; $U \rightarrow \infty$). In this way the sequential two-step separation of annual precipitation into its three major components (surface runoff, baseflow, and vaporization) can be accomplished.

In the present model, the proportional relation is defined as follows (Figure 1):

$$(X - \lambda Z_p - Y)/[(1 - \lambda)Z_p] = Y/(X - \lambda Z_p) \quad (13)$$

For the special case of zero initial abstraction ($\lambda = 0$), equation 13 reduces to:

$$(X - Y)/Z_p = Y/X \quad (14)$$

Solving equation 13 for $Y = f(X)$ leads to :

$$Y = (X - \lambda Z_p)^2/[X + (1 - 2\lambda)Z_p] \quad (15)$$

subject to $X \geq \lambda Z_p$; and $Y = 0$ otherwise.

Using equation 15, the surface runoff submodel is:

$$S = (P - \lambda_s W_p)^2 /[P + (1 - 2\lambda_s)W_p] \quad (16)$$

Subject to $P \geq \lambda_s W_p$, and $S = 0$ otherwise, with λ_s = surface runoff initial abstraction coefficient.

Then:

$$W = P - S \quad (17)$$

Likewise, the baseflow submodel is:

$$U = (W - \lambda_u V_p)^2 /[W + (1 - 2\lambda_u)V_p] \quad (18)$$

Subject to $W \geq \lambda_u V_p$, and $U = 0$ otherwise, with λ_u = baseflow initial abstraction coefficient.

For a given annual precipitation P, a set of surface flow and base flow initial abstraction coefficients, and wetting and vaporization potentials are used to separate P into surface runoff S, baseflow U, and vaporization V. The runoff, baseflow, surface runoff, wetting, vaporization, runoff coefficients, baseflow coefficients, baseflow gain and runoff gain can be simulated by the model.

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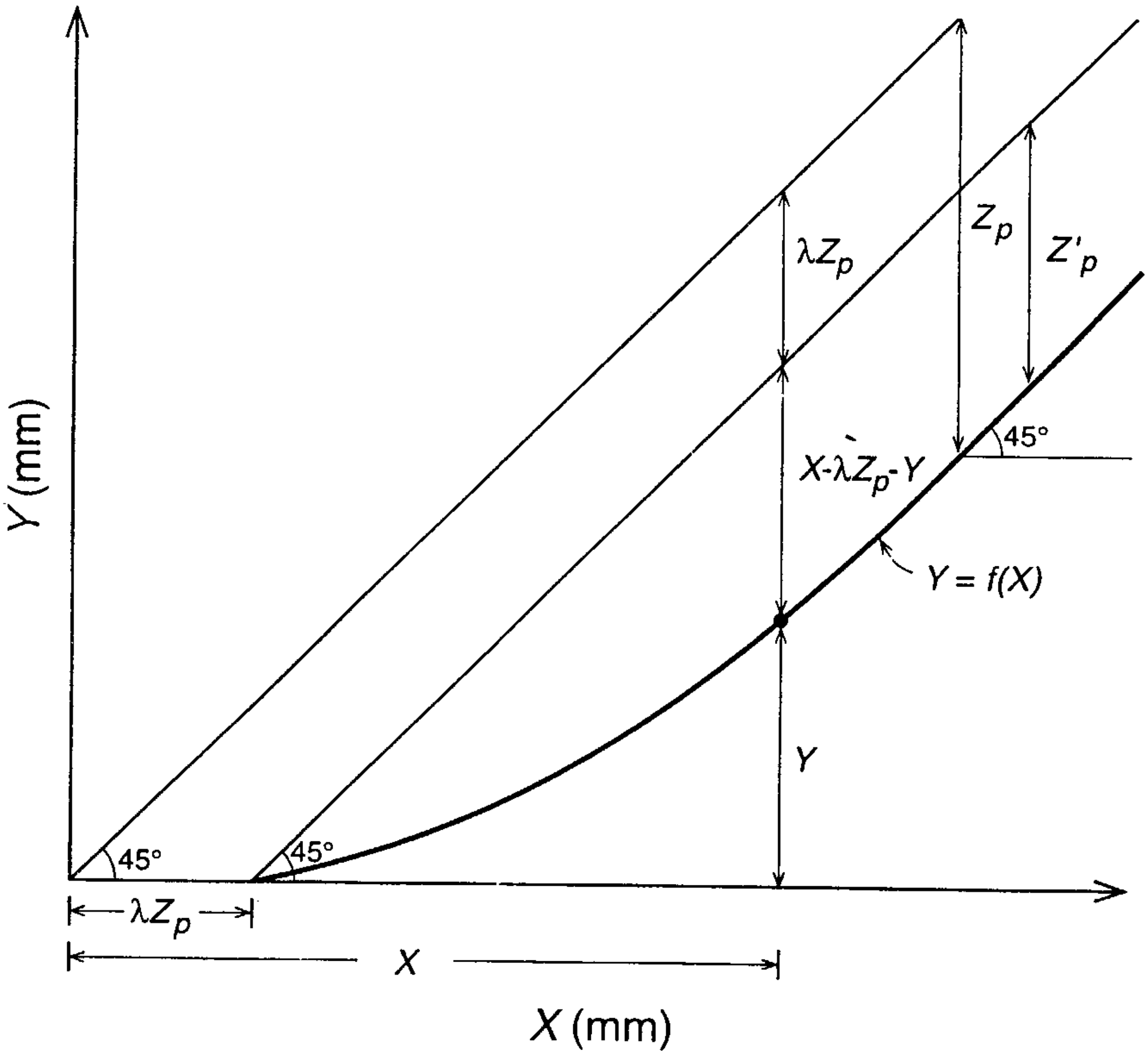


Fig. 1: DEFINITION SKETCH FOR INITIAL ABSTRACTION COEFFICIENTS AND POTENTIAL Zp.

Malaprabha river basin upstream of Khanapur, Karnataka. Malaprabha river basin is seasonally humid (monsoon driven), receives rainfall only from June to October. The wetting and vaporization potentials, and surface runoff and baseflow initial abstraction coefficients have been calibrated using the conceptual model of catchment water balance.

DESCRIPTION OF THE STUDY AREA

The Malaprabha basin upstream of Khanapur located in the Western Ghat and sub-basin of Krishna River as shown in Figure 2.

The Malaprabha originates from Kanakumbi in the Western Ghat at an altitude of about 793 m and 16 km west of Jamboti in the Belgaum district of Karnataka state. The river flows first in on easterly and then in a northerly direction and joins the Krishna river at an elevation of about 488 m and about 300 km from its source. The total catchment area of Malaprabha basin is 11,549 square kilometers. In the present study, the basin upstream of Khanapur has been considered with an catchment area 520 square kilometers. It is a principal source of supply from Ghat section of the basin.

The location of the catchment area lies between 74° E and 75° E longitude and around 16° latitude along the border of Karnataka and Maharashtra.

The Malaprabha basin has four distinct season in the year, such as cold weather, the hot weather and the southwest monsoon and postmonsoon.

The red, black and laterite soils are the principal soils found in the study area.

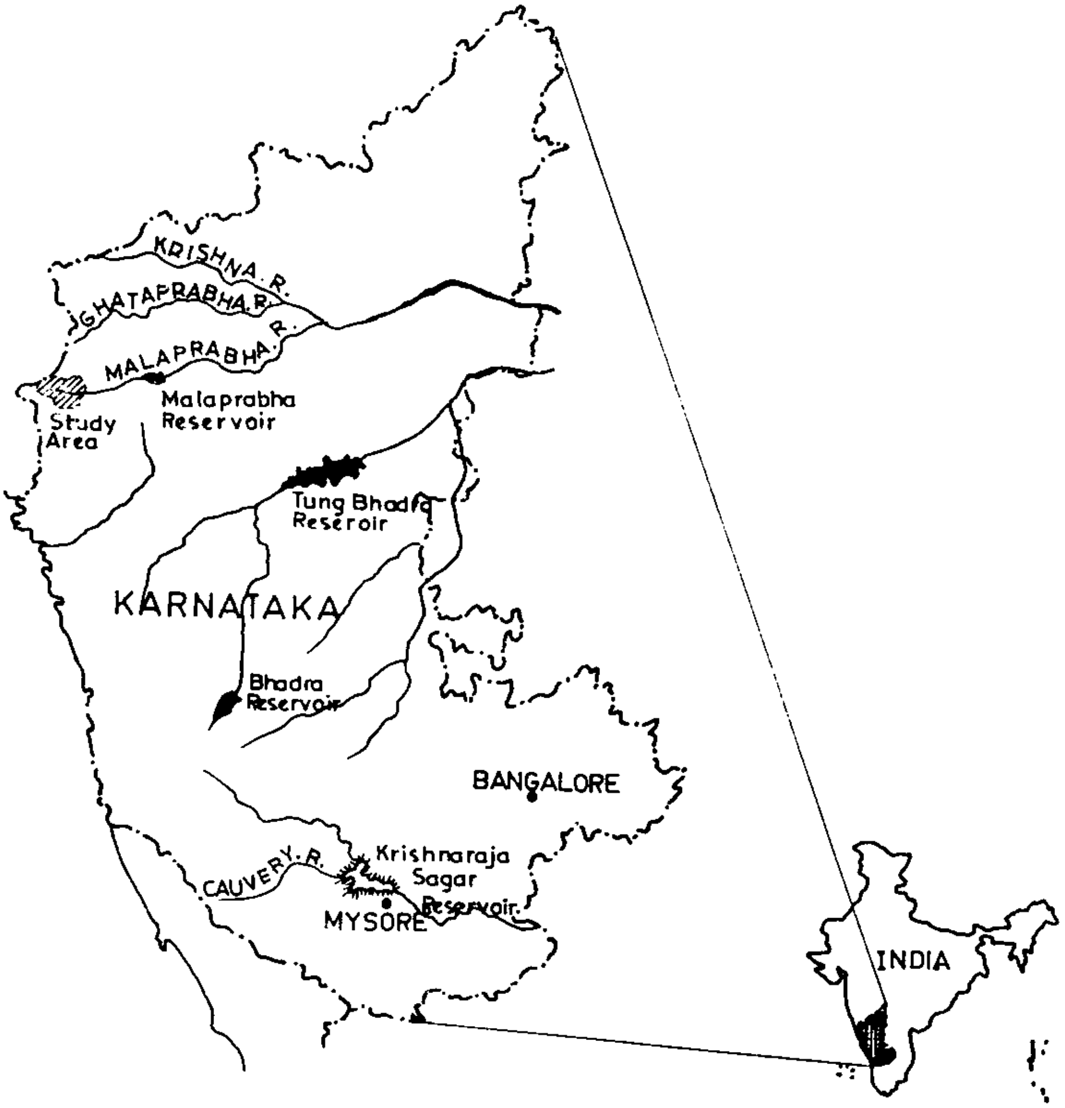


FIG. 2: LOCATION MAP OF MALAPRABHA BASIN.

APPLICATION OF THE MODEL

The catchment water balance model has been applied to separate the precipitation into wetting and surface runoff, and wetting into vaporization and baseflow. The model parameters were determined using measured monthly rainfall at Kanakumbi, Jamboti and Khanapur and daily discharge at Khanapur. The location of raingauge stations and discharge gauging point are shown in Figure 3.

RAINFALL

The variation of rainfall is found to be very much significant in the study area. Therefore, measured point rainfall of raingauge stations at Kanakumbi, Jamboti and Khanapur have been considered for the period of 11 years (1980-1990). The rainfall data of Jamboti is missing for five years. The missing rainfall data of Jamboti has been generated by correlating monthly data of the Khanapur raingauge station. Using the Thiessen polygon method, monthly and yearly rainfall has been calculated for the study area. The mean annual rainfall during the study period is found to be between 2000 mm and 3500 mm. The mean annual rainfall for the study period is shown in Figure 4.

DISCHARGE

The daily discharge at Khanapur has been taken for this study for the period from 1980 to 1990. The daily discharge is shown in Figure 5. Yearly runoff has been calculated by integrating the daily hydrograph over a year.

