SMHI HYDROLOGY
No10, 1987

APPLICATION OF THE HBV-MODEL TO BOLIVIAN BASINS

ENDE EMPRESA NACIONAL DE ELECTRICIDAD

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The cover photo shows the spillway of the Corani reservoir.

Photo: C. Ambjörn

SMHIs tryckeri, Norrköping 1987.

1. INTRODUCTION

The work described in this report is part of a collaboration project between Empresa Nacional de Electricidad (ENDE), Bolivia, and the Swedish Meteorological and Hydrological Institute (SMHI).

Empresa Nacional de Electricidad is in charge of the electrical power production in Bolivia. At present (1986) hydroelectric power accounts for nearly 70% of all generated electricity, and there is a vast potential that can be exploited. The purpose of this project has been to introduce new and efficient methods for hydroelectric project studies through the use of mathematical modelling techniques. One conceptual (HBV) and one stochastic (HEC-4) model system have been transferred from SMHI to ENDE, as well as the knowledge of using them.

This report deals with the application of the conceptual HBV-model to three Bolivian basins. The use of the model aims at extension of time series of daily discharge data. The stochastic model is based on monthly data and its application to Bolivian rivers is described in the report "Monthly Streamflow Simulation in Bolivian Basins with a Stochastic Model" (Ambjörn et al, 1987).

The collaboration project was started in February 1986 and completed in March 1987. The Swedish Agency for Technical and Economic Co-operation (BITS) was contributing to the financing.

2. CONCEPTUAL MODELS

The basic need for river basins development, both at the planning and management stages, is the evaluation of temporal and spatial water availability in the region. A common experience is that river runoff records at a particular site in a basin are too short for reliable statistical analysis. Missing data of critical highflow periods at the desired site are also frequent problems. Often, however, there is a relatively long period of rainfall data available in the basin. In this situation, mathematical models conceptually representing the land phase of the hydrologic cycle are very useful. These models can be used to simulate runoff response of the catchment by quantifying the most dominant physical processes through a series of mathematical functions, combined together to represent the time-variant interaction of the processes. These models continuously account for the water in storage in the basin, relate loss functions for the rainfall to current condition of the basin, and are capable of continuous simulation of flow for as long a period of time as there are input data available.

Another very common application of rainfall-runoff models is for forecasting purposes. The lead time of the forecast is then depending on the reliability of the weather forecast available and on the dynamics of the river system. A river with a very slow response is thus easier to forecast than one with quick response to rainfall or snowmelt. For long range forecasting, historic climate records can be fed into the model, and the forecast can be based on a statistical analysis of several sequences of computed hydrographs.

Several rainfall-runoff simulation models, viz. the Stanford Watershed Model (Linsley and Crawford, 1960), the SSARR model (Rockwood, 1958), the Dawdy and O'Donell model (Dawdy and O'Donell, 1965), the Boughton model (Boughton, 1966), the Hydrocomp Simulation Program (Hydrocomp Inc., 1969), the UBC model (Quick and Pipes, 1972), the HBV-model (Bergström, 1976), the TANK model (Sugawara, 1961), and the NWSRFS (NOAA, 1972) etc., have been developed since the late 1950ies.

The complexity of these models varies over a wide range, which also entails variable demands as concerns computer facilities and input data. The HBV-model developed by the Swedish Meteorological and Hydrological Institute (Bergström, 1976) is one of the simpler models in the range but has proved to yield satisfactory results for both forecasting and simulation. Its formulation is easily understood, and computer and input data demands are moderate. The model is run on daily values of rainfall and monthly values of the potential evapotranspiration. If the snow-routine of the model is to be used, it requires mean daily air temperatures as well. The model has been adapted to an IBM personal computer.

2.1. Description of the HBV-model

The HBV-model is a conceptual runoff model for continuous calculation of runoff. Input data are observations of precipitation, air temperature and estimates of potential evapotranspiration. The time scale is one day but the potential evaporation values used are normally monthly averages. Air temperature data are used for snow accumulation and ablation calculations only and can be omitted in snowfree areas.

The HBV-model includes possibilities for geographical zoning and different vegetation cover, its basic structure is shown in Figure 1.

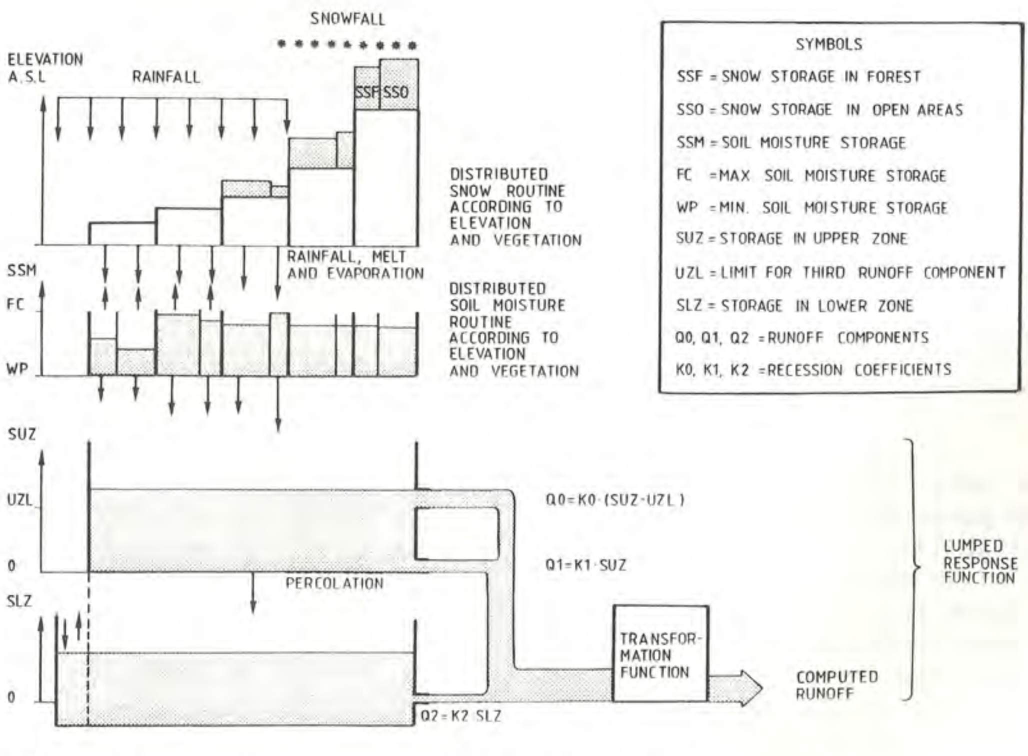
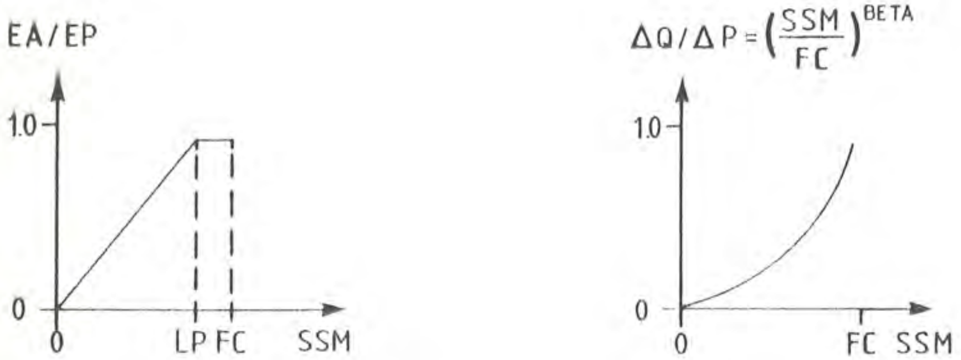


