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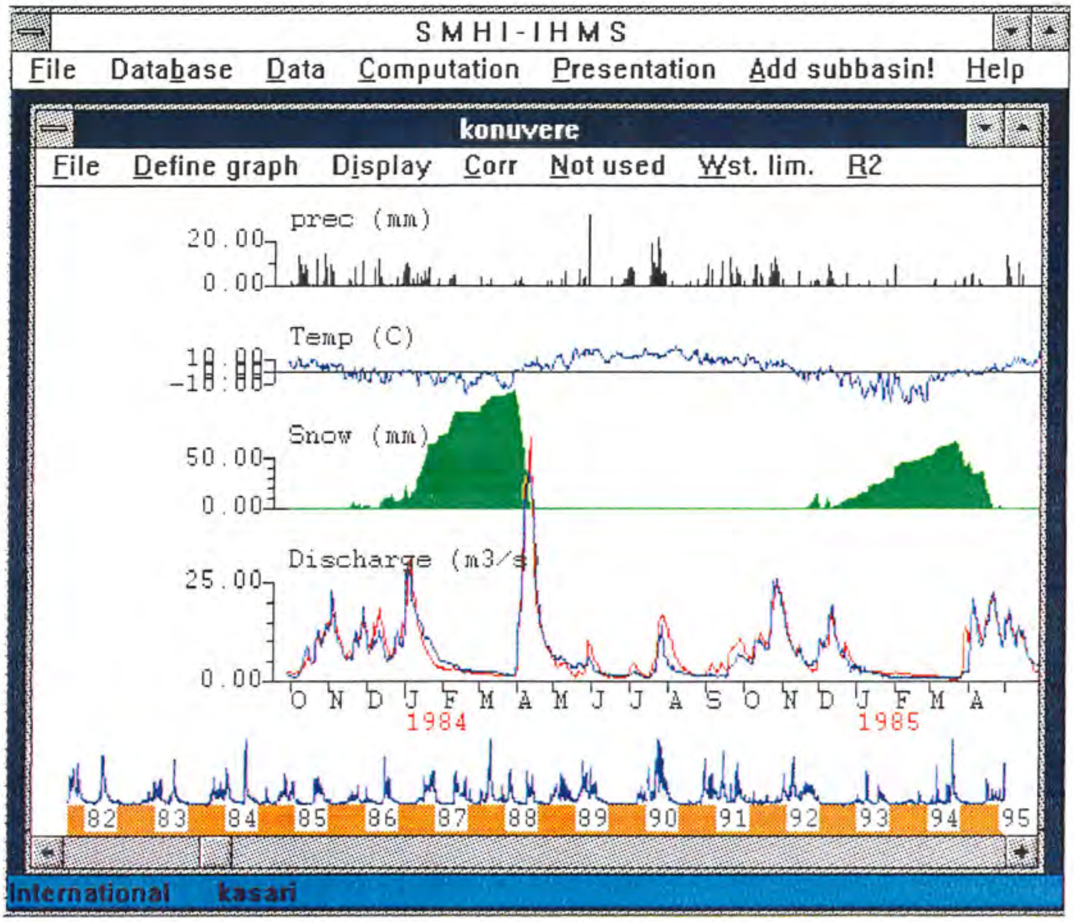

APPLICATION OF THE INTEGRATED HYDROLOGICAL MODELLING SYSTEM IHMS-HBV TO PILOT BASIN IN ESTONIA

SMHI EMHI

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APPLICATION OF THE INTEGRATED HYDROLOGICAL MODELLING SYSTEM IHMS-HBV TO PILOT BASIN IN ESTONIA

Final report

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CONTENTS

1. INTRODUCTION

1.1 General

This report describes calibration and application of the IHMS-HBV model on a daily time step to Kasari River basin in Estonia. The Swedish Meteorological and Hydrological Institute (SMHI) have as consultant been responsible for the set-up, calibration, training and delivery of the Integrated Hydrological Model System with the HBV-model (IHMS-HBV). The Swedish Board for Investment and Technical Support (BITS) financed the project. The training and transfer of technology were addressed to the Estonian Meteorological and Hydrological Institute (EMHI).

1.2 Background

Co-operation between the national hydrometeorological institutes in Estonia (EMHI) and Latvia (LHMA) and SMHI is ongoing. With financial support from BITS a management training course was carried out at SMHI during spring 1992 and in the beginning of 1993 the BALTMET project started up. The main objective of BALTMET was to give improved hydrometeorological servicies in the Baltic countries by making it possible for the institutes to give general weather forecasts and warnings using up to date technology.

Following the training course a three year co-operation agreement was signed and high priority project areas were listed. Among the problems facing EMHI and LHMA were at project start-up the need for a modern computer model for current water resources estimation, hydrological forecasts for hydropower operation, catchment water balance for the possibility of computing available water and water balance for ungauged basins and flood forecasts and warning.

1.3 Project objectives

The overall development objectives of the project is to support the water resources and environmental strategy planning in Estonia by strengthening the capacity of EMHI to undertake hydrological forecasts and evaluations.

The specific objectives are to transfer knowledge about the basic design, applications, performance and data requirements of operational hydrological models in use at SMHI and to calibrate and install the IHMS-HBV model to a pilot basin so that it can be used in operational work and adapted for relevant hydrological applications. The Kasari River basin was selected as pilot basin in Estonia. Examples of model application to Kasari River are rationalisation of existing hydrological network, more effective management of existing hydro power installations, control of runoff data quality, extending discharge series and filling in of gaps in run-off series, modelling the distribution of run-off in rivers and tributaries, modelling of snowpack and soil moisture deficit, calculation of substance-transport in rivers, calculation of mean discharge from unmeasured subbasins, flood-forecasting for flood warning and extreme flood studies among others.

2. THE HBV HYDROLOGICAL MODEL

2.1 Model structure and data requirements

The HBV hydrological model was developed at SMHI and the first applications to hydropower developed rivers were made in the early seventies (Bergström, 1976). The model is normally run on daily values of rainfall and air temperature and monthly estimates of potential evapotranspiration. The model contains routines for snow accumulation and melt, soil moisture accounting, runoff generation and a simple routing procedure (Figure 2). It can be used in a distributed mode by dividing the catchment into subbasins. Each subbasin is then divided into zones according to altitude, lake area, glaciers and vegetation.

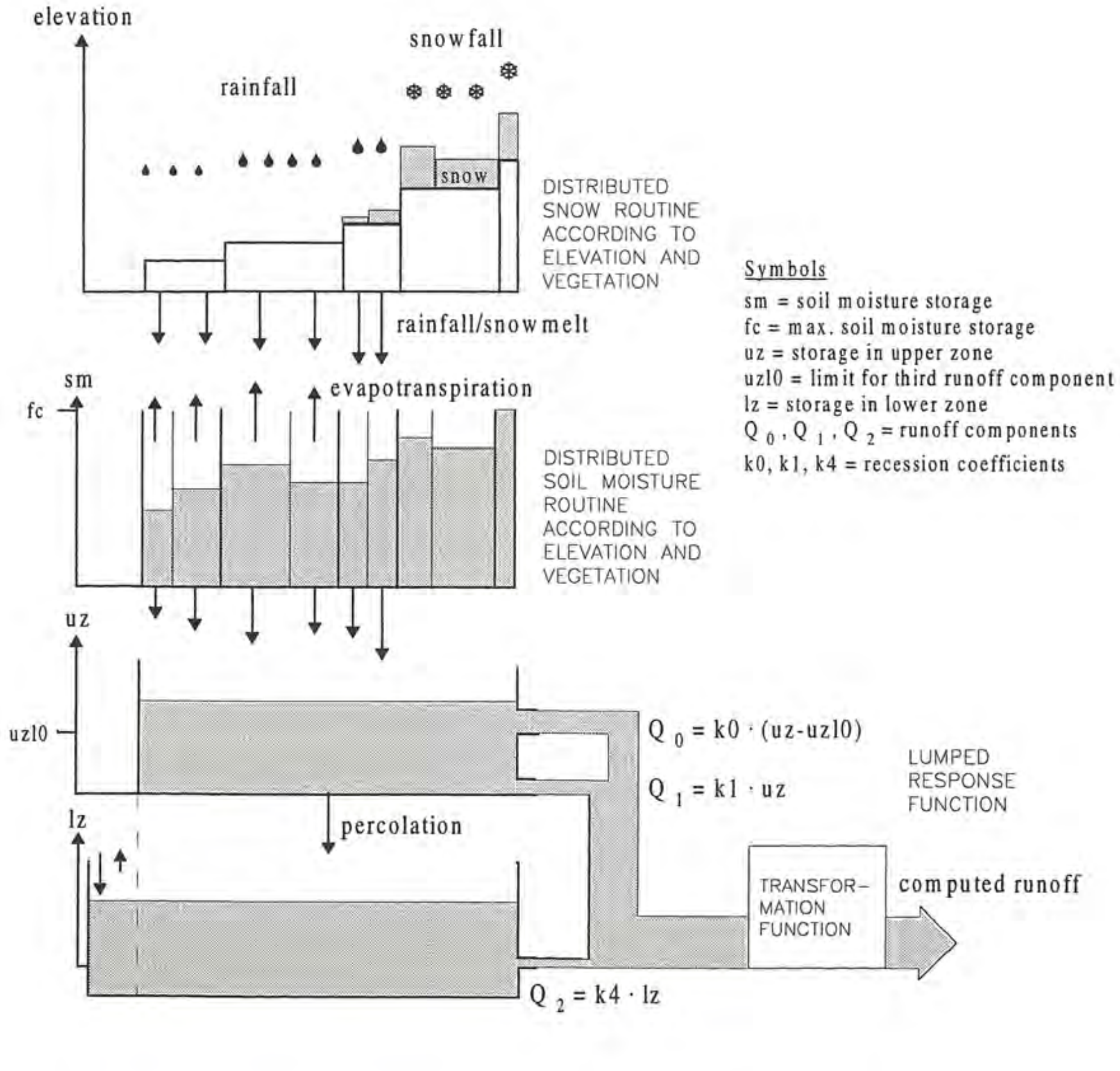

Figure 1. The general structure of the HBV model when applied to one subbasin.