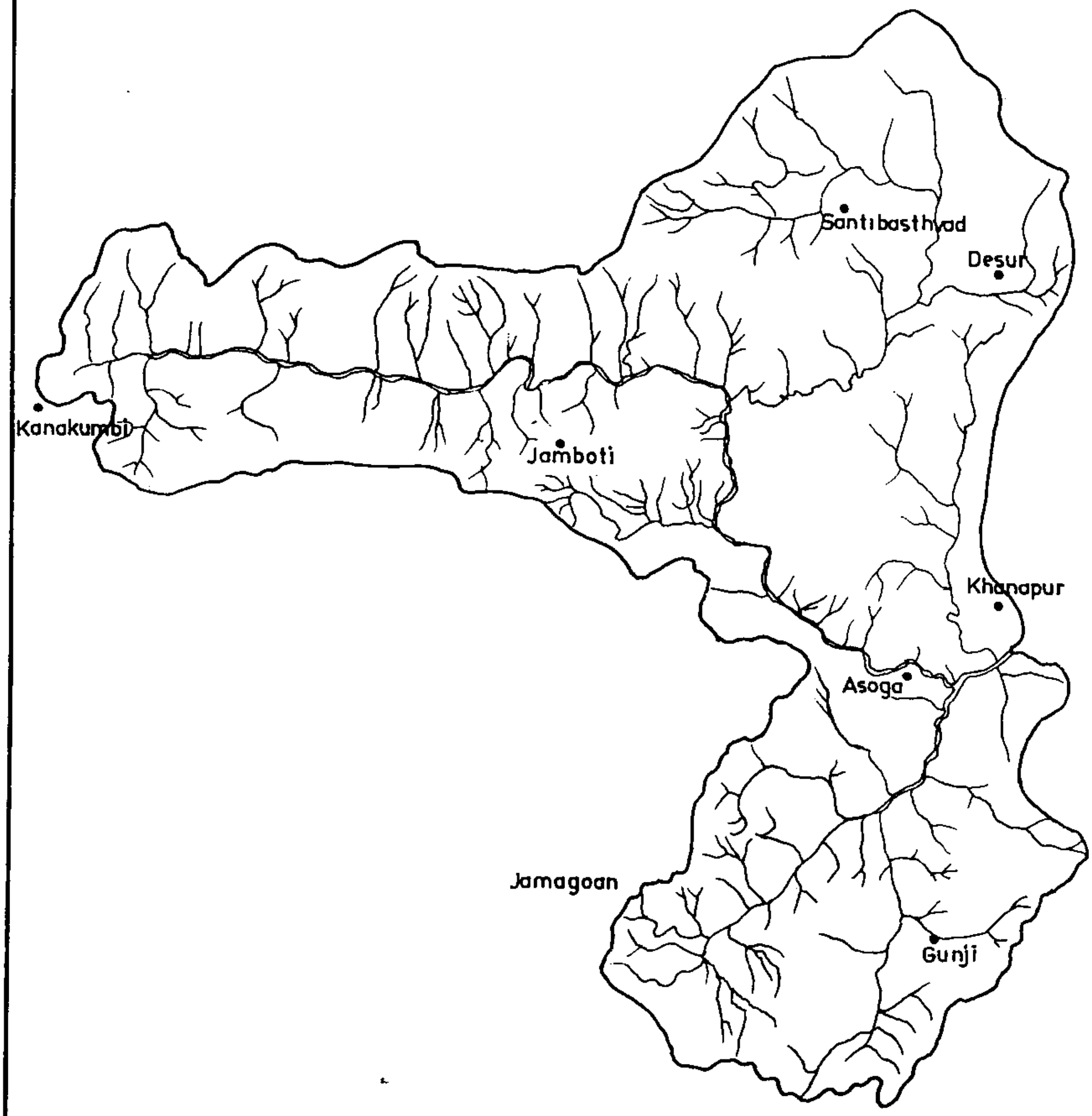
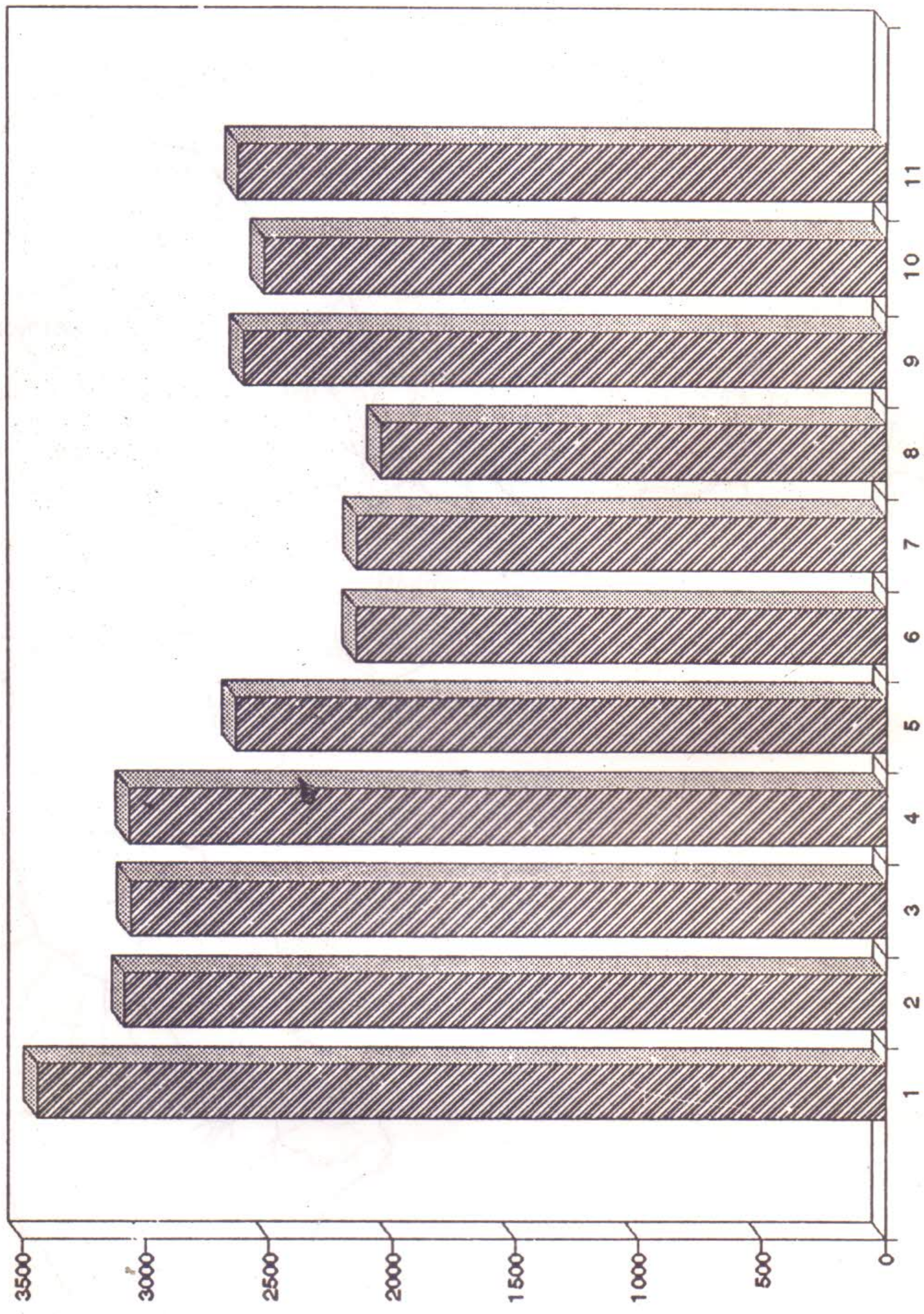


FIG. 3: LOCATION OF RAINGAUGE STATION WITH DRAINAGE SYSTEM.

FIGURE 4: Mean Annual Rainfall
1980-1990



SEPARATION OF BASEFLOW

The daily hydrograph is drawn based on the daily discharge data obtained at Khanapur. The baseflow separation line has been drawn as shown in Figure 5. The area under these curves has been integrated to find out the volume of the baseflow. Consequently, surface runoff, wetting and vaporization have been calculated using catchment water balance equations 1 to 6, and tabulated in Table 1 for 11 years.

The proportional curve has been fitted for (1) precipitation and surface runoff, and (2) wetting and baseflow based on the observed data as shown in Figures 6a and 6b. A set of paired values of surface runoff and precipitation, and wetting and baseflow has been obtained from the fitted proportional curve for the calibration of the model parameters.

CALIBRATION OF THE MODEL

In order to calibrate the initial abstraction coefficient of surface flow λ_s and baseflow λ_u, and potentials of wetting W_p and vaporization V_p of the study area, the observed data has been used to fit the proportional curves for precipitation and surface runoff, and wetting and baseflow. A set of paired values of precipitation and surface runoff, and wetting and baseflow has been derived from the fitted proportional curves respectively to calibrate the parameters.

Step 1: Initially λ_s is chosen as zero for the set of paired values of precipitation and surface runoff.

Step 2: Use the equation $W_p = (P/S)(P-S)$ to find out the wetting

TABLE 1: OBSERVED DATA SET

YEAR	ANNUAL RAINFALL	SURFACE RUNOFF	WETTING	BASEFLOW	ANNUAL RUNOFF
	IN MM	IN MM	IN MM	IN MM	IN MM
1980	3436	1348	2265	859	2207
1981	3085	1146	1939	591	1737
1982	3060	1272	1788	465	1737
1983	3066	989	2077	743	1732
1984	2635	674	1961	666	1340
1985	2148	608	1540	393	1001
1986	2148	687	1454	382	1069
1987	2041	504	1536	399	904
1988	2598	950	1648	697	1648
1989	2515	659	1856	592	1250
1990	2622	921	1701	570	1491