Figure 1. Basic structure of the HBV-model.

The model consists of subroutines for snow accumulation and melt, a soil moisture accounting procedure, routines for runoff generation, and finally a simple routing procedure.

The snow routine is based on a degree-day approach with lapse rates of climatological data according to the hypsographic curve.

The soil moisture accounting routine is the main part controlling runoff formation. This routine is based on three parameters, BETA, LP and FC, as shown in Figure 2. BETA is controlling the contribution to the response function ($\Delta Q/\Delta P$) or increase in soil moisture storage ($1-\Delta Q/\Delta P$) from each millimetre of rainfall or snowmelt, LP is a value above which evapotranspiration reaches its potential value, and FC is the maximum soil moisture storage in the model. In order to avoid problems with non-linearity the soil moisture routine is fed by snowmelt and rainfall mm by mm.



SYMBOLS

SSM = COMPUTED SOIL MOISTURE STORAGE
ΔP = CONTRIBUTION FROM RAINFALL OR SNOWMELT
ΔQ = CONTRIBUTION TO THE RESPONSE FUNCTION/RUNOFF
FC = MAXIMUM SOIL MOISTURE STORAGE
BETA = EMPIRICAL COEFFICIENT
EP = POTENTIAL EVAPOTRANSPIRATION
EA = COMPUTED ACTUAL EVAPOTRANSPIRATION
LP = LIMIT FOR POTENTIAL EVAPOTRANSPIRATION

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

The routine will have the effect that the contribution to runoff from rain or snowmelt is small when the soil is dry (low SSM-values) and great at wet conditions. The actual evapotranspiration decreases as the soil dries out.

For catchments of considerable elevation range, the altitude effect on precipitation is accounted for by division of subbasins into elevation zones and application of a precipitation lapse rate (PCALT) for each zone. The corrections are made from the average altitude of the precipitation stations to the mean altitude of each zone. There is also an option for a general precipitation correction factor (PCORR) in case systematic errors in these data are obvious.

The runoff generation routine is the response function which transforms excess water from the soil moisture zone to runoff. It also includes the effect of direct precipitation and evaporation on a part (LAKE) which represents lakes, rivers and other wet areas. The function consists of one upper and one lower quasi-linear reservoir, as shown in Figure 3. These are the origin of the quick and slow runoff components of the hydrograph.

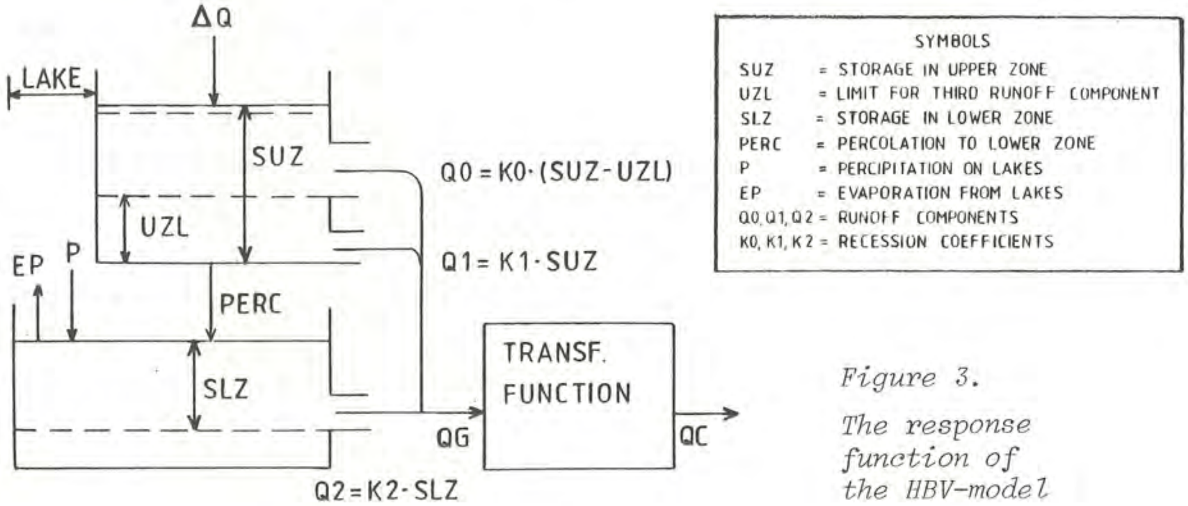


Figure 3.

The response function of the HBV-model

The upper zone may be interpreted as follows: If the yield (ΔQ) from the soil exceeds a certain percolation capacity (PERC), the water will start to drain through more superficial channels and thus reach the rivers and streams with a higher drainage coefficient (K1). At a storage in the upper zone exceeding UZL, even more rapid drainage according to K0 will start. The lower zone, on the other hand, represents the total groundwater storage of the catchment contributing to the base flow.