2.1.1 Snow

Snowmelt is calculated separately for each elevation and vegetation zone according to the degree-day equation:

$$Q_m(t) = CFMAX \bullet (T(t) - TT) \tag{1}$$

where: Q_m = snowmelt
CFMAX = degree-day factor
T = mean daily air temperature
TT = threshold temperature for snowmelt.

Because of the porosity of the snow, some rain and meltwater can be retained in the pores. In the model, a retention capacity of 10 % of the snowpack water equivalent is assumed. Only after the retention capacity has filled, meltwater will be released from the snow. The snow routine also has a general snowfall correction factor (SFCF) which adjusts for systematic errors in calculated snowfall and winter evaporation.

2.1.2 Soil moisture

Soil moisture dynamics are calculated separately for each elevation and vegetation zone. The rate of discharge of excess water from the soil is related to the weighted precipitation and the relationship depends upon the computed soil moisture storage, the soil saturation threshold (FC) and the empirical parameter β, as given in equation 2. Rain or snowmelt generates small contributions of excess water from the soil when the soil is dry and large contributions when conditions are wet (Figure 2).

$$Q_s(t) = \left(\frac{S_{sm}(t)}{FC}\right)^{\beta} \bullet P(t) \tag{2}$$

where: Q_s = excess water from soil,
S_{sm} = soil moisture storage,
FC = soil saturation threshold,
P = precipitation, and
β = empirical coefficient.

The actual evapotranspiration is computed as a function of the potential evapotranspiration and the available soil moisture (Eq. 3, Figure 2):

$$E_a(t) = \begin{cases} \dfrac{E_p \bullet S_{sm}(t)}{LP} & if\ S_{sm} \le LP \\ E_p & if\ S_{sm} > LP \end{cases} \quad (3)$$

where:

E_a		= actual evapotranspiration
E_p		= potential evapotranspiration
LP		= S_{sm} threshold for E_p

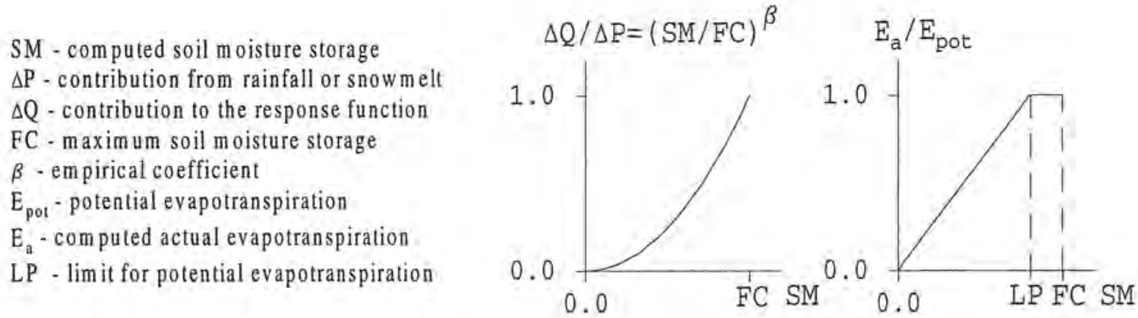

Figure 2. Schematic presentation of the soil moisture accounting subroutine.

2.1.3 Runoff response

Excess water from the soil and direct precipitation over open water bodies in the catchment area generate runoff according to equations (4) and (5).

$$Q_u(t) = \begin{cases} S_{uz}(t) \bullet (K_0 + K_1) - K_0 \bullet UZL & if\ S_{uz} > UZL \\ K_1 \bullet S_{uz}(t) & if\ S_{uz} \le UZL \end{cases} \quad (4)$$

$$Q_l(t) = K_4 \bullet S_{lz}(t) \quad (5)$$

where:

Q_u	= runoff generation from upper response tank
K_0, K_1, K_4	= recession coefficients
UZL	= storage threshold between K_0 and K_1
S_{uz}	= storage in upper response tank
PERC	= percolation rate between the tanks
Q_l	= runoff generation from lower response tank
S_l	= storage in lower response tank

In order to account for the damping of the generated flood pulse ($Q = Q_u + Q_l$) in the river, a simple routing transformation is made. This is a filter with a triangular distribution of weights with the base length MAXBAS. There is also an option of using the Muskingum routing routine to account for the river flow hydraulics.

Lakes in the subbasins are included in the lower response tank, but can also be modelled explicitly by a storage discharge relationship. This is accomplished by subdivision into subbasins defined by the outlet of major lakes. The use of an explicit lake routing routine has also proved to simplify the calibration of the recession parameters of the model, as most of the damping is accounted for by the lakes.

2.2 Model applications

The HBV model was originally developed for inflow forecasting to hydropower reservoirs in Scandinavian catchments, but has now been applied in more than 30 countries all over the world (Figure 3). Despite its relatively simple structure, it performs equally well as the best known model in the world (see WMO, 1986 and 1987).

Some examples of model applications are: inflow and flood forecasting and computation of design floods in totally about 170 basins in Scandinavia (Häggström, 1989; Bergström et al., 1989; Harlin, 1992; Killingtveit and Aam, 1978; Vehviläinen, 1986), modelling the effects of clearcutting in Sweden (Brandt et al., 1988), snowmelt flood simulation in Alpine regions (Capovilla, 1990; Renner and Braun, 1990; Braun and Lang, 1986), hydrological modelling in Arctic permafrost environment (Hinzman and Kane, 1991), inflow forecasting to a dam in River Indus (Sanner et al., 1994) and flood forecasting in Central America (Häggström et al., 1990).

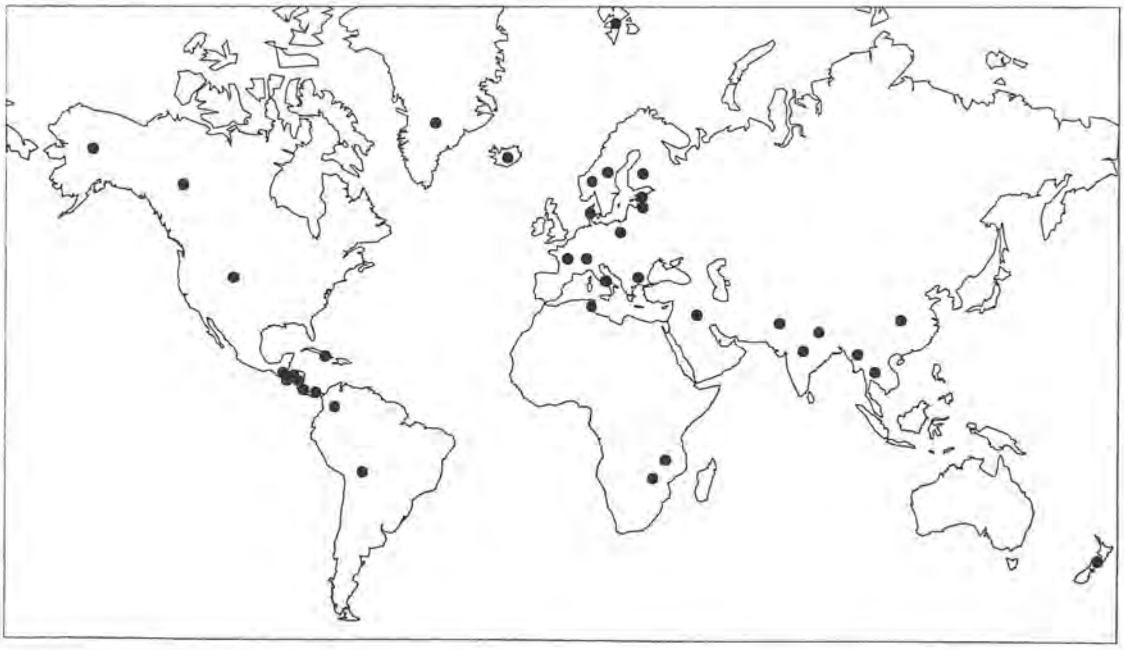

Figure 3. Countries or regions where the HBV model is known to have been applied.

2.3 Model calibration

The HBV model, in its simplest form with only one subbasin and one type of vegetation, has altogether 12 free parameters. The calibration of the model is usually made by a manual trial and error technique, during which relevant parameter values are changed until an acceptable agreement with observations is obtained. The judgement of the performance is also supported by statistical criteria, normally the R^2-value of model fit, ≈ explained variance, (Nash and Sutcliffe, 1970):

$$R^2 = \frac{\Sigma\ (\bar{Q}_o - Q_o)^2 - \Sigma\ (Q_c - Q_o)^2}{\Sigma\ (\bar{Q}_o - Q_o)^2} \tag{6}$$

where: Q_o = observed runoff
$\bar{Q}_o$ = mean of observed runoff
Q_c = computed runoff

R^2 has a value of 1.0, if the simulated and the recorded hydrographs agree completely, and 0 if the model only manages to produce the mean value of the runoff record. Another useful tool for the judgement of model performance is a graph of the accumulated difference between the simulated and the recorded runoff. This graph reveals any bias in the water balance and is often used in the initial stages of calibration, for example for assessment of the snow parameters.