FIGURE 5: DAILY HYDROGRAPH
YEAR 1980

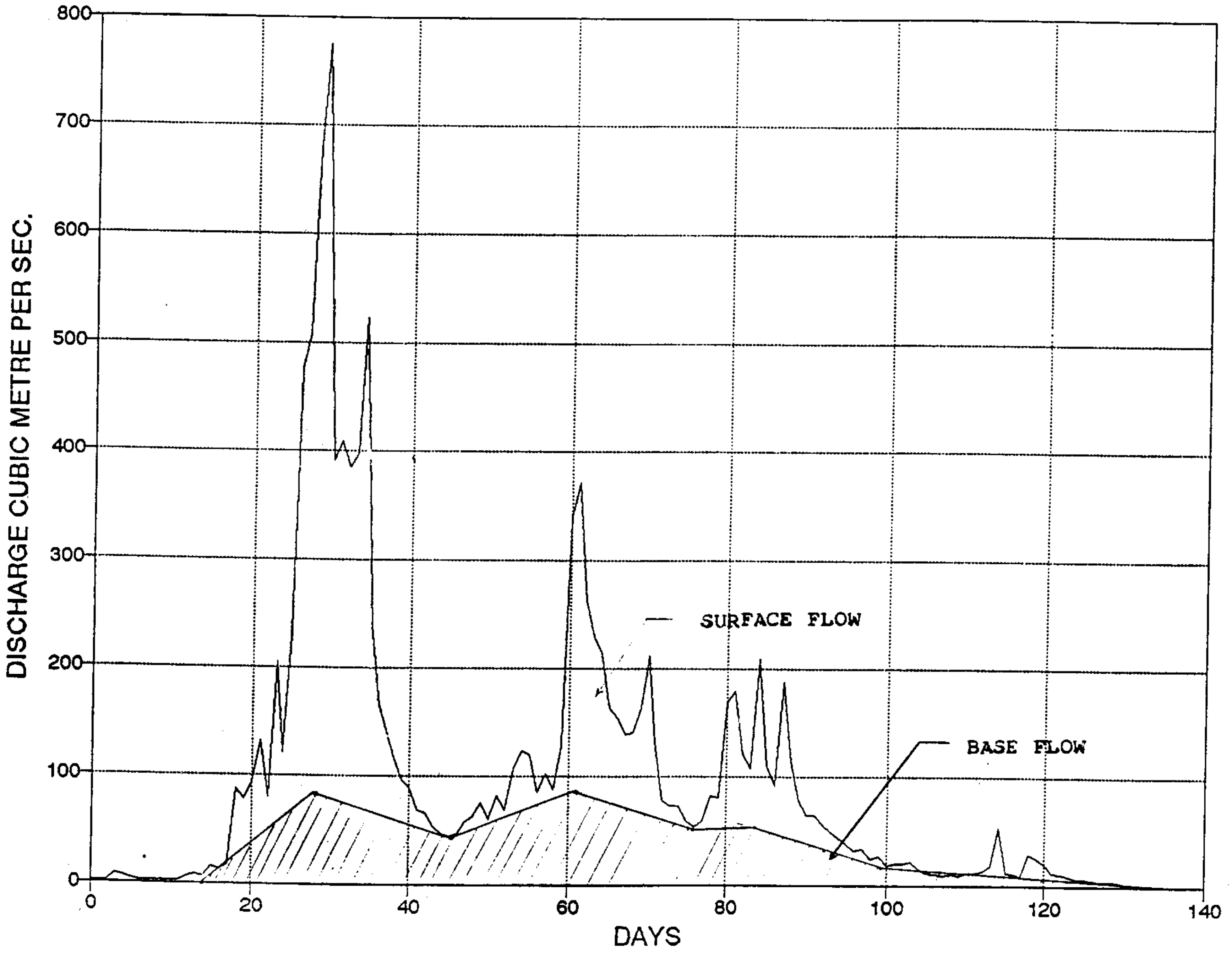


FIGURE 5: DAILY HYDROGRAPH
YEAR 1981

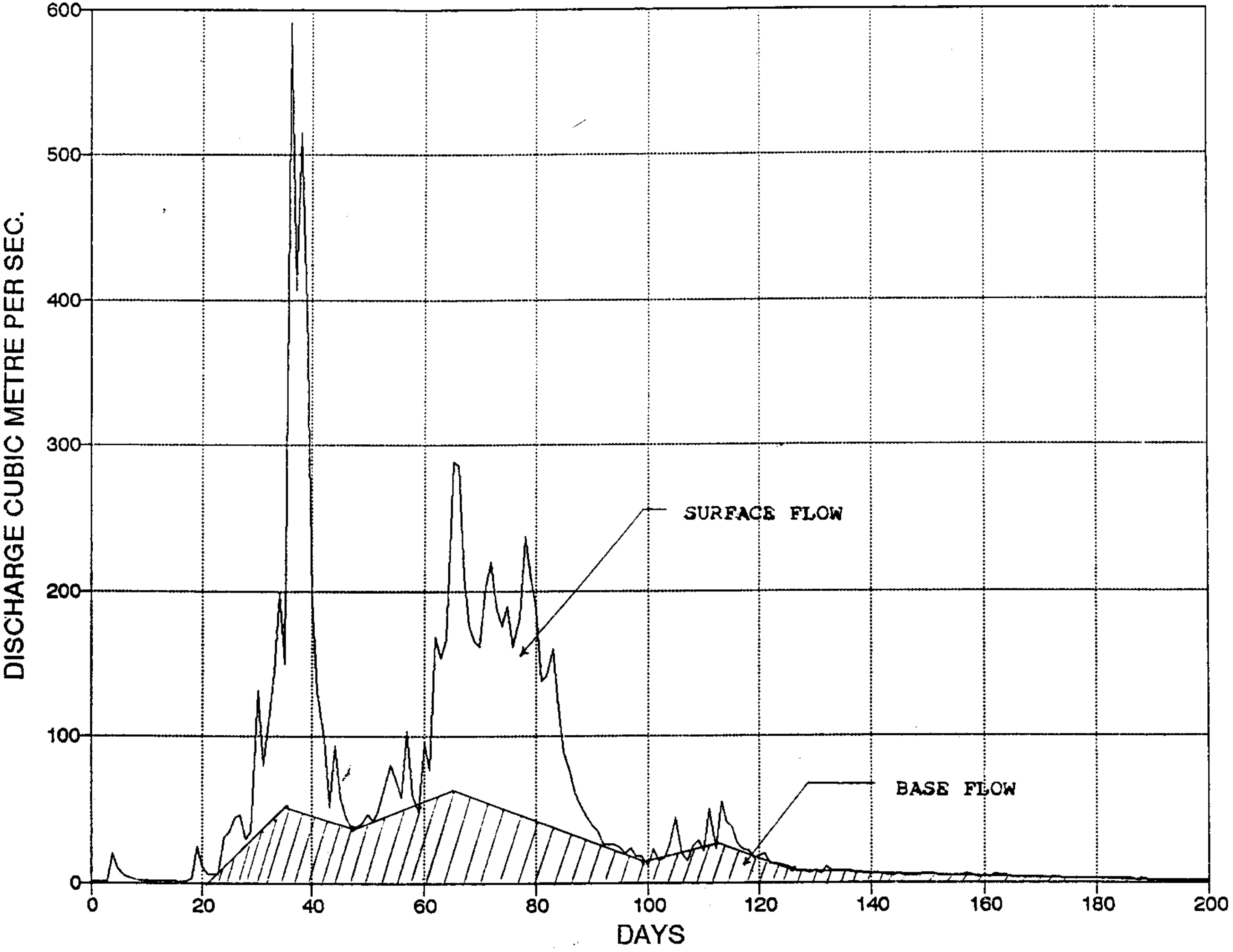


FIGURE 5: DAILY HYDROGRAPH
YEAR 1982

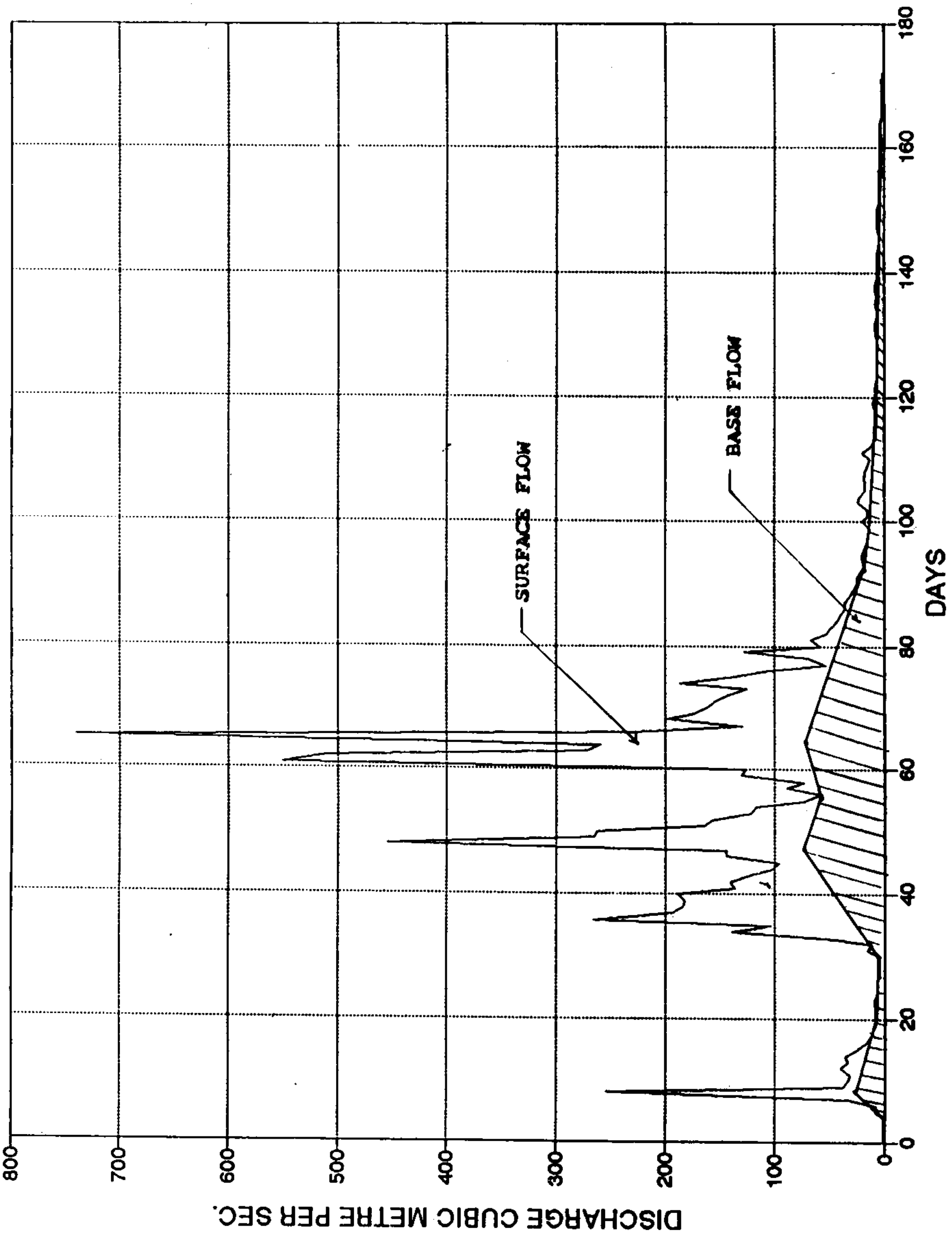


FIGURE 5: DAILY HYDROGRAPH
YEAR 1983

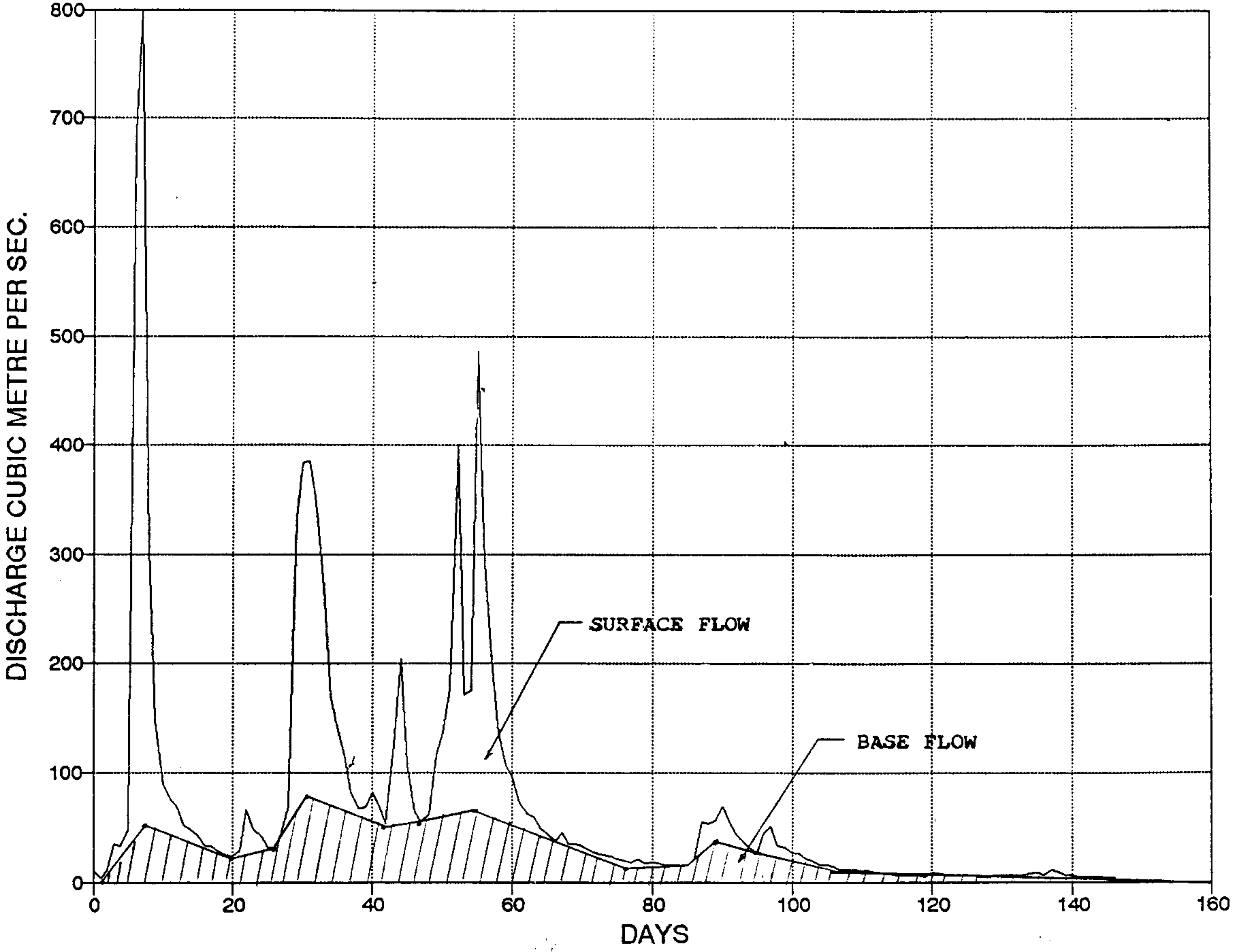