Each one of the subbasins has individual soil moisture accounting procedures and response functions. The runoff is generated independently from each one of the subbasins and is then routed through a transformation function in order to get a proper shape of the hydrograph. The transformation function is a simple filter technique with a triangular distribution of weights, as shown in Figure 4. If a translation of the hydrograph due to travel time is needed, this is accounted for by a parameter BLAG. Finally the discharge from each subbasin is combined by superposition to arrive at total discharge at the outlet.

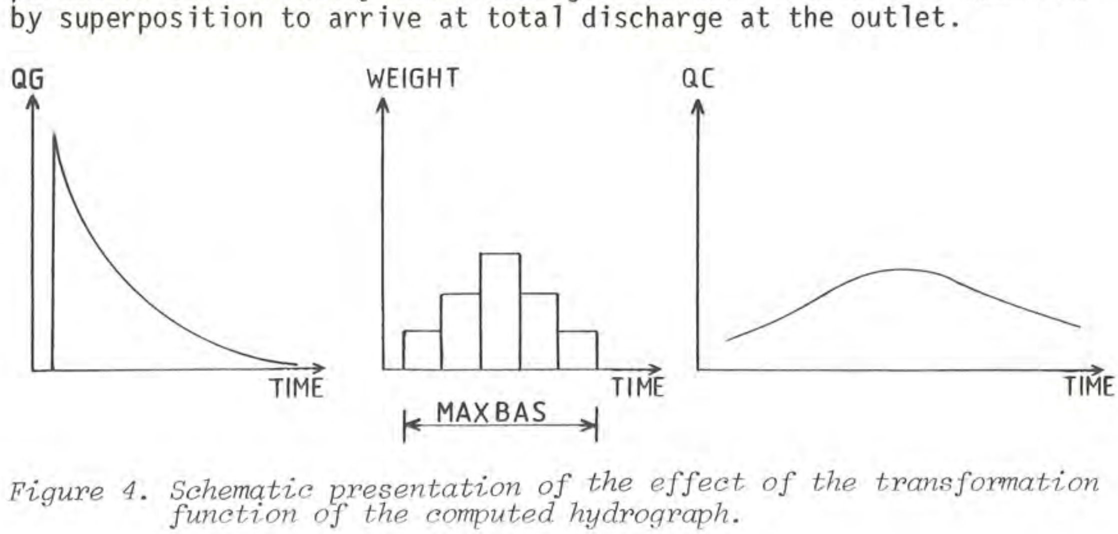


Figure 4. Schematic presentation of the effect of the transformation function of the computed hydrograph.

2.2. Model calibration

For the calibration 5-10 years data of observed daily dicharges are required.

The model is calibrated by a manual trial and error procedure, where three main criteria of fit are used:

1) Visual inspection of the computed and observed hydrographs.

2) A continuous plot of the accumulated difference between the computed and the observed hydrographs expressed as

$$ACC.DIFF = \sum_t (QC-QO)*C$$

QC=computed discharge
QO=observed discharge
t =time
C =constant transforming to mm over the basin.

3) The explained variance around the mean expressed as

$$R^2 = \frac{\sum_t (QO-\overline{QO})^2 - \sum_t (QC-QO)^2}{\sum_t (QO-\overline{QO})^2}$$

where

$$\overline{QO} = \frac{1}{n} \sum_t QO$$

n=the number of days

In addition to these prime criteria, the calibration process is supported by plots of the observed and computed flow duration curves.

It is important to save a few years data for an independent test period.

3. DESCRIPTION OF BASINS AND INPUT DATA

At this first stage, the HBV-model was applied to three Bolivian basins. Two of them, Corani and Locotal, are situatad at the beginning of the Mamoré river, and the other, Miguillas, at the origin of the Beni river, both tributaries of the Amazone river (see the map of Figure 5). Although Corani and Locotal are neighbouring basins, the climatic conditions are very different with approximately twice as much precipitation in Locotal.