It is not possible to specify exactly the required length of records needed for a stable model calibration for all kinds of applications. The important thing is that the records include a variety of hydrological events, so that the effect of all subroutines of the model can be discerned. Normally 5 to 10 years of records are sufficient when the model is applied to Scandinavian conditions.

The HBV model is a conceptual model lumping many heterogeneous catchment characteristics into rather simple linear and non-linear equations. Although model components clearly represent individual hydrological processes, flow-generating pulses should not be interpreted as emanating from exact locations in the catchment. The model formulation has been developed so that the integrated response of all flow pulses during a time step is captured. Parameter values are therefore integrated and specific for each catchment and can not easily be obtained from point measurements in the field.

2.4 The forecasting procedure

The HBV model is often used for either short or long range forecasting. Before the day of forecast the model is run on observed input data until the time step (day) before the forecast. If there is a discrepancy between the computed and observed hydrographs during the last days of run, updating of the model should be considered. The HBV model is normally updated by an iterative procedure during which the input data a few days prior to the day of forecast is adjusted. Updating should always be done with caution, since the updating procedure may introduce additional uncertainty over the forecast period.

Short range forecasts are usually made in flood situations. The runoff development is forecasted until the culmination has passed. A meteorological forecast is used as input, and there is a possibility to use alternative precipitation and temperature sequences in the same run. This is often desirable due to the often low accuracy of quantitative meteorological forecasts, especially as concerns precipitation.

Long range forecasts are mainly used for two purposes: prediction of peak flow and of runoff volume. For operating hydropower reservoirs, the remaining inflow to a given date is often the most interesting figure, while in other basins the interest is concentrated towards the distribution of peak flows. The latter aspect is, of course, the most important if flood damage is the main problem. On the other hand, for some rivers, low flow forecasts can be the most interesting ones. The forecast uses precipitation and temperature data from corresponding periods of preceding years as input. Usually data from at least 10 years are used. The distribution of different simulations gives an indication of the probability that a given value will be exceeded. The volume forecast is supplemented with a statistical interpretation of the result.

2.5 Model calculation of river discharge

Information on river discharge is often needed in more detail than long term mean values. The discharge varies a lot during a year and also from one year to another. Since water flow measuring stations are expensive to run it is often easier to calculate the discharge at points without flow metering using a rainfall-runoff model. Normally measurements of precipitation and temperature are made more frequent than measurements of water discharge. After input of precipitation and mean temperature and information of subbasin elevation and distribution of lakes, open land and forest the HBV-model can calculate river discharge for any catchment without discharge measurements.

First the model has to be calibrated for catchments with discharge measurements. It is during the calibration process important to find variables valid for the whole region. For obtaining this, calibrations and verifications are made for all discharge stations in the region, trying to find variable values that gives acceptable results everywhere. These variables are then used for calculation of discharge in catchments in the region without discharge measurements. This method gives values with some uncertainty, and therefore only weekly or monthly values are proper. The method is, however, often the only possible way of getting information of the discharge and runoff, for example, in areas without

possibility to install a stream gauging station or when information is needed for years that already have passed. The method is also a less costly alternative to discharge stations.

3. THE IHMS-HBV MODEL APPLICATION TO KASARI RIVER BASIN IN ESTONIA

3.1 The climate and hydrology of the Kasari Basin

The Kasari River discharge in the Matsalu Bay, which is situated between the Gulf of Finland and the Gulf of Riga. The catchment is located on the lowest part of Estonia and its mean altitude is about 65 m. The length and width are more or less equal, 45-55 km. The long-term annual mean of precipitation varies from 700 mm on the west to 665 mm on the east of watershed (from coast to internal area). Temperature (annual mean) varies from 5 °C on the west to 4,5 °C on the east. Snow pack is observed from the beginning of December to the end of March. The features of the underlying surface are most important for hydrological regime formation. The regime of the Kasari River is characterised of the four classical seasons: the spring flood during March, April and May, summer low flow period with rain floods in June, July, August and September, autumn rain flood during October and November and winter low flow period with slash jam tips in December, January and February (Reference book on the USSR's climate, 1988).

The hydrological features of the water regime are caused by influence of underlying surface agents such as karst, friable sand-gravel depositions and swamps which are widely spread at the Kasari basin. Upper portion of watershed (Figure 4) is characterised by karst events. In the middle and lower portions of the Kasari catchment there are clay, moraine and swamped areas. 35 % of catchment area are covered by swamps.

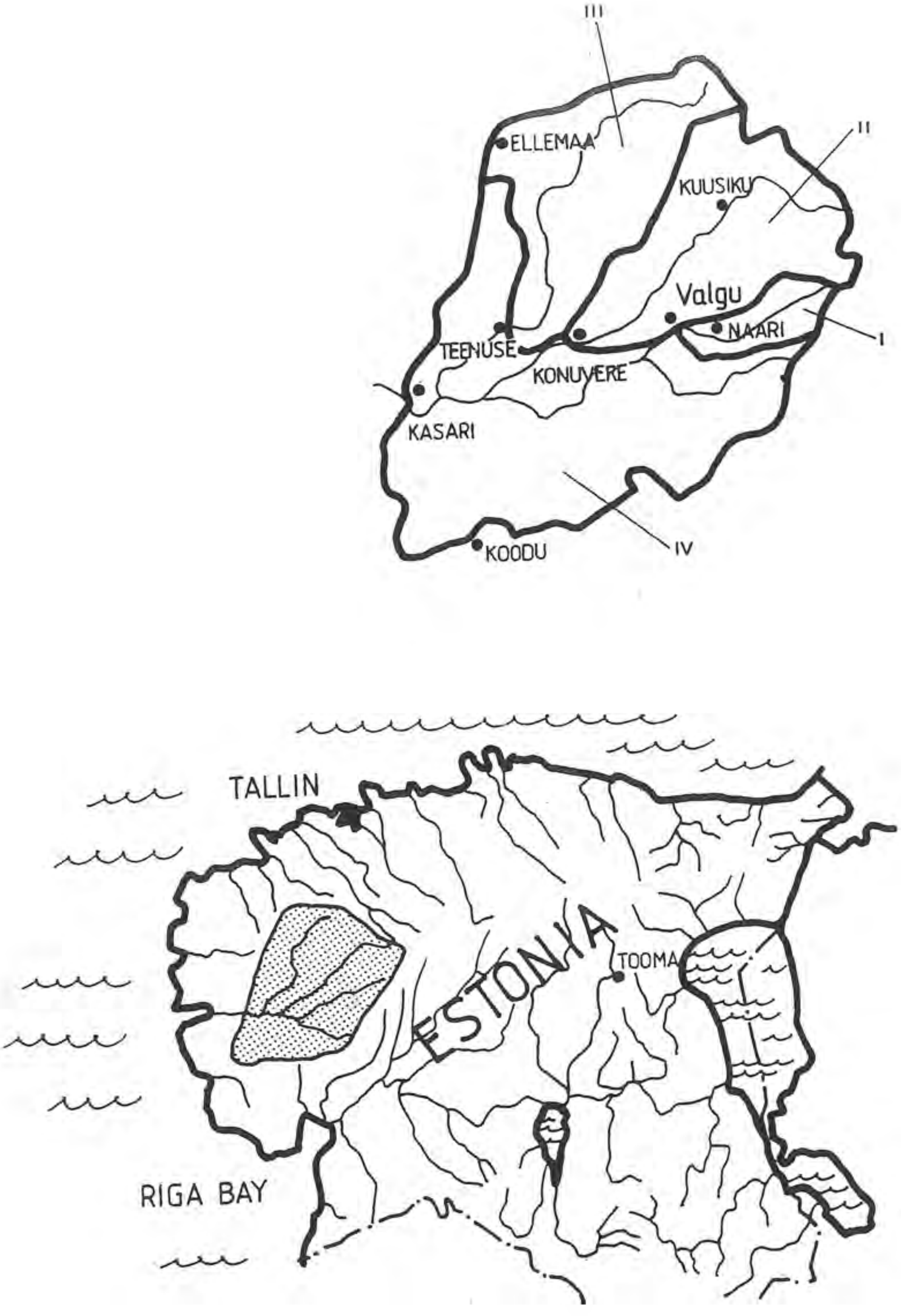

Figure 4. The Kasari catchment, basin subdivision and location of precipitation, temperature and discharge stations.

3.2 The IHMS-HBV model application to the Kasari River

3.2.1 Basin subdivision

The total catchment of Kasari river is 2640 km^2. In the model application it was divided into four subbasins (Table 1, Figure 4)

Table 1. Subbasins in Kasari river catchment.

no.	Catchment name	area(km^2)	Forest (%)	Open land (%)
I	Valgu	135	48	52
II	Konuvere	618	37	63
III	Teenuse	634	32	68
IV	Kasari	1253	15	85

The two subbasins Valgu and Konuvere are characterised by karst and swamp areas, up to 24% of the total area. Karst areas can be of forest as well as open land type. Teenuse is a subbasin with a dominated swampy vegetation, 35 % and finally Kasari, the most downstream area, has an area of 29 % covered by swamp.

3.2.2 Analysis of input data

Precipitation is the source of streamflow generation and consequently the most important input parameter to the HBV model. Furthermore, temperature data and long-term estimates of potential evapotranspiration are needed as input. In the model application to Kasari basin six precipitation and one temperature stations were available for the 10 years period (1981-01-01 1990-12-31). A summary of the station weights is given in Table 2.

Table 2. Stations and weights used in the HBV model application.