FIGURE 5: DAILY HYDROGRAPH
YEAR 1984

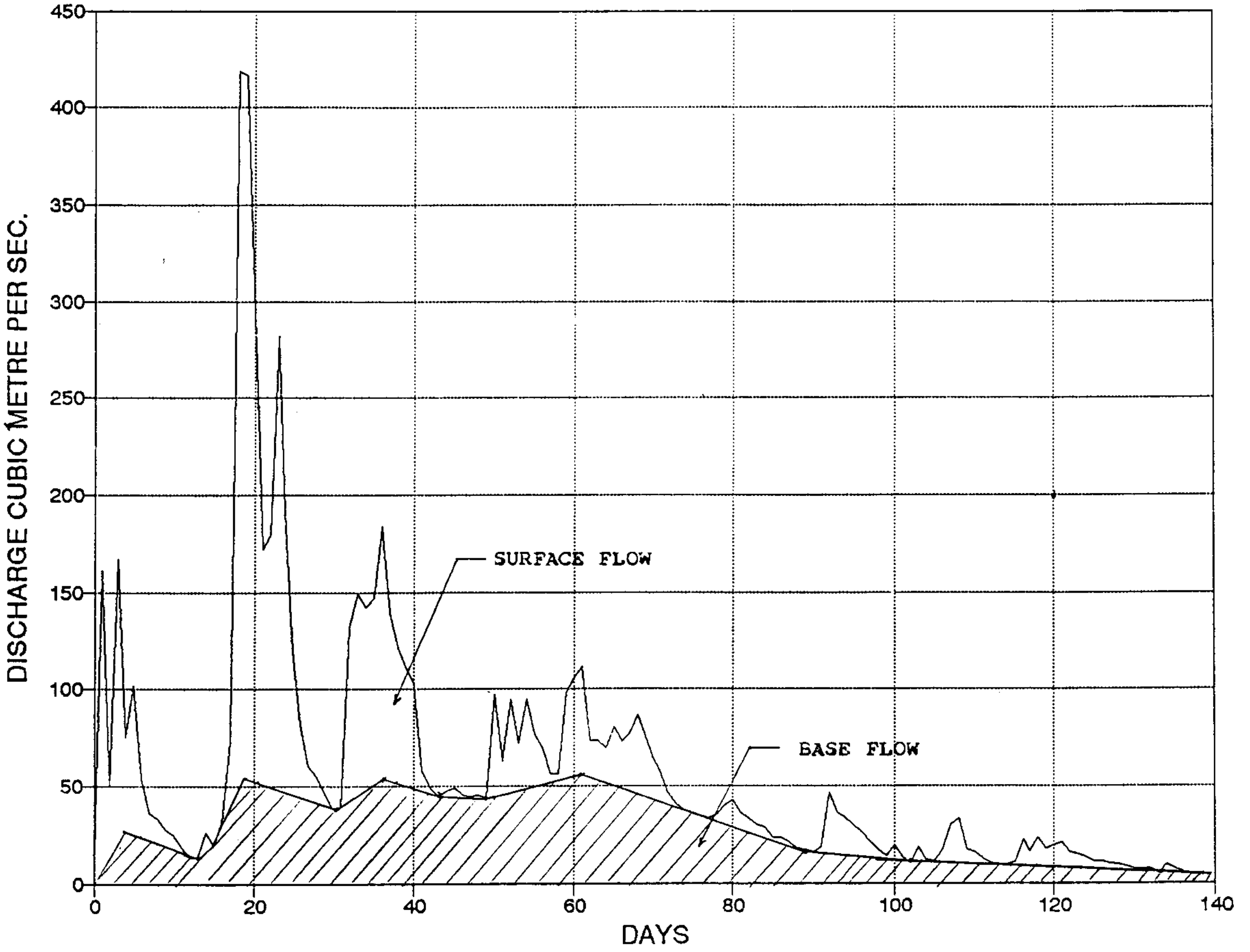


FIGURE 5: DAILY HYDROGRAPH
YEAR 1985

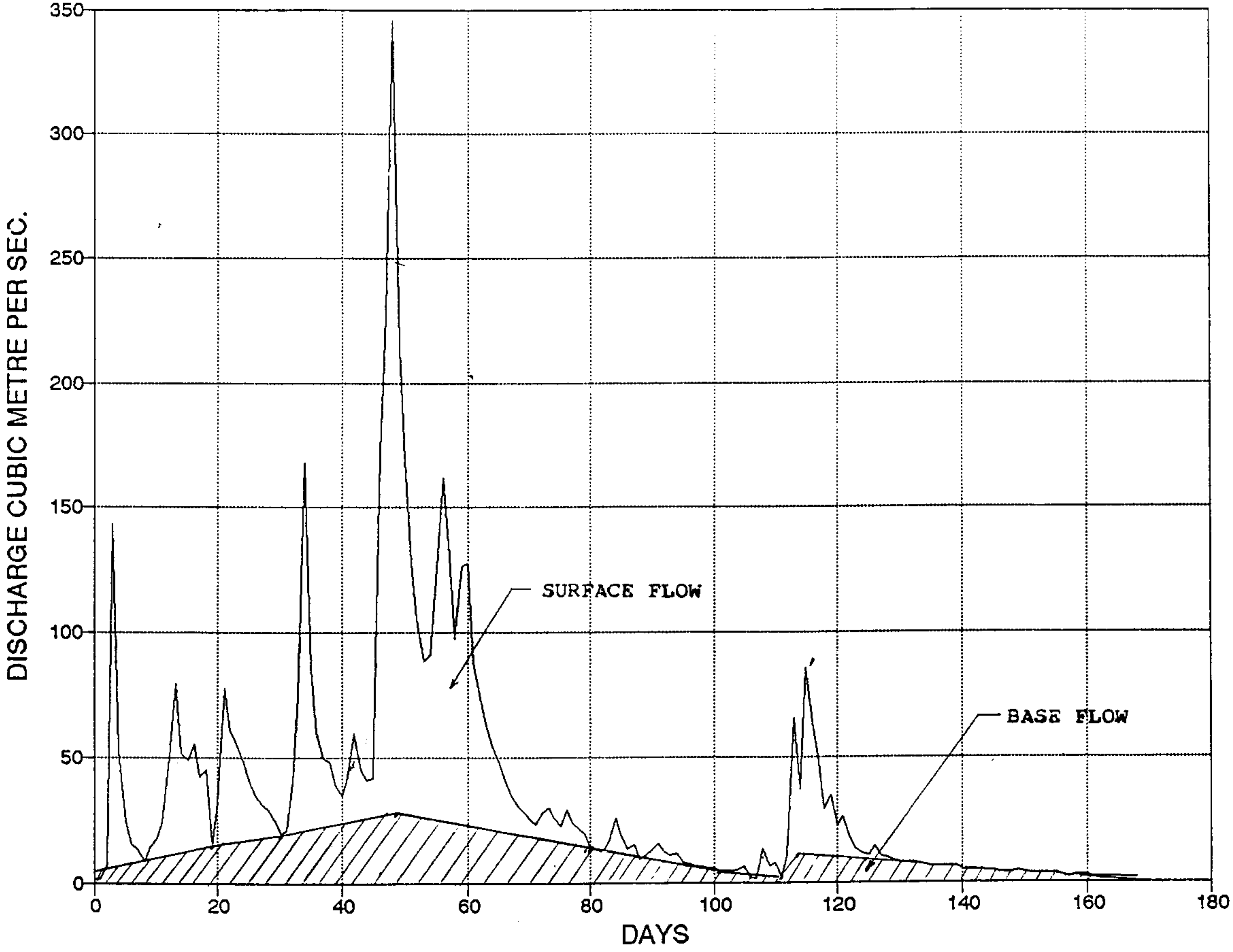


FIGURE 5: DAILY HYDROGRAPH
YEAR 1986

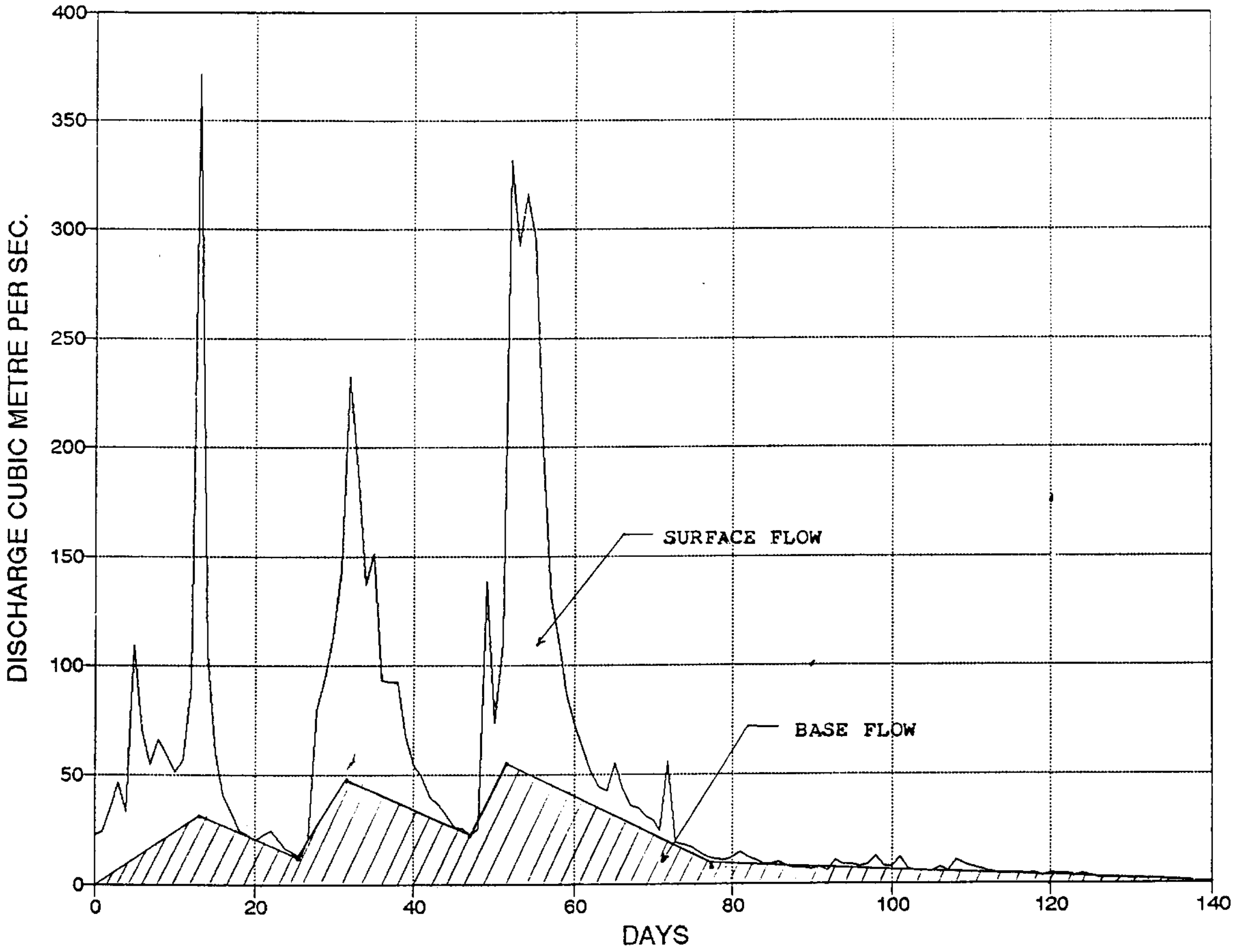


FIGURE 5: DAILY HYDROGRAPH
YEAR 1987

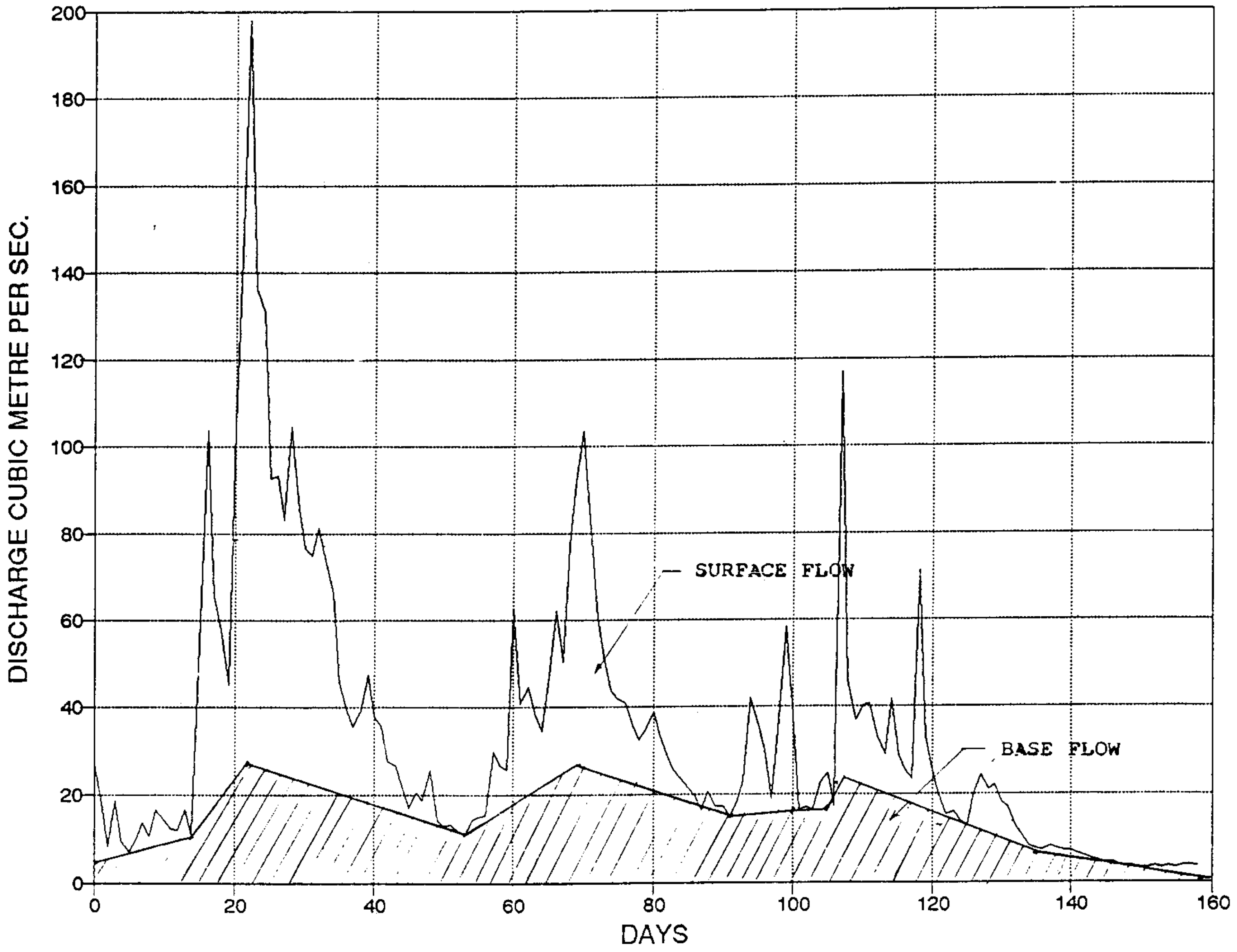