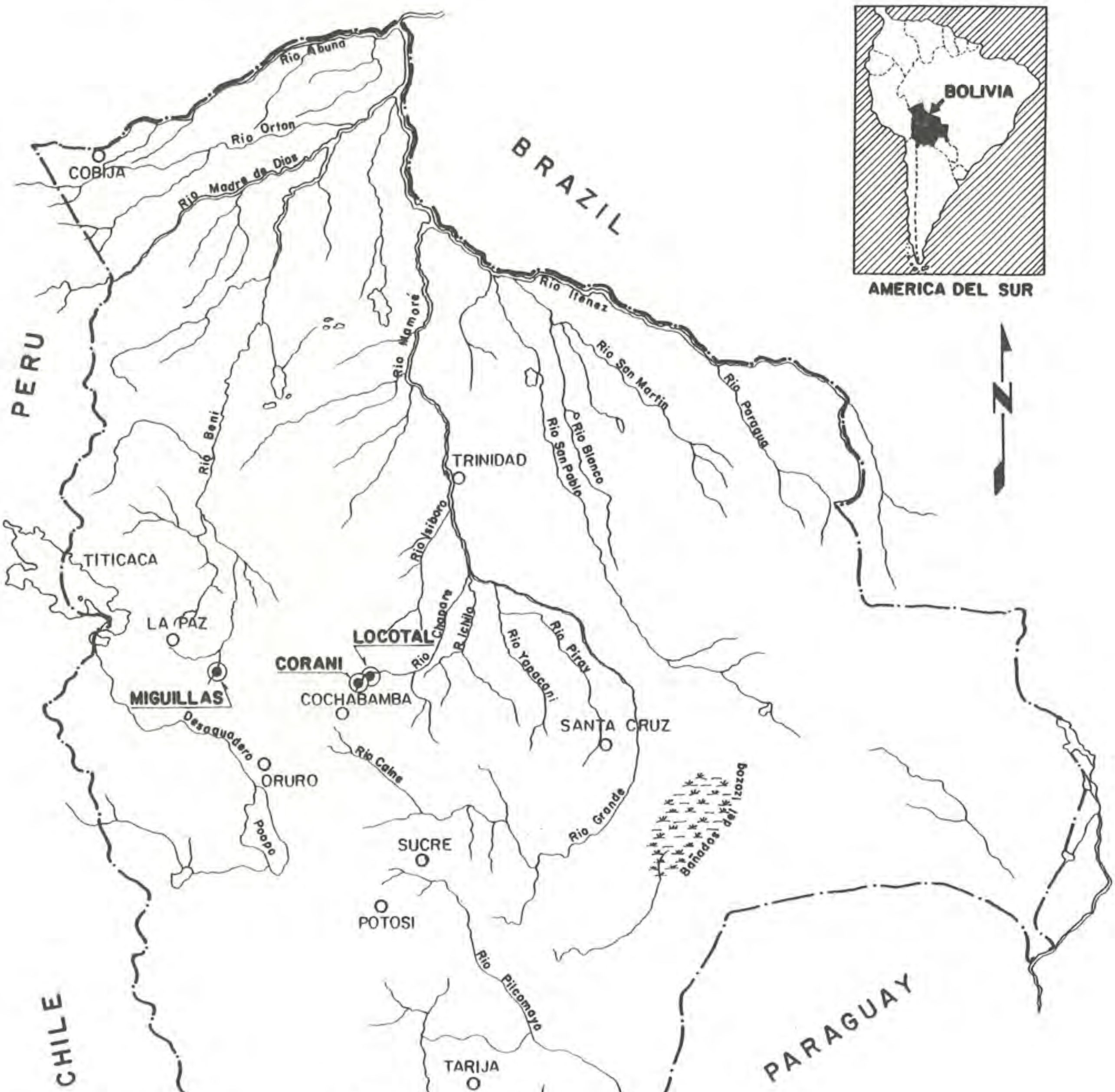


Figure 5. Map of Bolivia with location of basins where the HBV-model has been applied.

3.1. Corani

The area of the Corani basin is 287 km^2 and the elevation range is from 3200 m.a.s.l to 4200 m.a.s.l. The vegetation consists of bushes and grass and there are also areas with bare soil. At the outlet is situated the reservoir for the hydropower plant of Corani. The area of the reservoir is about 10km^2.

Five precipitation stations were used to calculate the areal precipitation (see Figure 6). The mean annual precipitation for each station is given in Table 1. The basin was divided into three subbasins with not too great differences in precipitation within each subbasin.

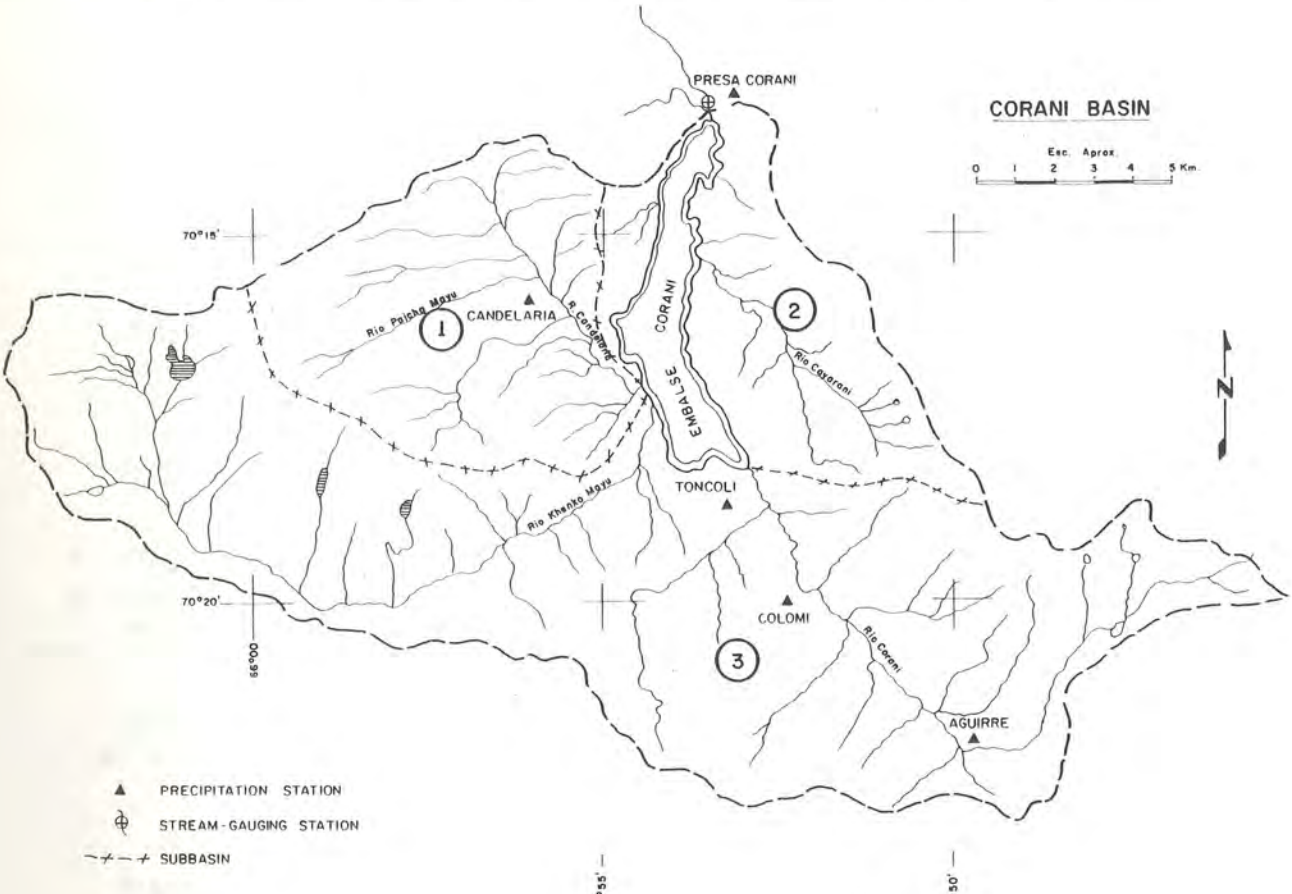


Figure 6. Map of the Corani basin with subbasins.

Station	Elevation (m.a.s.l)	Annual precipitation (mm)
Aguirre	3350	830
Candelaria	3380	920
Colomi	3300	670
Presa Corani	3200	2520
Toncoli	3280	680

Table 1. Precipitation stations used for Corani

For the estimates of potential evapotranspiration, monthly averages from observations at Toncoli were used.