Station (Type)	Precipitation Weight(%)	Temperature Weight(%)	Annual average precipitation (mm)
Ellamaa(P)	12.0	-	800
Kuusiku(P,T)	23.6	100.0	791
Konuvere(P)	18.0	-	748
Naari(P)	20.2	-	819
Kasari(P)	11.4	-	746
Koodu(P)	14.8	-	711

The double mass technique was used to check the homogeneity of the precipitation and discharge records. This technique takes advantage of the fact that the mean accumulated precipitation for a number of gauges is not very sensitive to changes at individual stations because many of the errors compensate each other, whereas the cumulative curve for a single gauge is immediately affected by a change at the station.

The mean accumulated precipitation for all others station is plotted on the X-axis against the data for the gauge being studied, which is plotted on the Y-axis. If the double mass curve has a change in slope at some point in time, it indicates a break in homogeneity. A jag in the double mass curve can be caused by missing values at the observed station or by seasonal differences in the precipitation pattern. The slope of the curve is proportional to the intensity, that is if the observed station records exactly as much as the mean of the rest, the curve follows the diagonal. If the station records more, the slope will be steeper and if it records less, the double mass curve will lie below the diagonal.

The double mass curves for the two stations Konuvere and Teenuse showed signs of inhomogeneity during 1983-86 years. Precipitation registration at Koodu have decreased compared to the other stations since 1983 while registrations at Nari have increased since middle of 1984. All double mass plots from precipitation stations in Kasari basin is presented in Appendix A.

Monthly mean values of potential evapotranspiration were compiled from available evaporimeter pans of the Class A type, situated at Kuusiko station located in subbasin Konuvere in the upper parts of the river basin. For the other subbasins there were no evaporation observations available, but due to homogeneity in soil, topography and climate conditions between the subbasins the same evaporation data could be used for all subbasins in the catchment. The evapotranspiration values used for calibration are given in Table 3.

Table 3. Mean evapotranspiration (mm/day) data used in the HBV model application.

Station	Jan	Feb	Mar	Apr R	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Kuusiko	0.05	0.10	0.32	1.11	2.08	2.37	2.47	1.78	1.30	0.78	0.10	0.09
Tooma	0.07	0.13	0.44	2.00	2.30	2.70	2.70	1.70	1.40	0.80	0.14	0.08

3.2.3 Calibration

In the set-up of the HBV model it is not possible to describe swamp areas or karst formations.

To find out how to handle the swamp areas the calibration was carried out in three steps. The first step was a calibration process without taking the difference in evaporation

between swamp and swamp-free areas into account. In the second step the swamps were classified as lakes and finally in the third step evaporation data from swamps (Station Tooma in table 3) were used as input in the model.

Calibration of these three types of model set-up was performed on runoff data from 1981-10-01 to 1990-12-31 in all four subbasins. All four subbasins were calibrated separately and modelled and observed hydrographs plotted and visually inspected. Some of the hydrographs are presented in Appendix B.

3.2.4 Model results

Table 4. Span of the most important model parameter values for the 4 calibrated subbasins in Kasari River.

Parameter	Value	Function
Snow routine		
SFCF	0.95 - 1.00	Snowfall correction factor
TT	0.5	Threshold temperature for snowmelt
CFMAX	2.5 - 3.0	Degree-day factor
FOCFMAX	1.5 - 3.0	Forest factor for CFMAX
Soil Routine		
FC	200 - 300	Maximum soil water capacity
LP	0.3 - 0.5	Threshold for potential evapotranspiration
BETA	5 - 7	Empirical coefficient
Upper response tank		
Ko	0.15 - 0.30	Flood recession parameter
K1	0.07 - 0.15	Intermediate flow recession parameter
UZL	30 - 45	Flood recession threshold
Lower response tank		
PERC	0.2 - 0.3	Ground water percolation
K4	0.010 - 0.015	Base flow recession parameter

The best results were obtained with the second step of calibration were the swamp areas were classified as lakes, table 5. By use of the lake parameter in the model set-up it was possible to express the equal influence of swamp, karst and friable depositions.

Table 5. *R^2 and accumulated difference values of model fit for the modelled outflow from the calibrated subbasins on the Kasari Basin.*

Subbasin	**R^2**			**Accumulated difference (mm/10 year)**		
	Step 1	**Step 2**	**Step 3**	**Step 1**	**Step 2**	**Step 3**
Valgu	0.77	0.83	0.79	-121	-32	138
Konuvere	0.77	0.87	0.80	451	181	15
Teenuse	0.71	0.83	0.81	35	0	-80
Kasari	0.72	0.89	0.86	124	52	-29

Lakes has a smoothing effect on runoff. High peaks will decrease because of the storage capacity and the losses because of evaporation will increase. With higher lake areas the free water surfaces will increase and more water is available to maximum potential evaporation. Swamp areas are very similar to lakes due to their high evapotranspiration capacity and flood decreasing effects (Valk, 1988). Table 5 indicate this increase of evaporation during step 2. The accumulated difference is in most cases lower than in step 1 were the swamp areas are considered as solid open or forested land. A comparison with step 3 with potential evaporation data from bog station Tooma is not applicable because the difference in input data between this two types of calibration.

Karst redistributes the runoff not only in time but also between catchments (Kilkus, 1990). The runoff peaks in hydrographs depend on the storage capacity of karst cavities. If the cavities are dry the first part of the rain will be stored and the resulting runoff flood will be delayed. This delay can be described in the model set-up. The peak will be registered later from an area rich in karst cavities than from surrounding non-karsted areas. A careful comparison between hydrographs in appendix B from the subbasin Valgu, rich in karst formations, and the karst free subbasin Kasari show this delay in peak runoff.

A result from the calibration process in Kasari River basin show that the influence of different kind of swamps and bogs on the river runoff is similar to the influence of lakes in the subbasin.

4. DISCUSSION

A very significant environmental problem for Estonia is the protection against pollution. For this reason a modern computer model for current water resources estimation is crucial. The quantitative estimation of underlying surface agent's influence on the surface flow and the catchment water balance, especially in the period of river low flow, gives the possibility for calculation of river flow and water balance of any ungauged Estonian rivers using physio-geographical parameters.

The result of the HBV model application in the Kasari River basin is good. The model responded at all flood events in the available data period, however not always with the correct magnitude. Periods of low summer- and winterflow were also well described by the model.

Swamps and bogs are frequent in the Kasari basin. In the optimal model set-up these are described as lakes. This way of describing the swamps in model set-up was successful and model performance after calibration was very good in subbasins with domination of karst formations.

5. CONCLUSIONS AND RECOMMENDATIONS

All the specific project objectives have been met and the following general conclusions have been made:

- The project has improved the hydrological information in Kasari river basin through quality control of ten years of daily historical hydrometeorological data.

- The Integrated Hydrological Model system (IHMS) has successfully been applied to the Kasari basin. The IHMS gives possibilities to compute long continuos series of runoff at different sites within the basin and as a result different flow characteristics can be obtained for the different sites. The IHMS also gives possibilities to perform flood forecasts in a flood warning system for the Kasari basin.

- When representative temperature and precipitation data are available the HBV-model, included in the IHMS, performs well in the Kasari basin.

- The transfer of knowledge within the project in the maintenance of the model system has been very successful. The EMHI personnel is now capable to operate the IHMS as well as set-up, calibrate and apply the system for new basins of interest.

The following recommendations are made:

- The results from the HBV-model could considerably be improved if the quality and consistency of the hydrometeorological data are increased. A prolongation of the hydrometeorological data base and input of real-time data is a prerequisite condition to enable the real-time runoff forecasting application.

- The knowledge of operating the IHMS-system should be spread further among the EMHI personnel and be maintained through operational use and new applications.

6. ACKNOWLEDGEMENTS

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APPENDIX A

Double mass plots of the precipitation stations

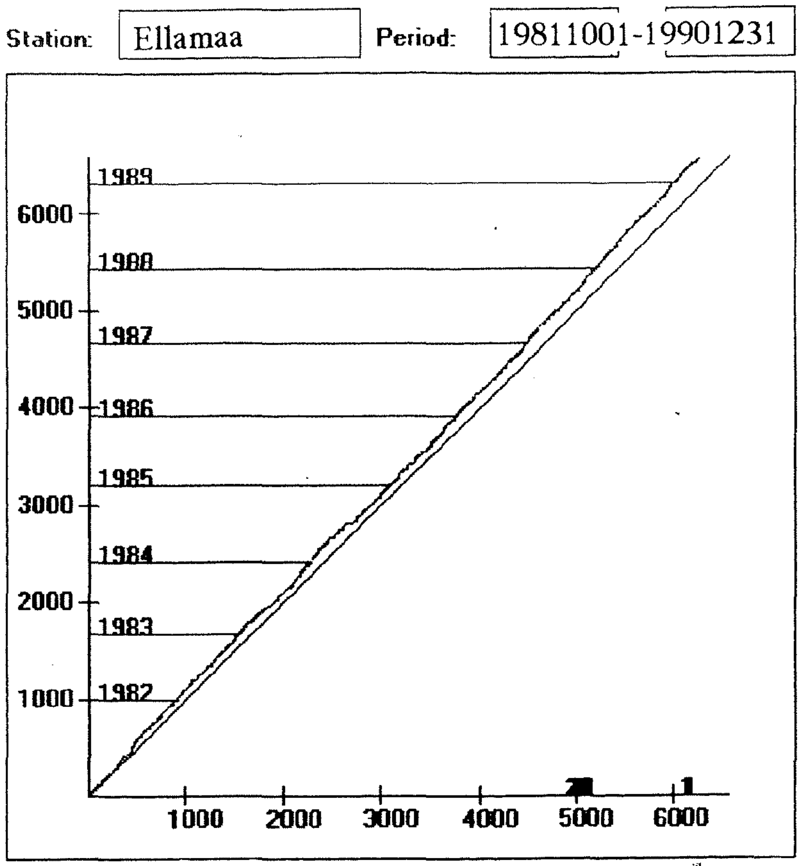

Figure 1. Double mass plot for precipitation recorded at Ellamaa.