FIGURE 5: DAILY HYDROGRAPH
YEAR 1988

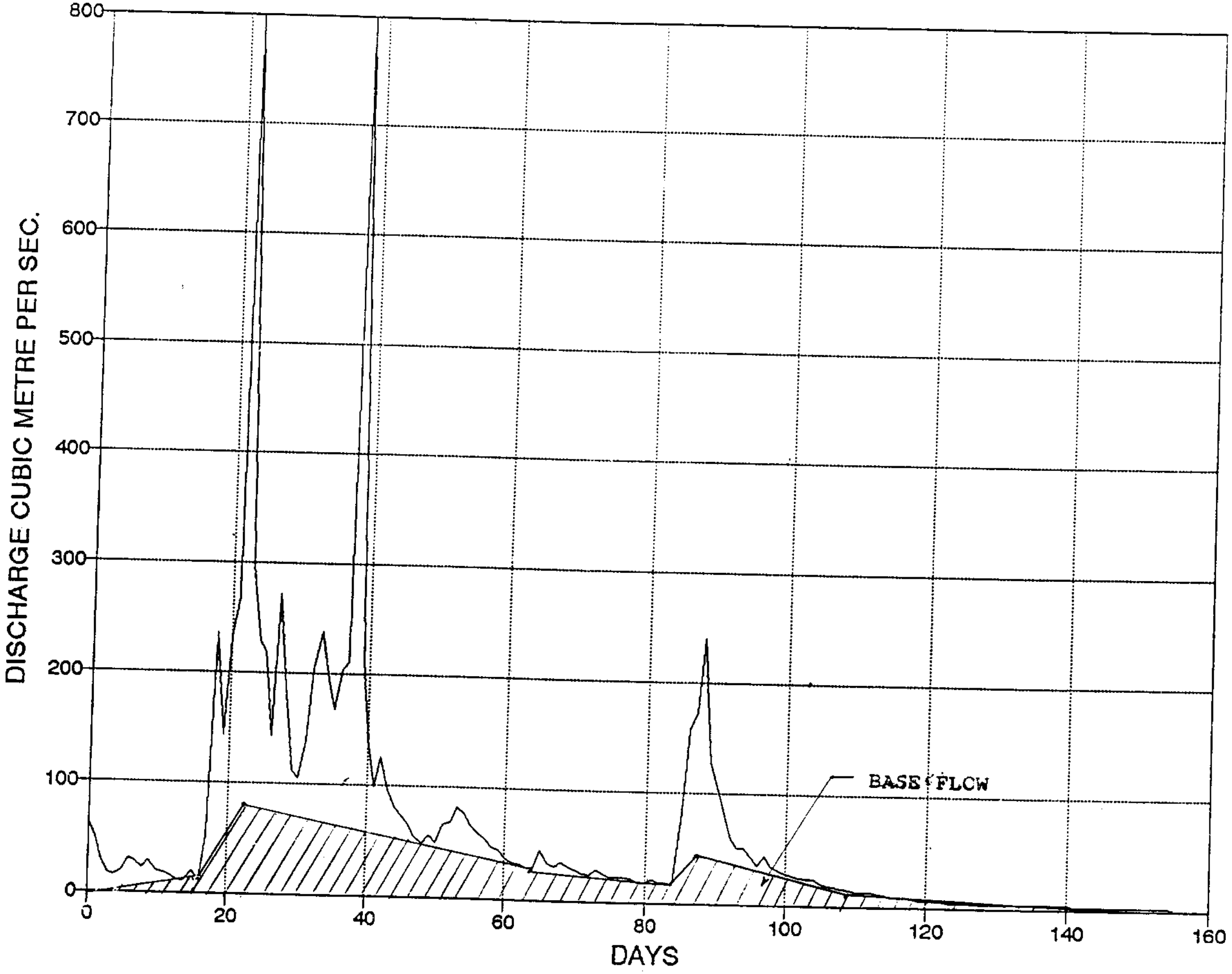


FIGURE 5: DAILY HYDROGRAPH
YEAR 1989

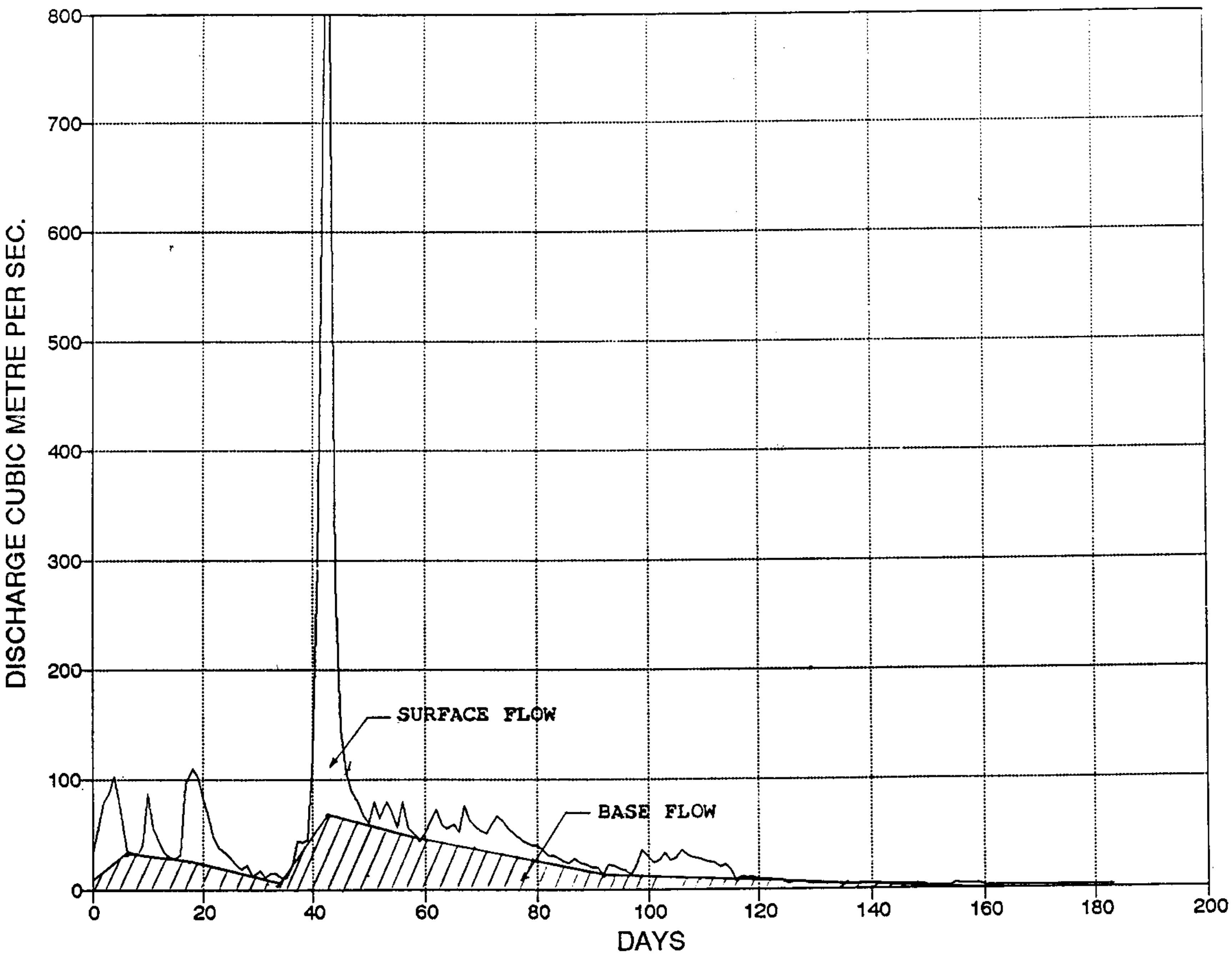
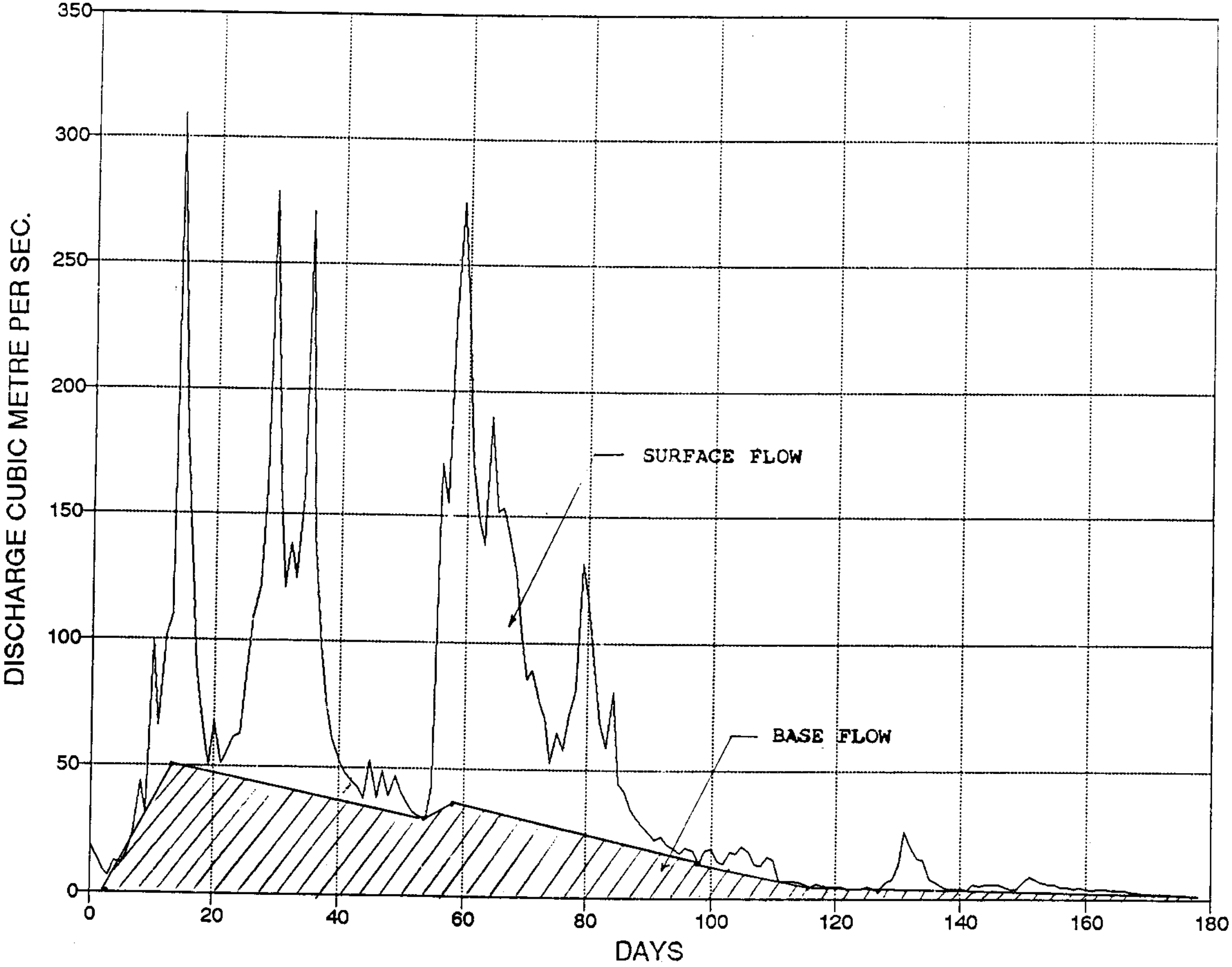


FIGURE 5: DAILY HYDROGRAPH
YEAR 1990



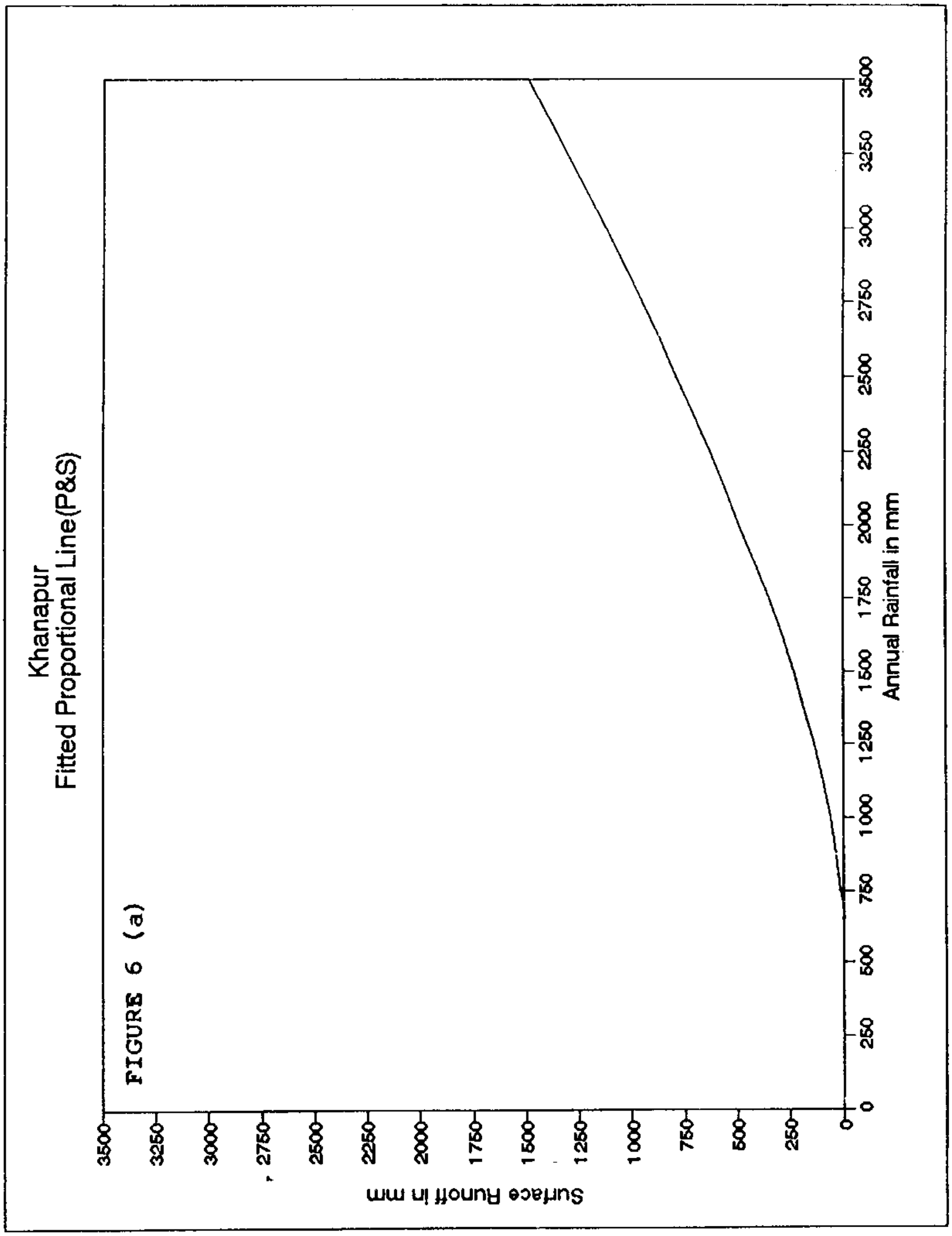
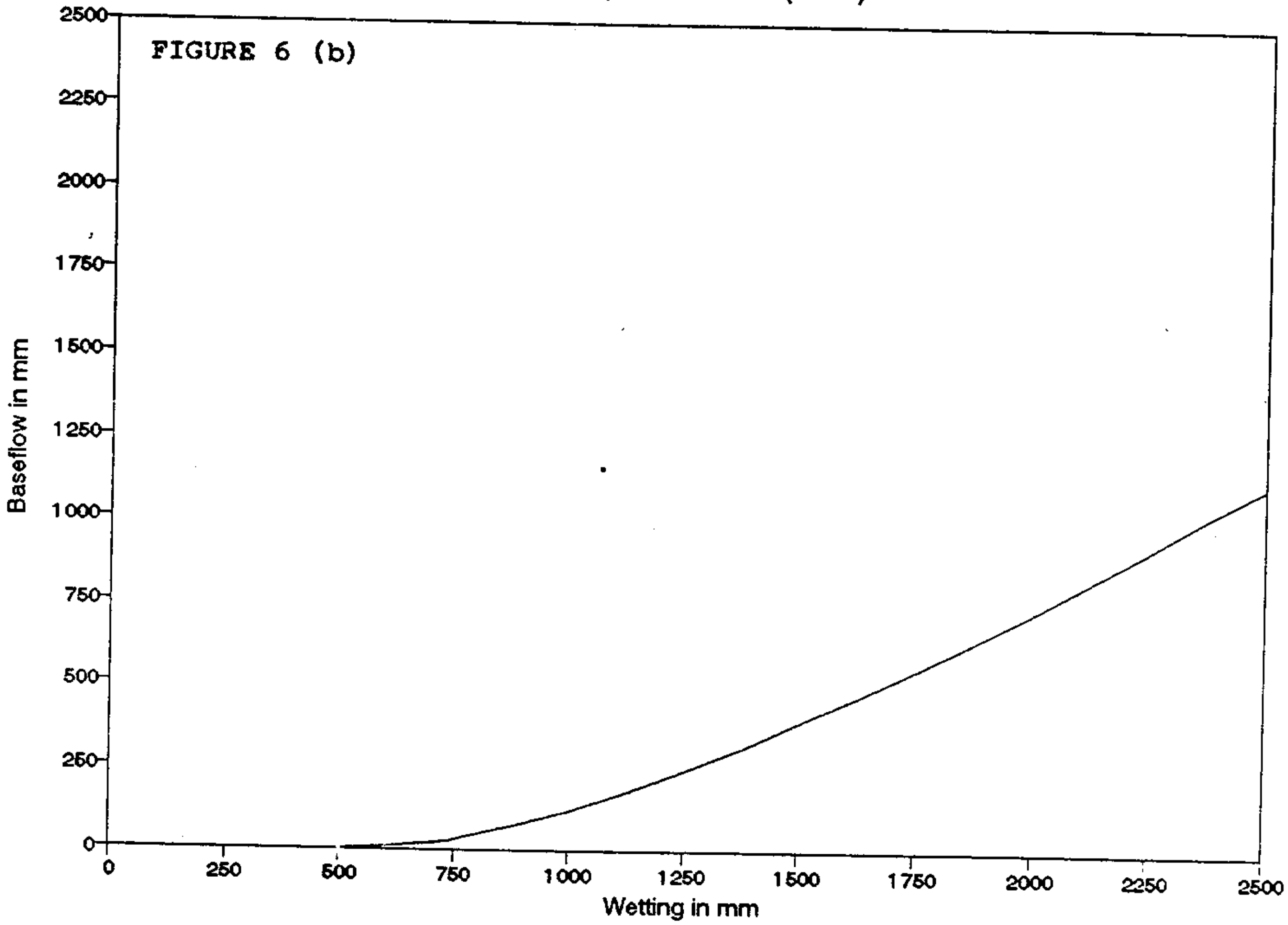