The inflow to the reservoir, used for the model calibration, was calculated from the flow through the turbines of the power plant, the reservoir levels and the spill across the reservoir spillway. During 1982 and 1983 the level of the dam was raised by 4 meters. No reliable data of the spill were available during this period, but it has been assumed that no water was spilled.

The model has been run from 1968 (when the construction of the dam was completed and reservoir level data available) until 1983. In 1984 the inflow to the reservoir was increased by a transfer from Rio Malaga. Due to a temporary lack of data of the magnitude of these disharges, the model was not run from 1984 and onwards.

3.2. Locotal

The area of the basin of Locotal is 200 km^2. The lower parts are covered with thick vegetation, decreasing with increasing altitude. The elevation ranges from 1700 m.a.s.l to 4200 m.a.s.l.

For the model calculations the basin was divided into four subbasins (see the map of Figure 7). One subbasin represents the area upstreams the discharge station Málaga 3200, and the model parameters for this part of the basin were determined separately. By having one subbasin for Rio Málaga and one for Rio Sta Isabel, the discharge from each of these rivers can easily be computed if desired.

Four stations were available for calculation of areal precipitation (see Table 2 for station characteristics). This was not quite satisfactory as the amount of precipitation differed considerably between the stations and no systematic variations could be found.

The potential evapotranspiration values used by the model were estimated from observations at Toncoli and Corani, both stations situated in the Corani basin.

The power plant of Corani is actually situated within the basin of Locotal, and the water from the Corani reservoir is lead to the plant through a tunnel. This means that the observed runoff values at the station at Locotal include the flow through the plant. The cross section at this station varies due to erosion and bed-load transport. Flow measurements are often made in order to have a correct stage - discharge relation, but there are still periods when the discharge values are uncertain.

Model calculations have been made from 1967 to 1983, whereafter the transfer from Rio Málaga to Rio Corani was started.

3.3. Miguillas

The area of the basin of Miguillas is 420 km^2 and the elevation ranges from 1950 m.a.s.l to 5600 m.a.s.l.

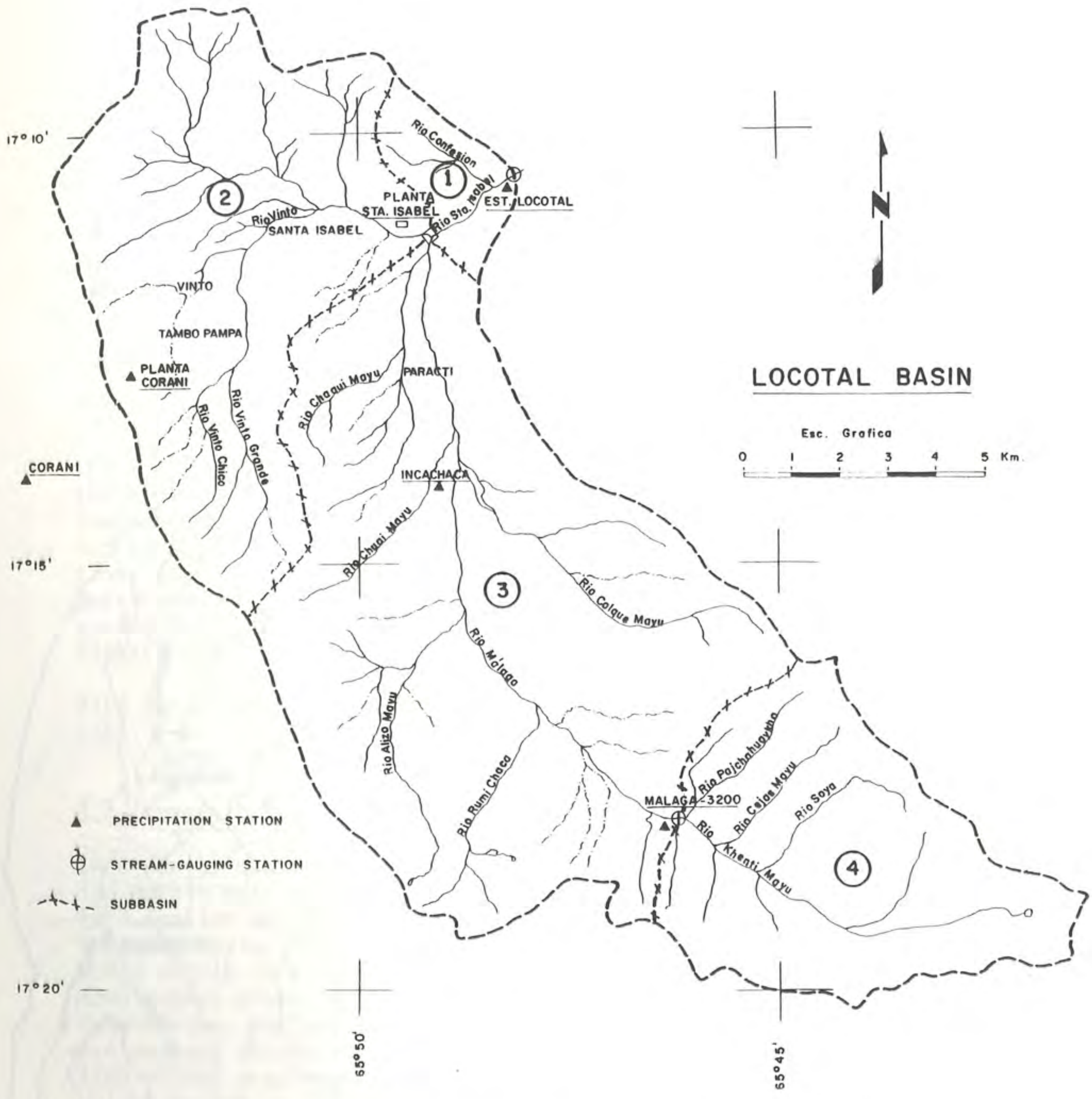


Figure 7. Map of the Locotal basin with subbasins.

Station	Elevation (m.a.s.l)	Annual precipitation (mm)
Incachaca	2300	1690
Locotal	1700	2630
Málaga 3200	3200	2070
Planta Corani	2700	2950

Table 2. Precipitation stations used for Locotal

Precipitation data from 9 stations were available for the model calculations (see Table 3 and Figure 8) but these stations were unevenly distributed within the basin. Due to this, the basin was divided into three subbasins, representing different altitudes. It was then assumed that the precipitation at a certain altitude could be represented by stations at approximately the same level.