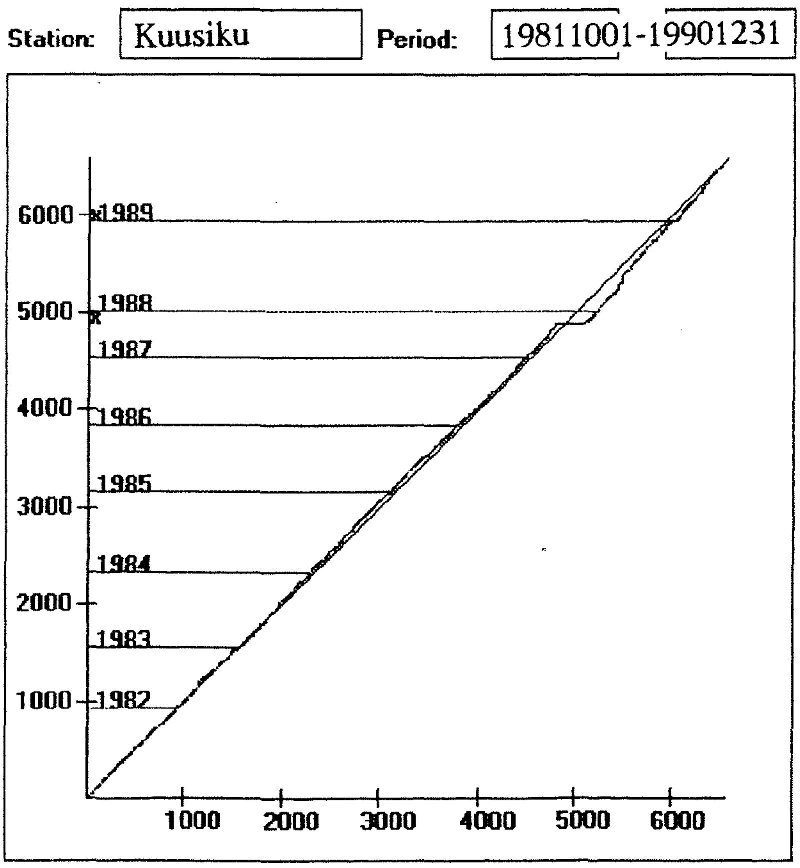

Figure 2. Double mass plot for precipitation recorded at Kuusiku.