FIGURE 6 (a)

Khanapur
Fitted Proportional Line(P&S)

Khanapur
Fitted Proportional Line(W&U)



potential values.

Step 3: Increase λ_s by 0.01 and calculate array of wetting potential using the equation:

$Wp = 1/\lambda_s(\{P+[(1/2\lambda_s)][(1-2\lambda_s)^2\ S^2 + 4\lambda_s(1-\lambda_s)PS]^{1/2}\})$ and

Step 4: Calculate the mean, standard deviation, and coefficient of variation of the estimated array of wetting potential values.

Step 5: Go back to step 3, repeat the computation for the new value of λ_s until the coefficient of variation of the array of wetting potential is a minimum. The original fitted proportional curve may be readjusted to get a minimum standard deviation of the calculated array of wetting potential.

Step 6: Choose parameter values W_p and λ_s. W_p is the mean value of the calculated wetting potential with value of λ_s for which coefficient of variation and standard deviation is a minimum.

The same steps are followed to calibrate the vaporization potential and baseflow initial abstraction coefficient.

A computer programme has been developed for the calibration of the model parameters, to simulate surface runoff, total runoff, baseflow, wetting, runoff and baseflow coefficients and its gains.

RESULTS AND DISCUSSION

The conceptual water balance model has been used to calibrate the parameters such as wetting potential, initial abstraction coefficient of surface flow, vaporization potential and initial abstraction coefficient of baseflow. The calibrated parameters are given below:

Wetting potential W_p = 3440 mm

Initial abstraction coefficient of surface flow $\lambda_s = 0.16$

Vaporization potential V_p = 2085 mm

Initial abstraction coefficient of base flow $\lambda_u = 0.24$

The annual total runoff, surface runoff, baseflow and wetting has been generated using calibrated parameters with variation of annual precipitation and presented in Figures 7 to 10.

Figure 11 shows runoff and baseflow coefficients for the study area with the variation of annual precipitation.

Figure 12 and 13 shows the runoff gain and baseflow gain with respect to the change in annual precipitation.

The mean annual precipitation P_a, runoff threshold precipitation P_{rt}, P_{rt}/P_a ratio, and peak runoff gain K_{rp}' for the study area as follows,

P_a = 3000 mm

P_{rt} = 900 mm

$P_{rt}/P_a = 0.3$

$K_{rp}' = 0.000390$

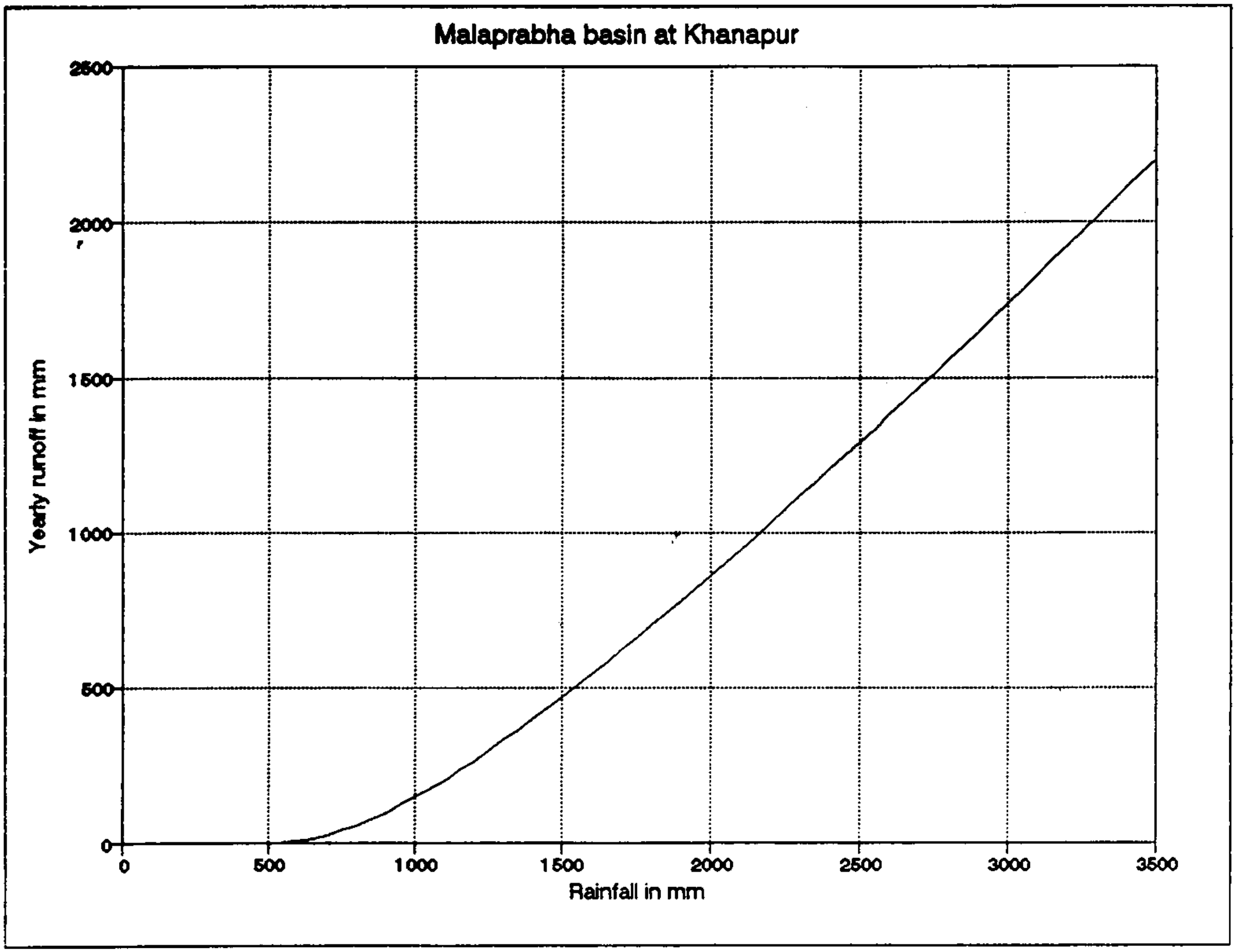


FIGURE 7: VARIATION OF TOTAL RUNOFF WITH ANNUAL RAINFALL

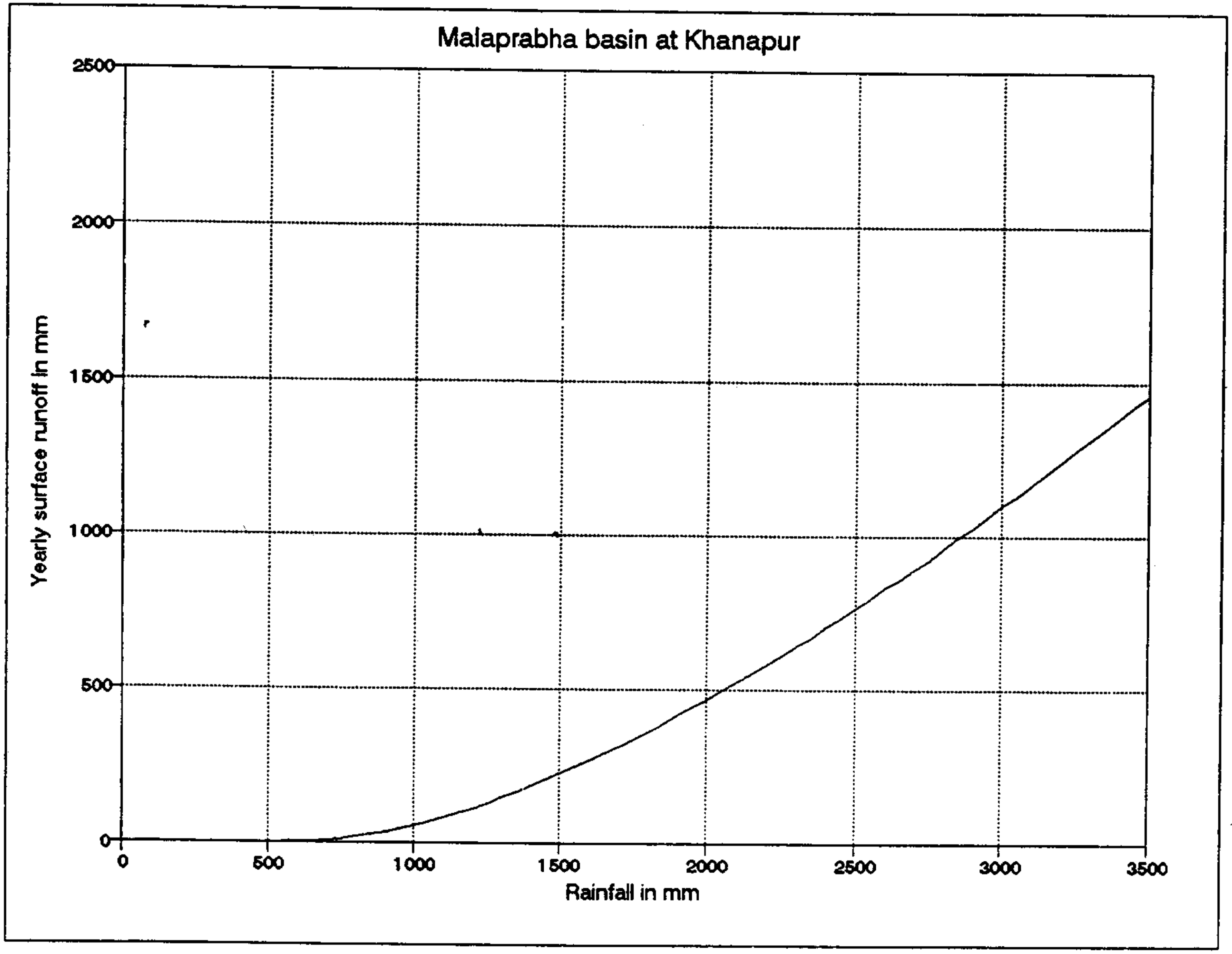


FIGURE 8: VARIATION OF SURFACE RUNOFF WITH ANNUAL RAINFALL.