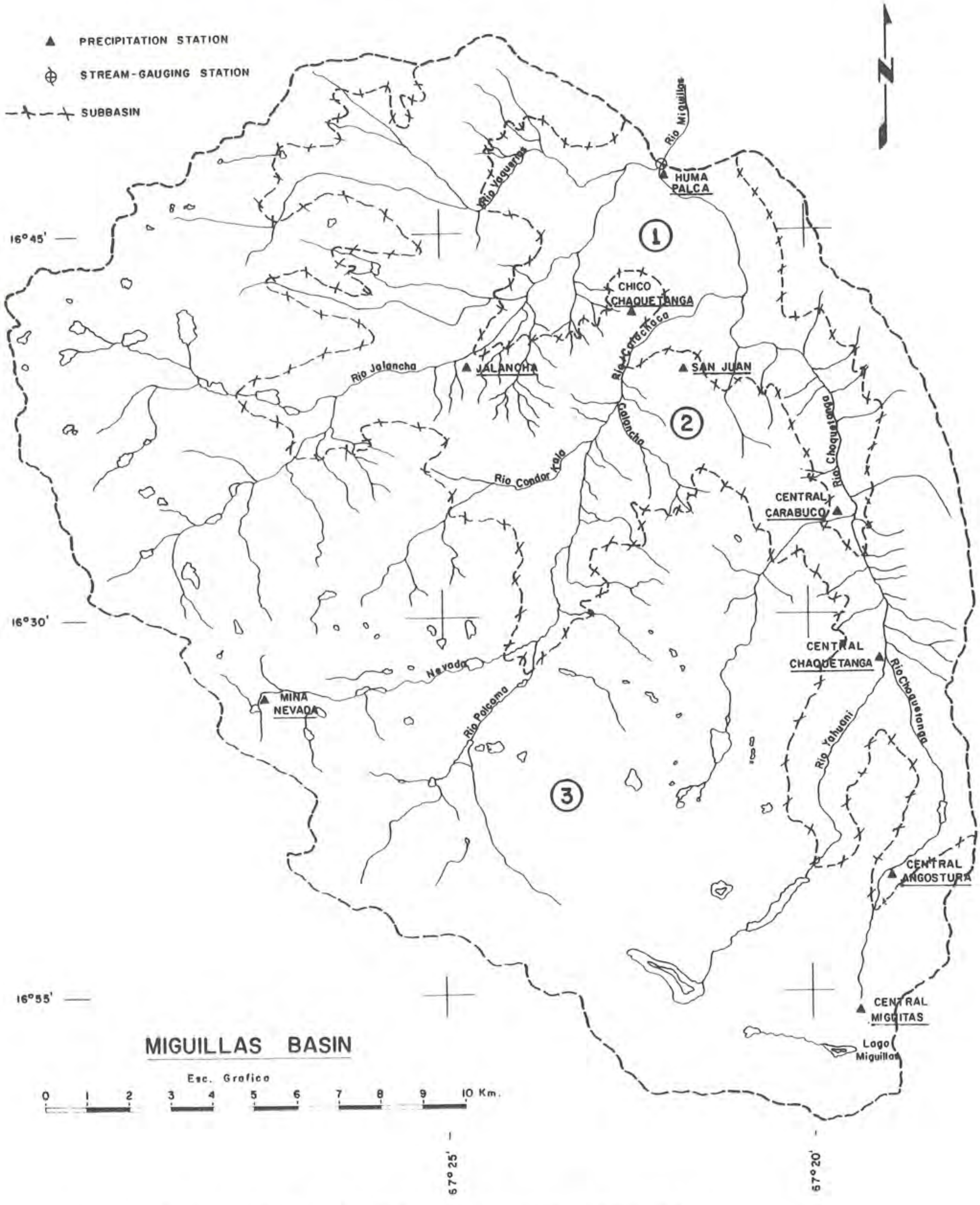


Figure 8. Map of the Miguillas basin with subbasins.

Station	Elevation (m.a.s.l)	Annual precipitation (mm)
Angostura	3800	1600
Carabuco	2900	1400
Choquetanga	3200	1300
Chico Choquetanga	3300	1690
Humapalca	1950	1360
Jalancha	3200	1680
Miguillas	4200	1630
Mina Nevada	4650	1030
San Juan (Calachaca)	3250	1480

Table 3. Precipitation stations used for Miguillas

The vegetation in the lowest altitudes consists of low forests and in the middle altitudes of bushes and grass. In the higher altitudes there are bare rocks and lichen. The highest mountain peaks are covered by snow, but this has not been considered in the model calculations as no temperature observations were available. As no evaporation measurements have been made in the region of Miguillas, the potential evapotranspiration was assumed to be the same as for Locotal were the climatic conditions are similar.

Data for running the model were available from August 1972 to October 1983.

3.4. Precipitation data

In order to check the homogeneity of the precipitation series, so called double mass plots were made. The accumulated precipitation for each station was plotted against the mean of the other stations within the same basin. If all the time series were perfectly homogenous this would result in a straight line. The appendix shows examples of these double-mass plots. Most of the precipitation series show slight inhomogeneities, but not such great ones that it has proved necessary to exclude any station. If one station has a great weight in the calculation of the areal precipitation an inhomogeneity may cause sudden volume errors in the computed discharges. This was, however, not observed in the model calculations referred in the report.

When there were short gaps (one or two months) in the precipitation series, these gaps were filled in with data from neighbouring stations. In some cases correlation between the stations was used to get the monthly sum (ENDE 1984, HEC-4 1971)

4. CALIBRATION AND RESULTS

The parameter values obtained in the calibration procedure are listed for each basin in Tables 4-6. Below is given a short guide to the understanding of these tables.

- The parameter AREA gives the area for each subbasin in km^2. The first value corresponds to subbasin number 1, the second to number 2 etc (see the maps of the basins).

- ELEV, PELEV and EVDAY are parameters not used in Corani, Locotal and Miguillas.

- LAKE is the part of each subbasin that consists of lakes and VEG is 1-LAKE.

- QFACT and CQ are coefficients used to convert observed discharges to m^3/s and reservoir levels to storage.

- CP are the weights for each precipitation station. The number of values for each subbasin equals the number of precipitation stations.