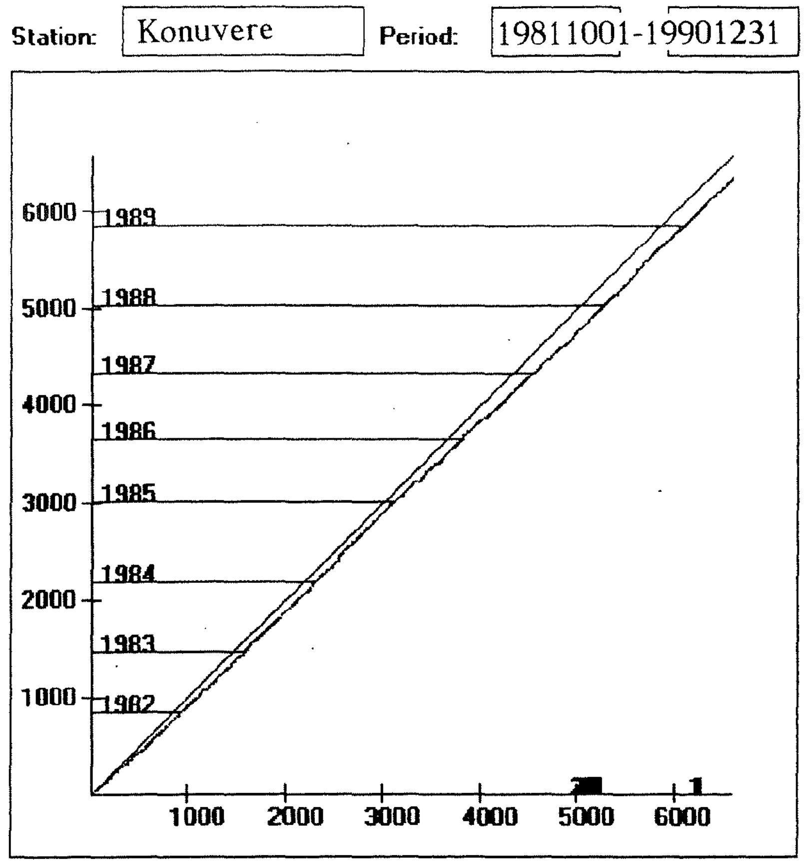

Figure 3. *Double mass plot for precipitation recorded at Konuvere.*

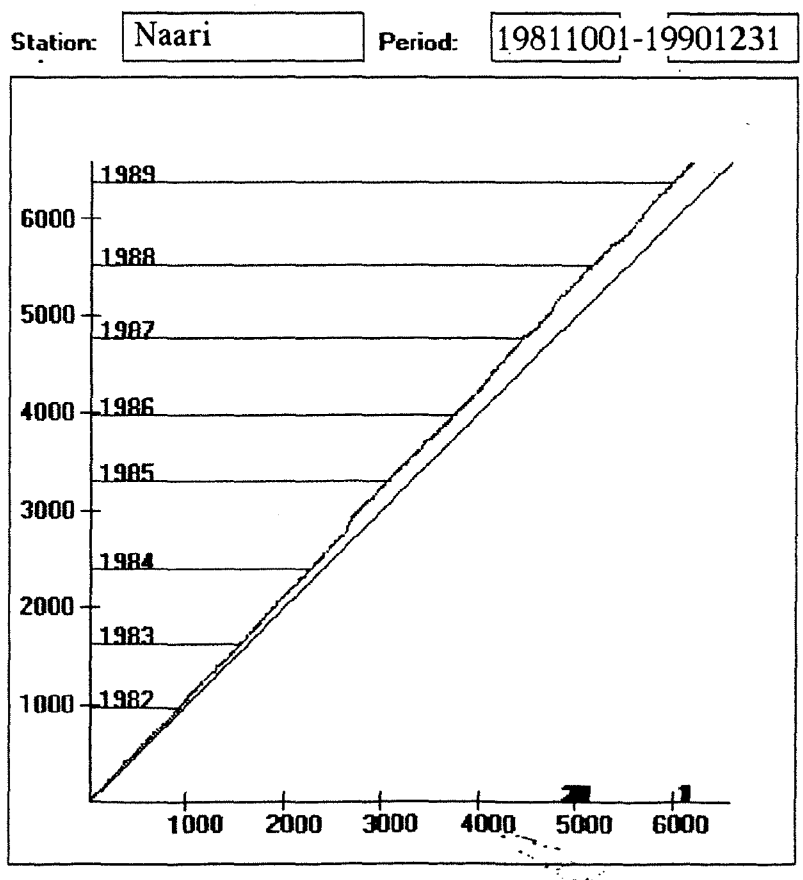

Figure 4. *Double mass plot for precipitation recorded at Naari.*

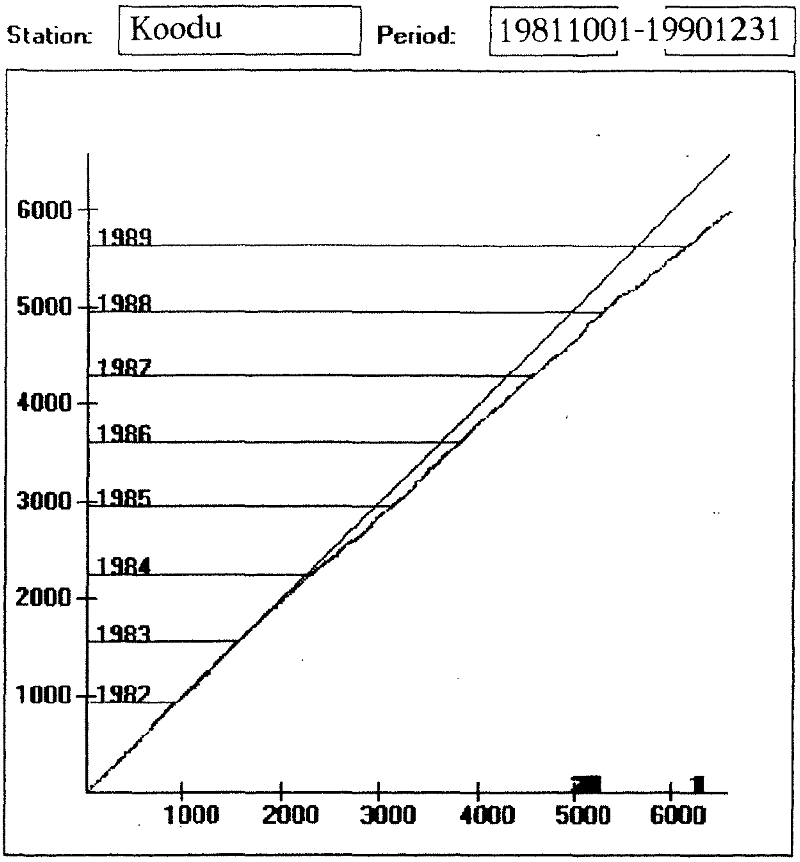

Figure 5. *Double mass plot for precipitation recorded at Koodu.*

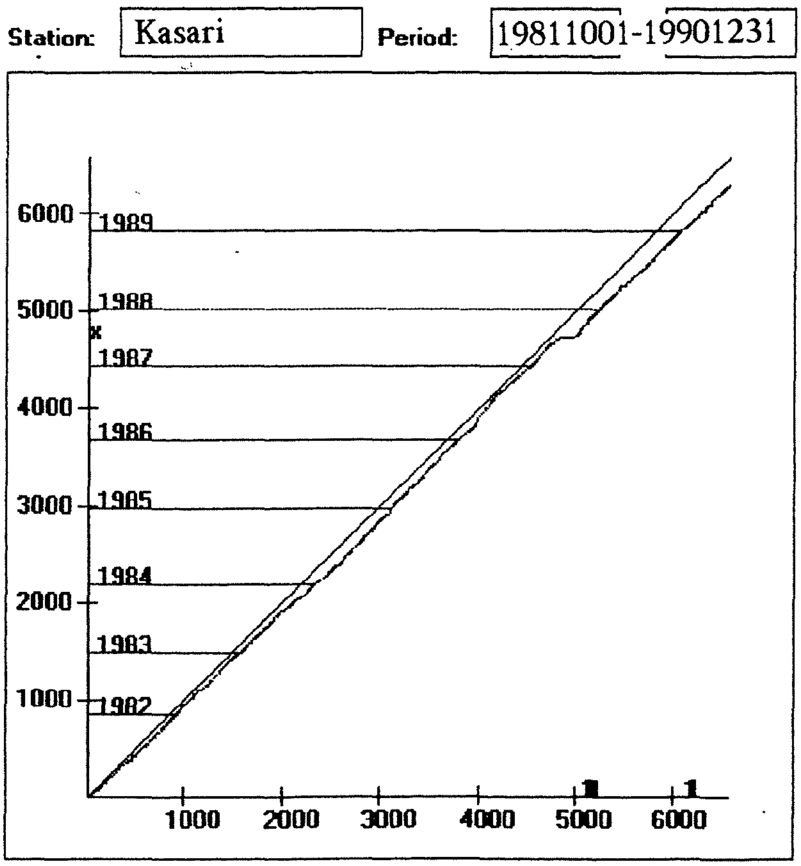

Figure 6. *Double mass plot for precipitation recorded at Kasari.*

APPENDIX B

Calibration plots for the four subbasins

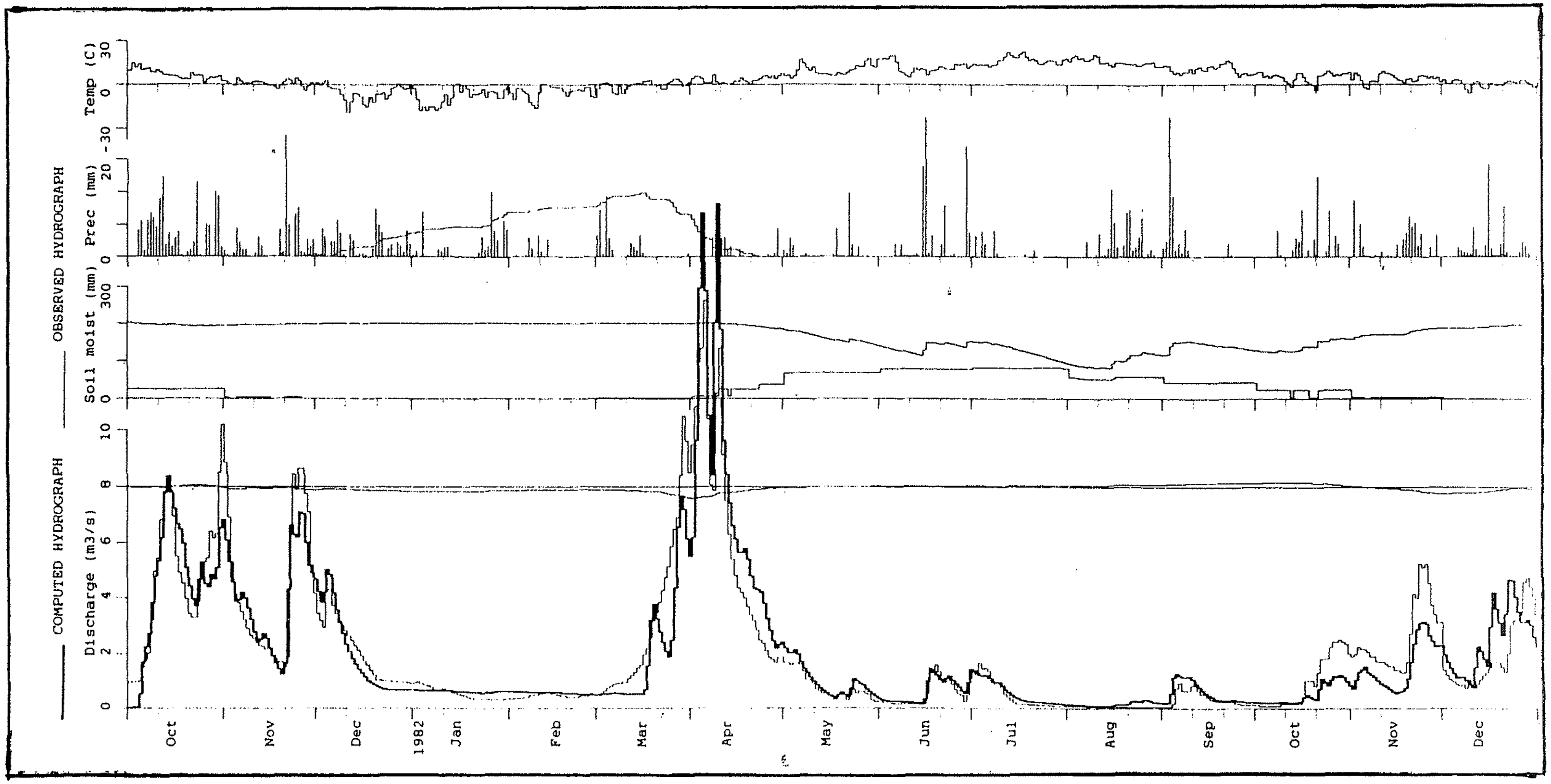

Figure 1. Calibration plot for Valgu catchment (1982).

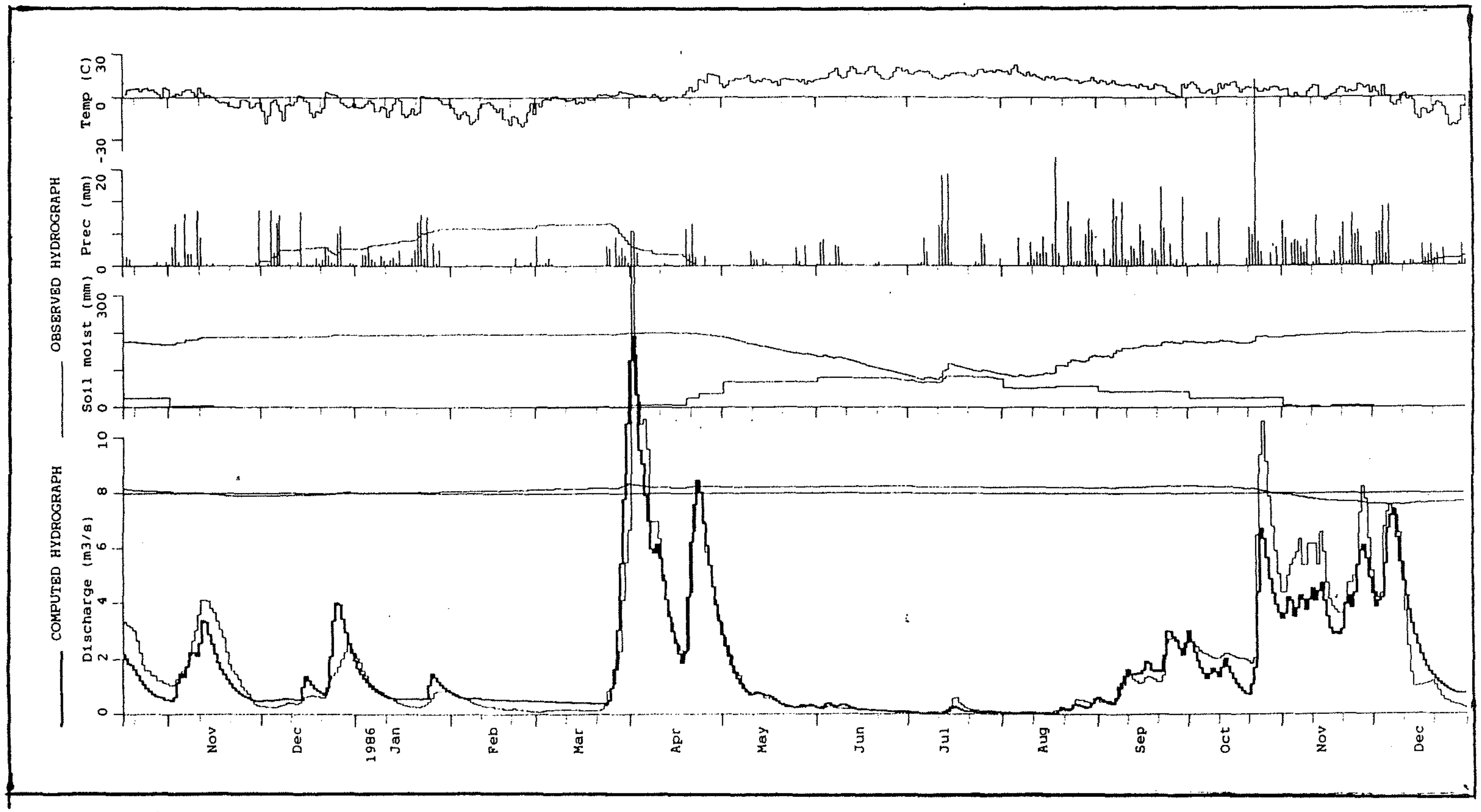

Figure 2. Calibration plot for Valgu catchmrnt (1986).