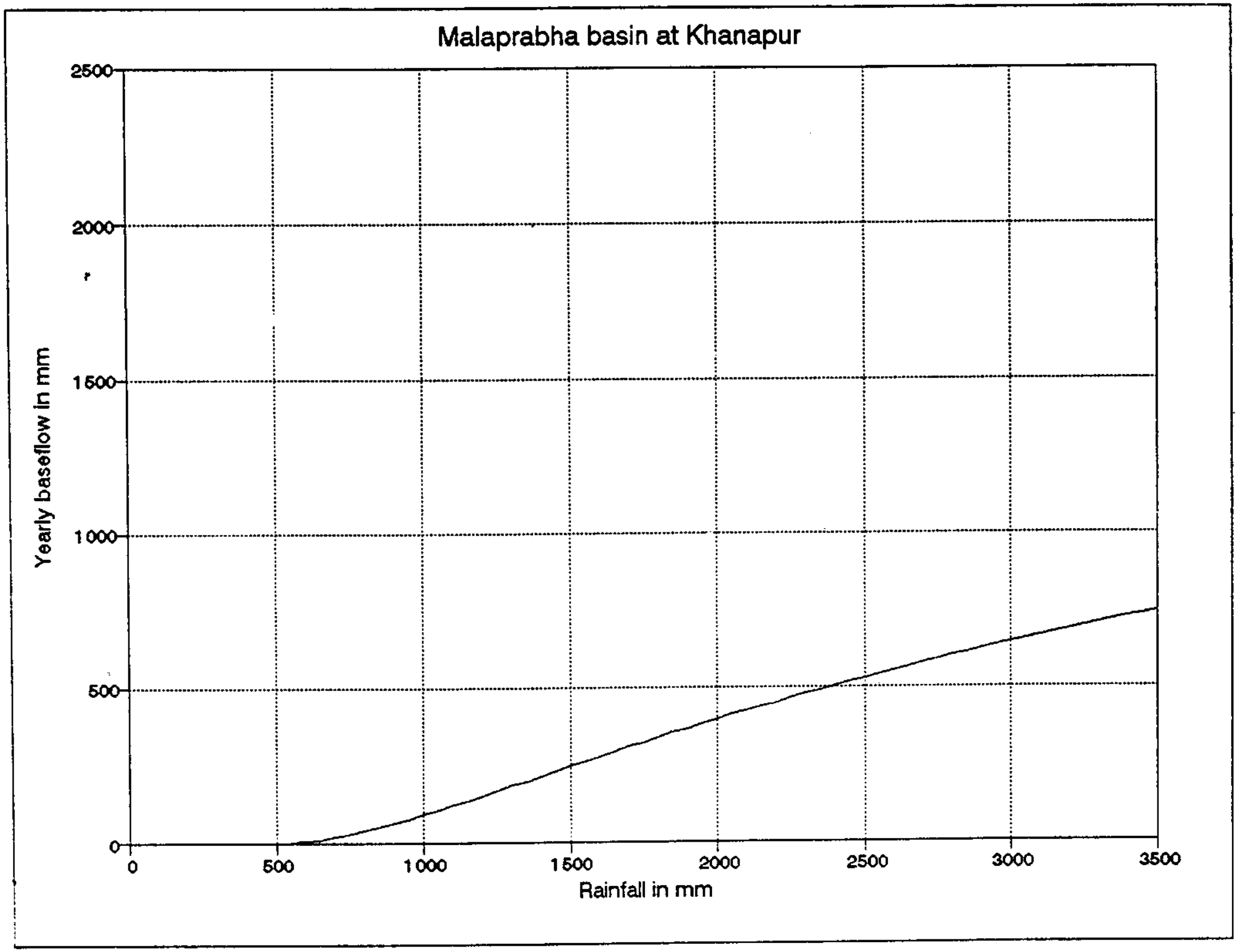


FIGURE 9: VARIATION OF BASEFLOW WITH ANNUAL RAINFALL.

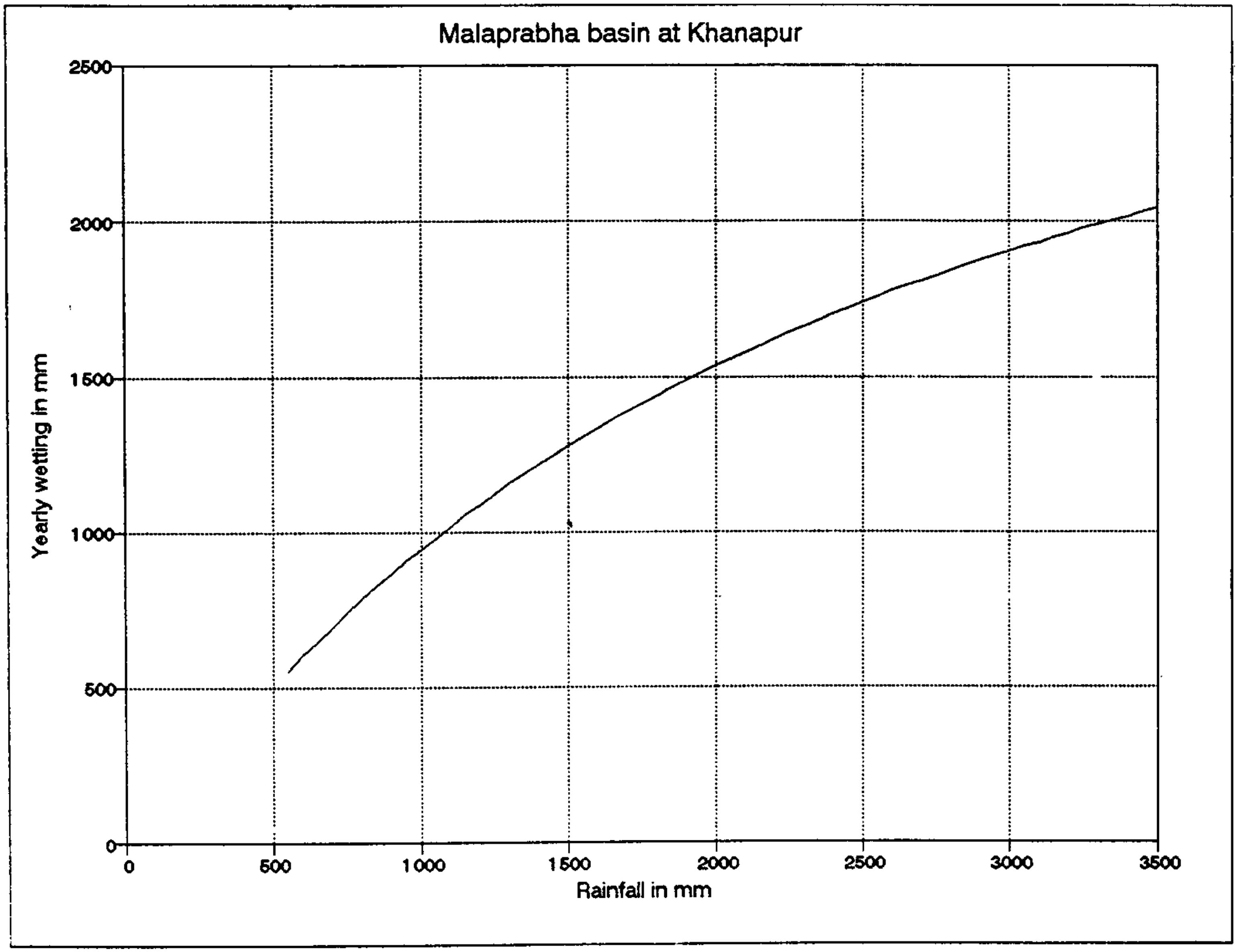


FIGURE 10: VARIATION OF WETTING WITH ANNUAL RAINFALL.

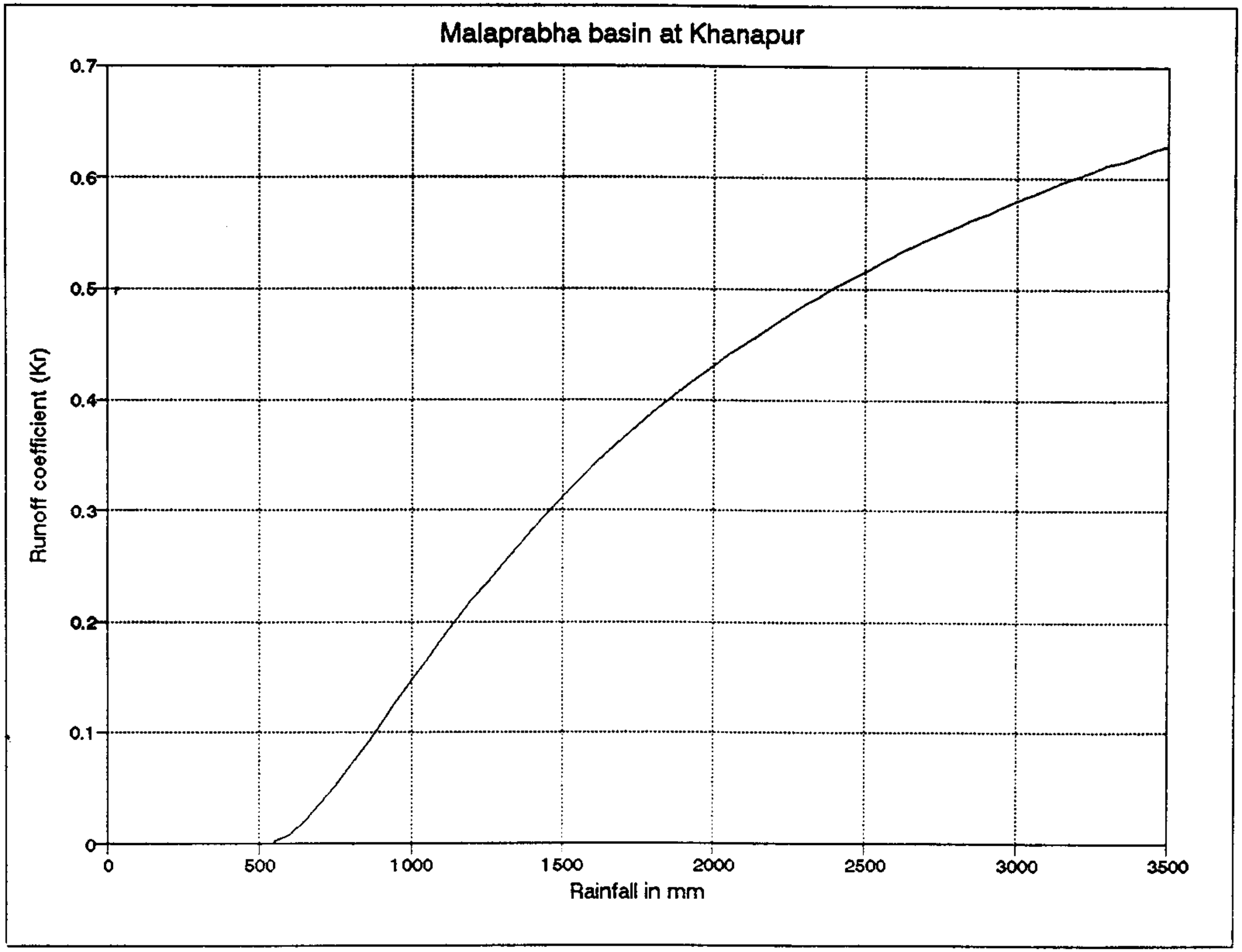


FIGURE 11 (a): RUNOFF AND BASEFLOW COEFFICIENTS WITH RAINFALL.

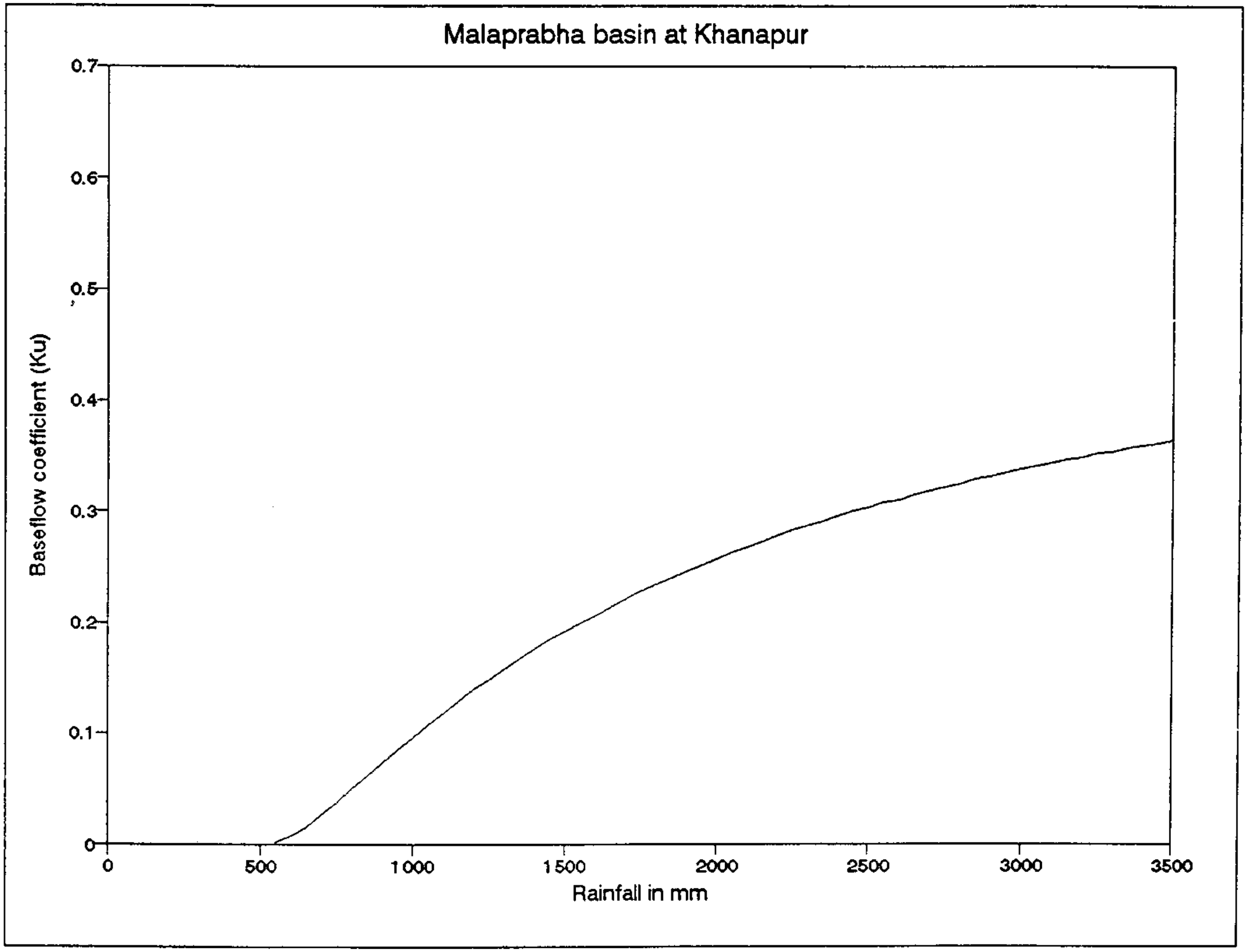


FIGURE 11 (b): BASEFLOW COEFF. WITH ANNUAL RAINFALL.