- The estimates of monthly mean potential evaporation (in mm/day) is given in the parameter EVAP.

- The parameters from PCORR to MAXBAS may be given one value for each subbasin or the same value for the whole basin. For their explanation, see the model description of section 2.

The parameters AREA, VEG, LAKE, CQ, QFACT and EVAP are fixed and normally not changed during the calibration procedure. Some parameters, like the station weights and PCORR, may have limited periods of validity, as a station is started or taken out of operation.

The areal precipitation is determined as the weighted mean of the precipitation of the stations. For Corani, Locotal and Miguillas these weights were determined in a subjective way. Another way is to use more objective methods, like the Thiessen polygones. However, when there are few stations, these methods do not take into consideration basin characteristics like topography and precipitation patterns.

In none of the model calculations described in this report, the possibility of dividing the subbasins into elevation zones and applying a precipitation lapse rate to each zone was used. It was not considered meaningful as no simple relation could be found between precipitation and elevation.

BASIN: EMBALSE CORANI

PARAMETERFILE VALID DATE: 12-03-1986
TIME: 15:42:12

Nr	Name	Valid from												
1	AREA	1968 2 1	59.00	52.00	176.00									
2	ELEV	1968 2 1	0.00	0.00	0.00									
3	VEG	1968 2 1	0.99	0.80	0.99									
4	LAKE	1968 2 1	0.01	0.20	0.01									
5	PELEV	1968 2 1	0.00	0.00	0.00	0.00	0.00							
7	QFACT	1968 2 1	0.01	-1.00	-1.00	0.00								
8	CP	1968 2 1	0.00	0.30	0.15	0.30	0.25	0.00	0.10	0.10	0.60	0.20	0.10	0.00
			0.40	0.00	0.50									
10	CQ	1968 2 1	1.00	0.00	1.00	-1.00	0.50	0.50	0.00	0.00				
11	EVAP	1968 2 1	3.32	3.68	3.10	3.10	3.55	3.40	3.16	3.30	3.33	3.48	3.93	3.48
12	EVDAY	1968 2 1	0.00											
20	PCORR	1968 2 1	1.00000											
21	PCALT	1968 2 1	0.00000											
27	FC	1968 2 1	200.00000											
28	LP	1968 2 1	175.00000											
29	BETA	1968 2 1	1.25000											
36	PERC	1968 2 1	1.00000											
37	UZL	1968 2 1	15.00000											
38	K0	1968 2 1	0.90000											
39	K1	1968 2 1	0.30000											
40	K2	1968 2 1	0.05000											
43	CEVP	1968 2 1	1.00000											
46	MAXBAS	1968 2 1	1.00000											
8	CP	1969 3 31	0.00	0.30	0.15	0.30	0.25	0.00	0.10	0.10	0.60	0.20	0.00	0.00
			0.45	0.00	0.55									
8	CP	1969 10 31	0.00	0.30	0.15	0.30	0.25	0.00	0.10	0.10	0.60	0.20	0.10	0.00
			0.40	0.00	0.50									
8	CP	1969 12 31	0.00	0.30	0.15	0.30	0.25	0.00	0.10	0.10	0.60	0.20	0.00	0.00
			0.45	0.00	0.55									
8	CP	1970 10 31	0.00	0.30	0.15	0.30	0.25	0.00	0.10	0.10	0.60	0.20	0.10	0.00
			0.40	0.00	0.50									
8	CP	1979 3 31	0.00	0.80	0.10	0.10	0.00	0.00	0.25	0.10	0.65	0.00	0.10	0.40
			0.40	0.10	0.00									
20	PCORR	1979 3 31	0.90000											
7	QFACT	1982 1 1	0.01	-1.00	0.00	-1.00								
10	CQ	1982 1 1	1.00	0.00	1.00	-1.00	0.00	0.00	0.50	0.50				

Table 4.

BASIN: LOCOTAL

PARAMETERFILE VALID DATE: 12-03-1986
TIME: 15:41:00

Nr	Name	Valid from												
1	AREA	1966 10 1	7.00	58.00	96.30	38.70								
2	ELEV	1966 10 1	0.00	0.00	0.00	0.00								
3	VEG	1966 10 1	1.00	1.00	1.00	1.00								
4	LAKE	1966 10 1	0.00	0.00	0.00	0.00								
5	PELEV	1966 10 1	0.00	0.00	0.00	0.00								
7	QFACT	1966 10 1	0.01	0.01	0.00									
8	CP	1966 10 1	0.00	1.00	0.00	0.00	0.30	0.30	0.00	0.40	0.60	0.20	0.10	0.10
			0.00	0.00	1.00	0.00								
10	CQ	1966 10 1	-1.00	0.00	1.00	0.00	0.00	0.00						
11	EVAP	1966 10 1	2.05	2.43	2.00	1.70	1.58	1.60	1.47	1.29	1.82	2.39	2.37	2.19
12	EVDAY	1966 10 1	0.00											
20	PCORR	1966 10 1	1.00000											
21	PCALT	1966 10 1	0.00000											
27	FC	1966 10 1	250.00000	260.00000	270.00000	380.00000								
28	LP	1966 10 1	225.00000											
29	BETA	1966 10 1	1.50000											
36	PERC	1966 10 1	10.00000	8.00000	6.00000	5.00000								
37	UZL	1966 10 1	50.00000	50.00000	50.00000	60.00000								
38	K0	1966 10 1	0.40000											
39	K1	1966 10 1	0.25000	0.25000	0.25000	0.15000								
40	K2	1966 10 1	0.05000											
43	CEVP	1966 10 1	1.10000	1.15000	1.15000	1.40000								
46	MAXBAS	1966 10 1	1.00000											
8	CP	1967 1 1	0.00	1.00	0.00	0.00	0.50	0.50	0.00	0.00	0.80	0.20	0.00	0.00
			1.00	0.00	0.00	0.00								
8	CP	1967 2 1	0.00	1.00	0.00	0.00	0.10	0.50	0.00	0.40	0.50	0.30	0.00	0.20
			1.00	0.00	0.00	0.00								
8	CP	1968 3 31	0.00	1.00	0.00	0.00	0.00	0.50	0.00	0.50	0.00	0.50	0.00	0.50
			0.00	0.40	0.00	0.60								
20	PCORR	1968 3 31	0.80000											
8	CP	1969 6 1	0.00	1.00	0.00	0.00	0.10	0.50	0.00	0.40	0.50	0.30	0.00	0.20
			1.00	0.00	0.00	0.00								
20	PCORR	1969 6 1	1.00000											
8	CP	1969 11 1	0.00	1.00	0.00	0.00	0.10	0.50	0.00	0.40	0.40	0.20	0.30	0.10
			0.00	0.00	1.00	0.00								
8	CP	1976 8 31	0.00	1.00	0.00	0.00	0.50	0.50	0.00	0.00	0.40	0.20	0.40	0.00
			0.00	0.00	1.00	0.00								
8	CP	1978 1 1	0.00	1.00	0.00	0.00	0.10	0.50	0.00	0.40	0.40	0.20	0.30	0.10
			0.00	0.00	1.00	0.00								

Table 5.