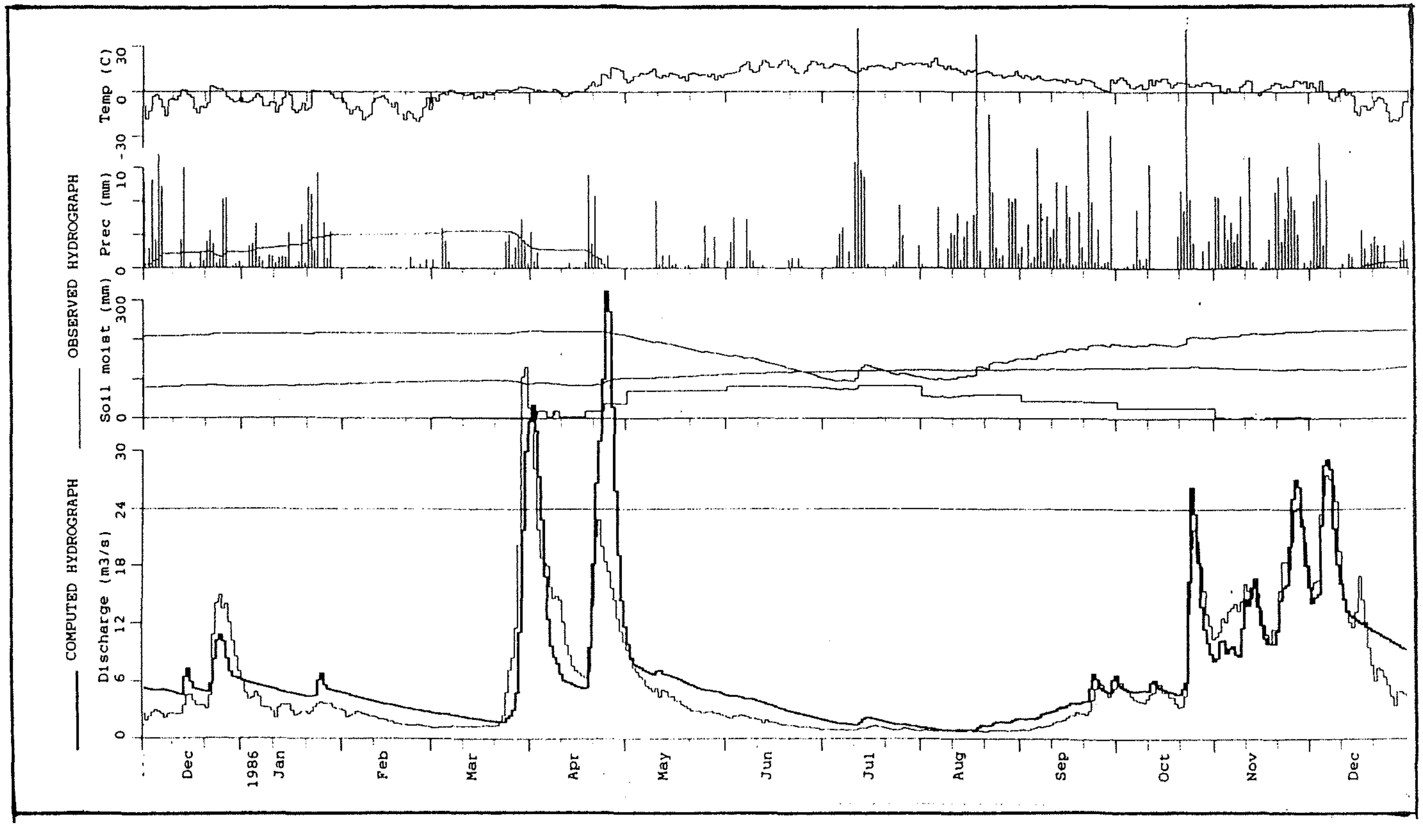

Figure 3. Calibration plot for Konuvere catchment (1986).

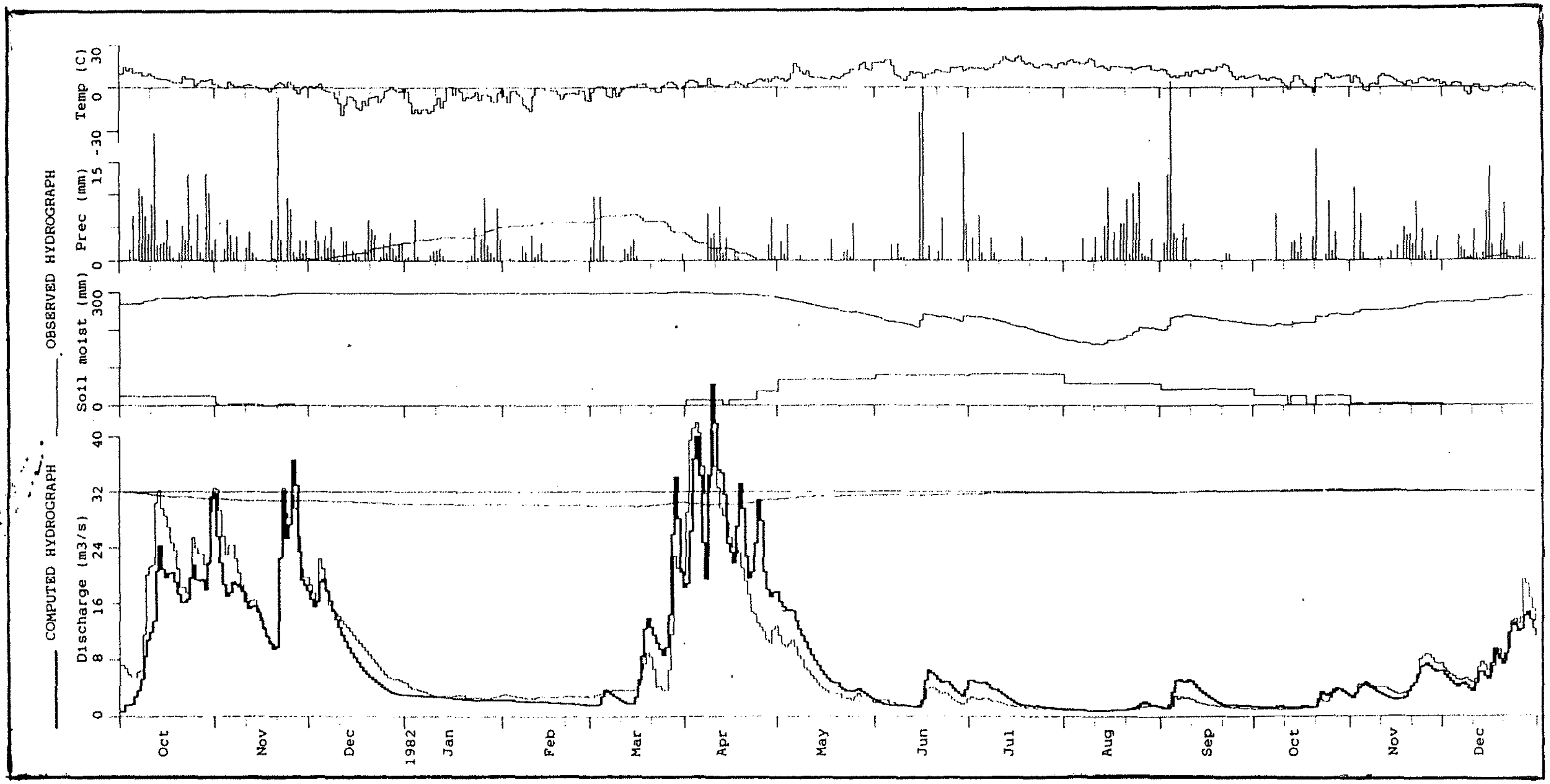

Figure 4. Calibration plot for Teenuse catchment (1982).