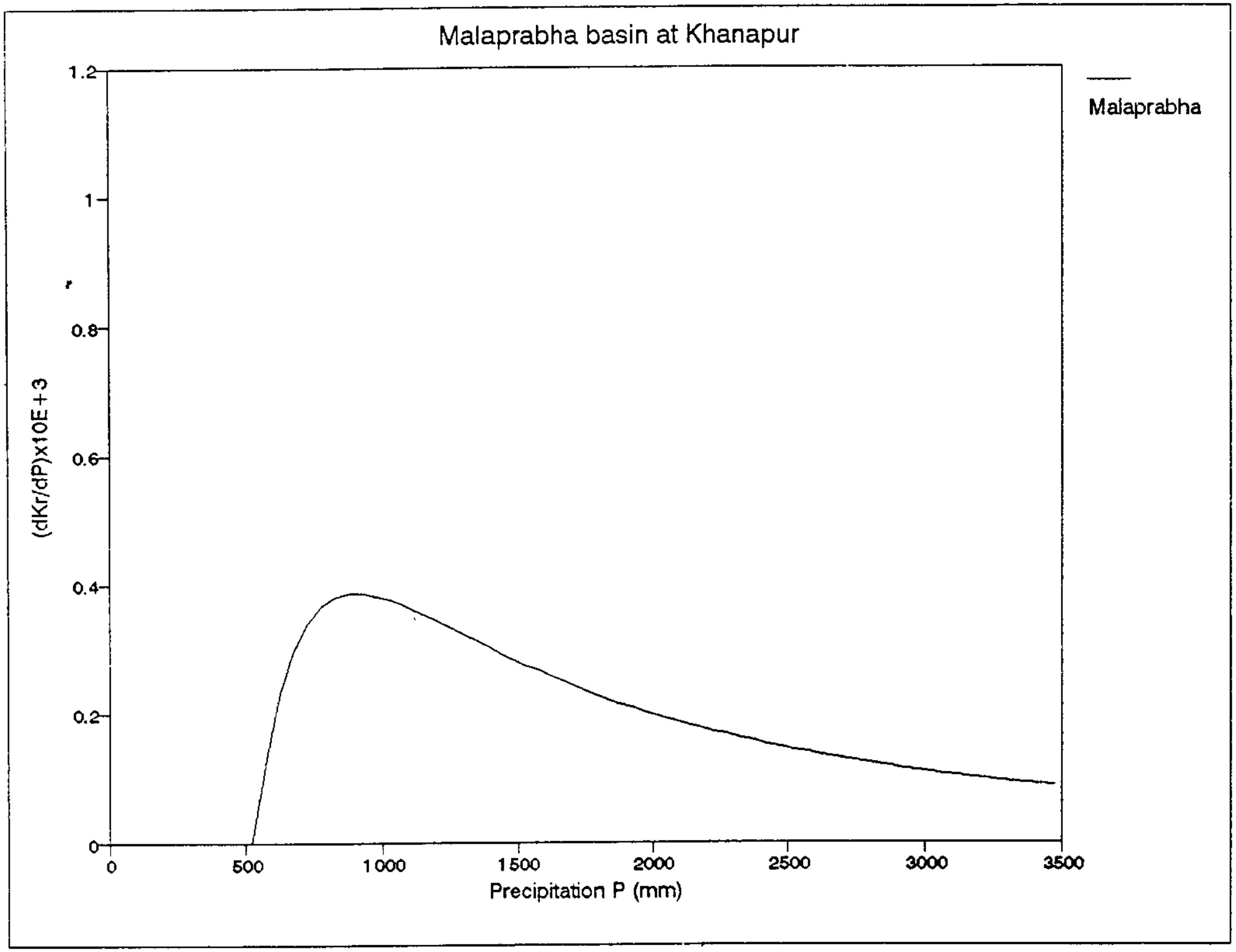


FIGURE 12: RUNOFF GAIN WITH ANNUAL RAINFALL.

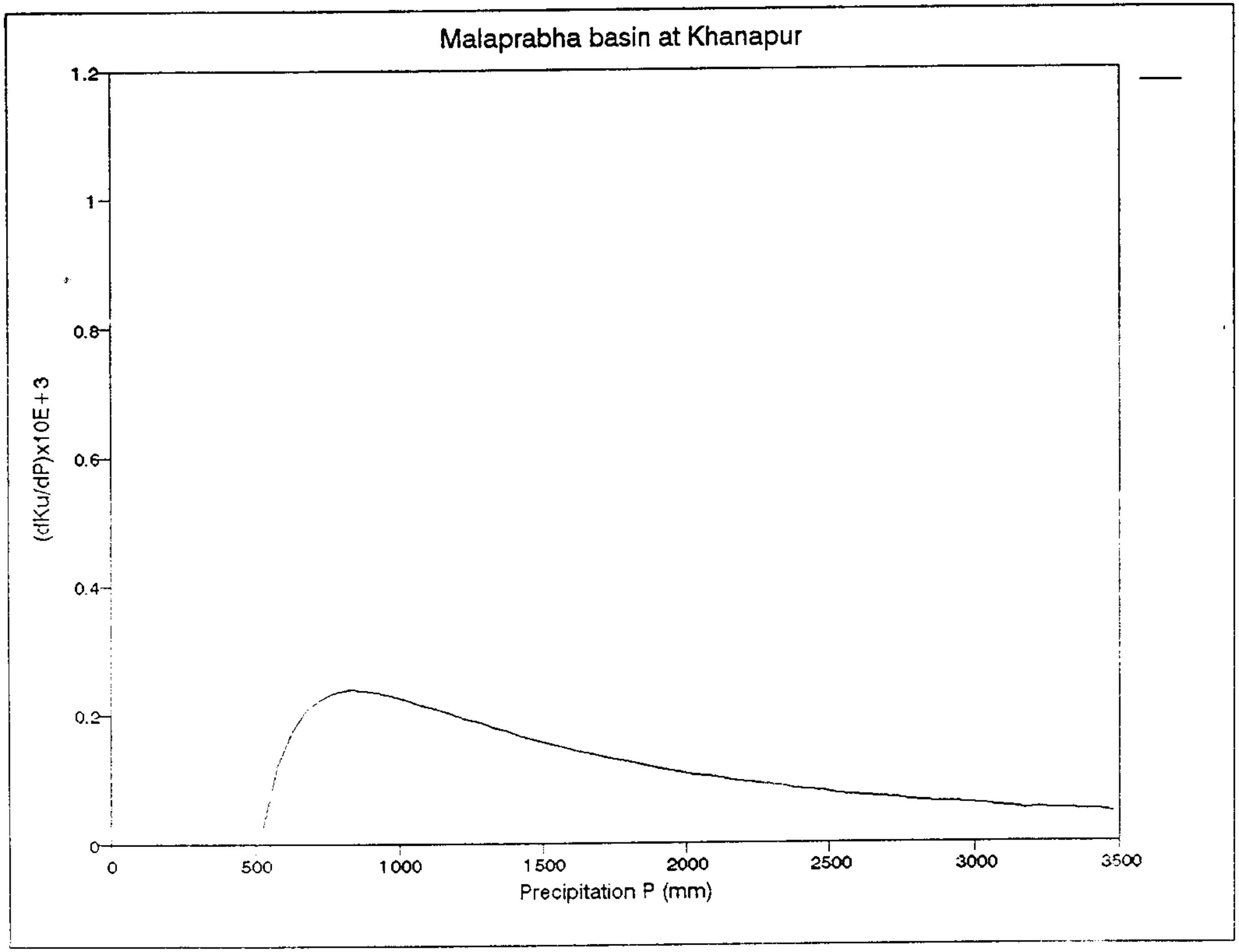


FIGURE 13: BASEFLOW GAIN WITH ANNUAL RAINFALL.

The mean annual precipitation P_a, baseflow threshold coefficient P_{ut}, ratio of P_{ut}/P_a and peak baseflow gain K_{up}' for the study area is given below,

P_a = 3000 mm

P_{ut} = 850 mm

P_{ut}/P_a = 0.28

K_{up}' = 0.000239

Figure 14 shows the simulated and observed annual runoff of the study area for 1980-1990.

DISCUSSION

Runoff and baseflow coefficient increase monotonically with annual precipitation starting from zero.

The runoff and baseflow coefficients increases markedly in the midrange of annual precipitation and also have the tendency to reach an upper bound for high values of annual precipitation.

Runoff and baseflow gains are always positive. Runoff gain reaches a peak K_{rp}' for the threshold precipitation P_{rt}. Likewise, baseflow gain reaches a peak K_{up}' for threshold precipitation P_{ut}.

The vaporization loss is equal and opposite to the runoff gain. Since runoff gains are always positive, it follows that vaporization losses always negative.

The ratio P_{rt}/P_a = 0.29 is less than 0.4 and belongs to the category of seasonally humid , humid, and subarctic regions.

The ratio P_{ut}/P_a = 0.28, also less than 0.4 is grouped under seasonally humid, humid, and subarctic regions.

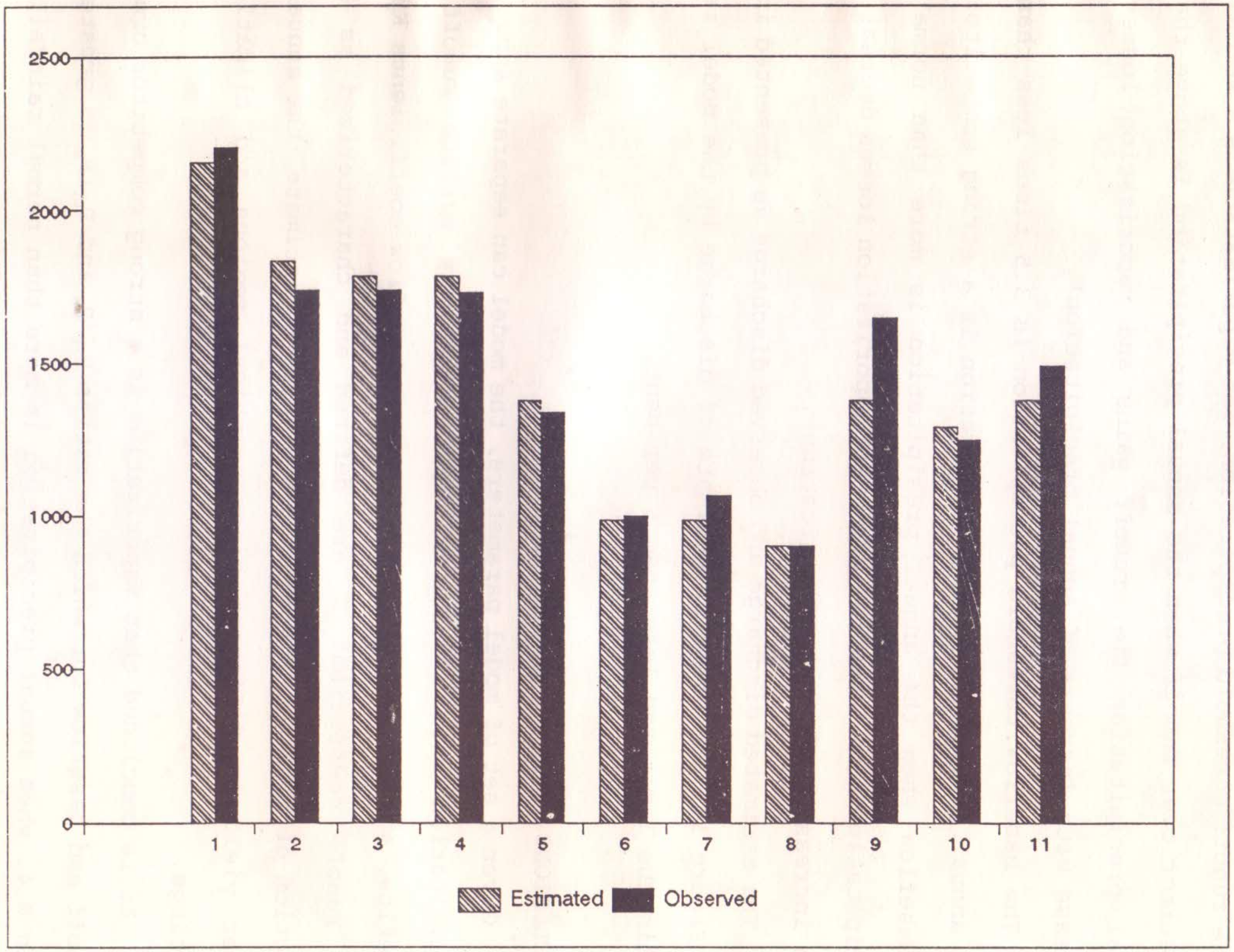


FIGURE 14: OBSERVED AND SIMULATED RUNOFF.

In this study area annual precipitation is more than 3.5 times of the runoff threshold precipitation. The vaporization is a strong competitor over runoff when the annual precipitation is above the normal precipitation (ie. runoff gains and vaporization losses decrease with increase of annual precipitation).

The baseflow threshold precipitation is 3.5 times less than mean annual precipitation and vaporization is a strong competitor of baseflow when the annual precipitation is more than normal precipitation (ie. baseflow gains and vaporization losses decrease with increase of annual precipitation).

The estimated discharge and observed discharge as presented in the Figure 14, the error of estimate of discharge by the model is within the limit and less than 6 per cent.

CONCLUSIONS

Given a set of model parameters, the model can separate annual precipitation into its three major components surface runoff, baseflow, and vaporization. Furthermore, baseflow coefficients K_u, and runoff coefficient K_r are defined and characterized as a function of climate. The model can be used to estimate the annual water yield in different biogeographical regions and climatic settings.

It is concluded that vaporization is a strong competitor over runoff and baseflow for which the ratios P_{rt}/P_a and P_{ut}/P_a is greater than 0.4, when annual precipitation is more than normal rainfall.

Substantial decrease in runoff and baseflow gains will occur as the wet side of mean annual precipitation (ie. P_{rt} or P_{ut} less than annual precipitation P) for the study area. In other words increase in runoff and baseflow gains will occur when P_{rt} or P_{ut} are greater than annual precipitation.

Additional research is needed to determine initial abstraction coefficients and potentials for a wide range of biogeographical regions.

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