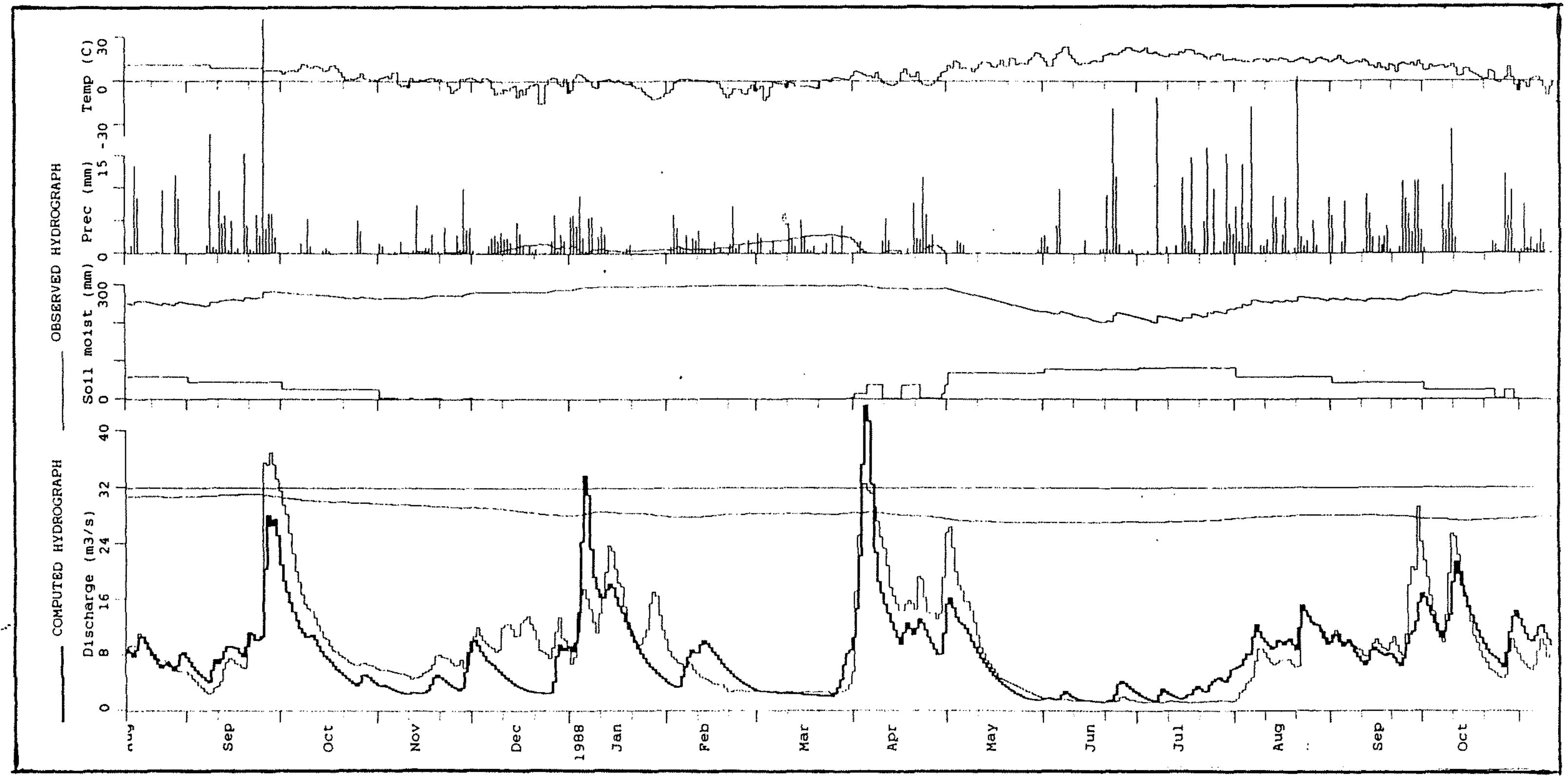

Figure 5. Calibration plot for Teenuse catchment (1988).

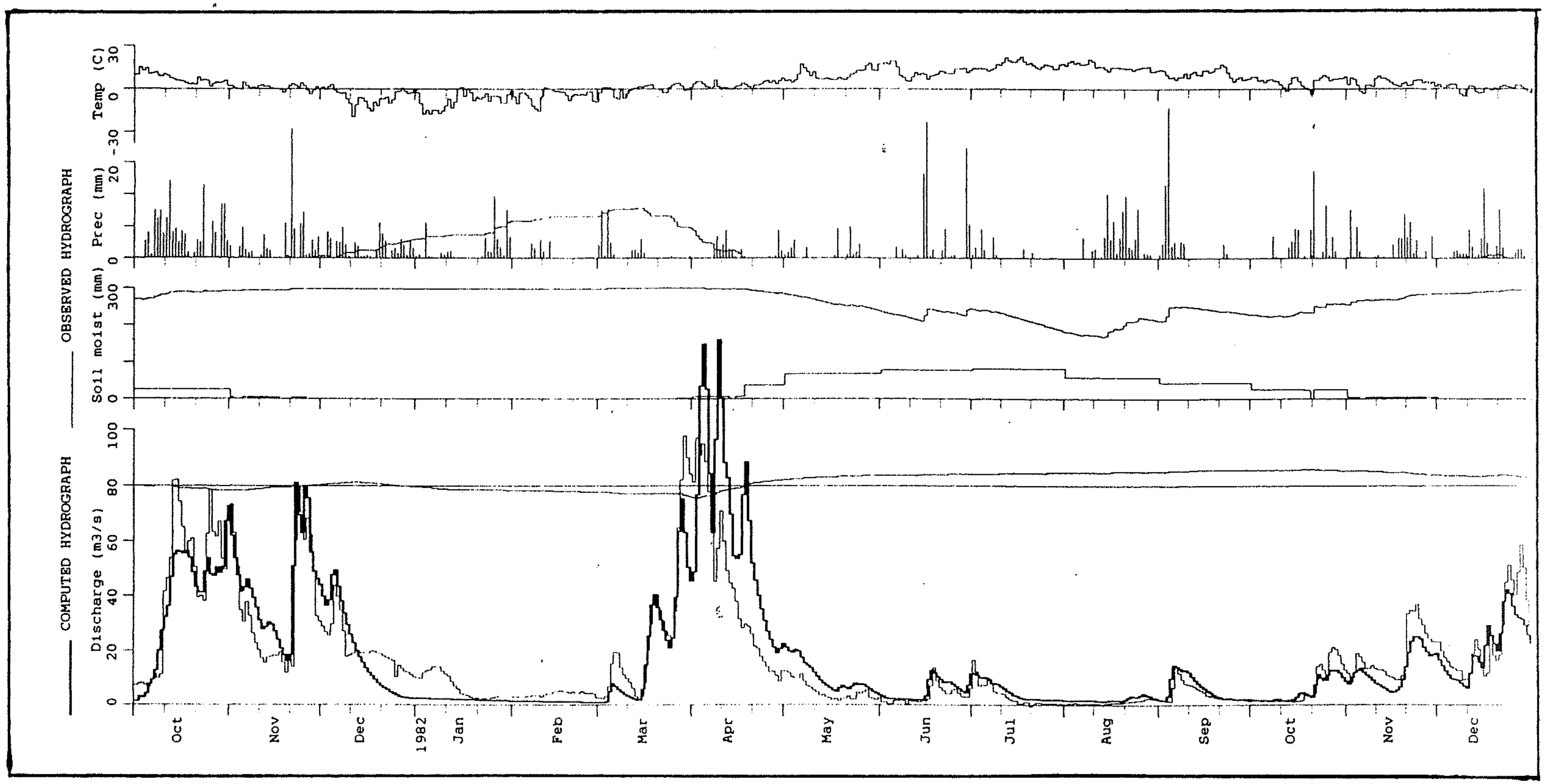

Figure 6. Calibration plot for Kasari (IV) subbasin (1982).

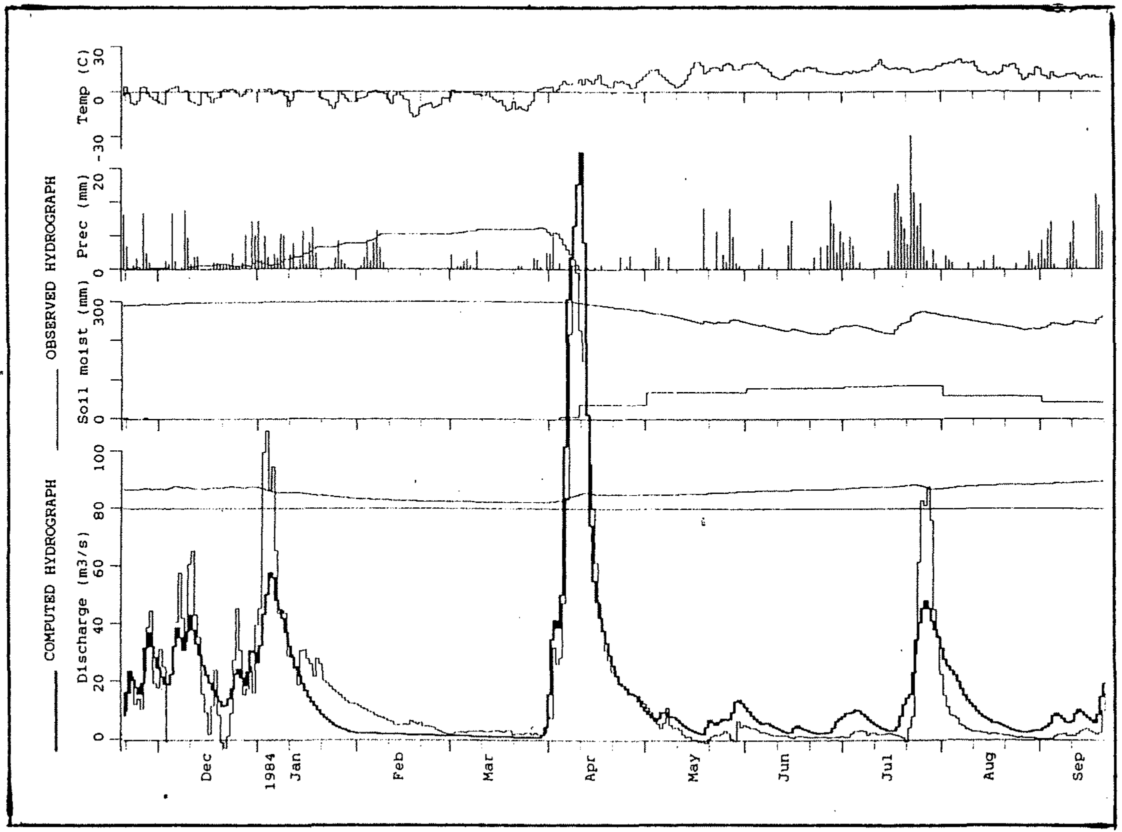

Figure 7. Calibration plot for Kasari (IV) subbasin (1984).