BASIN: MIGUILLAS

PARAMETERFILE VALID DATE: 12-03-1986
TIME: 15:38:53

Nr	Name	Valid from												
1	AREA	1971 6 1	45.00	145.00	230.00									
2	ELEV	1971 6 1	0.00	0.00	0.00									
3	VEG	1971 6 1	1.00	1.00	0.95									
4	LAKE	1971 6 1	0.00	0.00	0.05									
5	PELEV	1971 6 1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00			
7	QFACT	1971 6 1	0.01											
8	CP	1971 6 1	0.00	0.00	0.25	0.75	0.00	0.00	0.00	0.00	0.00	0.20	0.00	0.35
			0.45	0.00	0.00	0.00	0.00	0.00	0.15	0.00	0.15	0.20	0.00	0.00
			0.00	0.50	0.00									
10	CQ	1971 6 1	1.00											
11	EVAP	1971 6 1	2.05	2.43	2.00	1.70	1.58	1.60	1.47	1.29	1.82	2.39	2.37	2.19
20	PCORR	1971 6 1	1.05000	1.05000	1.26000									
21	PCALT	1971 6 1	0.00000											
27	FC	1971 6 1	250.00000											
28	LP	1971 6 1	200.00000											
29	BETA	1971 6 1	1.10000											
36	PERC	1971 6 1	3.00000											
37	UZL	1971 6 1	50.00000											
38	K0	1971 6 1	0.40000											
39	K1	1971 6 1	0.10000											
40	K2	1971 6 1	0.01000											
43	CEVP	1971 6 1	1.00000											
46	MAXBAS	1971 6 1	1.00000											
8	CP	1971 12 1	0.00	0.25	0.15	0.35	0.00	0.00	0.25	0.00	0.00	0.10	0.13	0.25
			0.30	0.10	0.00	0.12	0.00	0.00	0.11	0.08	0.11	0.08	0.11	0.00
			0.08	0.23	0.20									
8	CP	1972 7 1	0.00	0.15	0.15	0.15	0.00	0.40	0.15	0.00	0.00	0.10	0.10	0.25
			0.25	0.10	0.10	0.10	0.00	0.00	0.34	0.06	0.11	0.06	0.11	0.06
			0.06	0.00	0.20									
8	CP	1975 5 1	0.00	0.15	0.15	0.15	0.00	0.40	0.15	0.00	0.00	0.00	0.10	0.35
			0.35	0.00	0.10	0.10	0.00	0.00	0.00	0.06	0.22	0.06	0.00	0.06
			0.40	0.00	0.20									
8	CP	1978 1 1	0.00	0.15	0.15	0.15	0.00	0.40	0.15	0.00	0.00	0.10	0.10	0.25
			0.25	0.10	0.10	0.10	0.00	0.00	0.15	0.06	0.11	0.23	0.11	0.02
			0.06	0.06	0.20									
20	PCORR	1978 1 1	1.05000	1.05000	1.26000									
8	CP	1978 12 1	0.00	0.35	0.15	0.35	0.00	0.00	0.15	0.00	0.00	0.10	0.15	0.25
			0.30	0.10	0.00	0.10	0.00	0.00	0.06	0.11	0.11	0.10	0.28	0.00
			0.34	0.00	0.00									
20	PCORR	1978 12 1	0.90000	0.90000	1.10000									

Table 6.

4.1. Corani

The parameters determined in the calibration procedure gave an explained variance (the R^2-value) of 0.75 for the period with observed discharge data (approximately 1968 to 1983). The volume errors in the computed discharges were small. Figure 9 a-b shows examples of model results for the subperiods December 1969 - April 1971 and December 1980 to April 1982. The duration curves for observed and computed discharges are shown in Figure 12. Rio Corani responds guickly to precipitation, which shows for instance in the parameter K0, which is close to 1. As the reservoir levels are used in the computation of the "observed" inflow to the reservoir, quite small errors in these measurements may sometimes cause considerable errors in the observed hydrograph, see for example July 1981.

4.2. Locotal

By setting the areas of subbasins numer 1 to 3 to zero the parameters for subbasin number 4 (see map, Figure 7) were determined by a separate calibration to discharge observations at Málaga 3200. This calibration showed that the evaporation in this part was higher than for the rest of the basin (see parameters FC and CEVP), while the percolation to the lower zone of the response function was smaller. From knowledge of the basin characteristics, it was assumed that these parameters should be changed gradually from the lower to the upper parts of the basin.

Figure 10a shows examples of model results for subbasin number 4, and figure 10 b-c for the whole basin of Locotal.

The explained variance for the period with observed disharges was for Locotal 0.71. The volume errors are greater than for Corani and Miguillas but still of an acceptable order of magnitude. During some periods (for example 1981 and 1983) it is difficult to draw any conclusions about the model behaviour, as the observed discharge values are uncertain.

4.3. Miguillas

The highest mountain peaks in this basin are covered by snow, which could not be considered in the model calculations due to the lack of temperature data. However, when comparing the observed and computed hydrographs, it does not seem that the influence of snow melt and ablation is of great importance (see examples of Figure 11 and Figure 12 d).

The precipitation correction factor, PCORR, was for subbasin number 3 (the one of the highest altitudes) assigned quite a high value, 1.26. It was assumed that the station mainly representing the altitudes of this subbasin considerably underestimated the precipitation.

The volume errors in the computed discharges were small for Miguillas. For the periods with observed discharge data the explained variance was determined to 0.80.

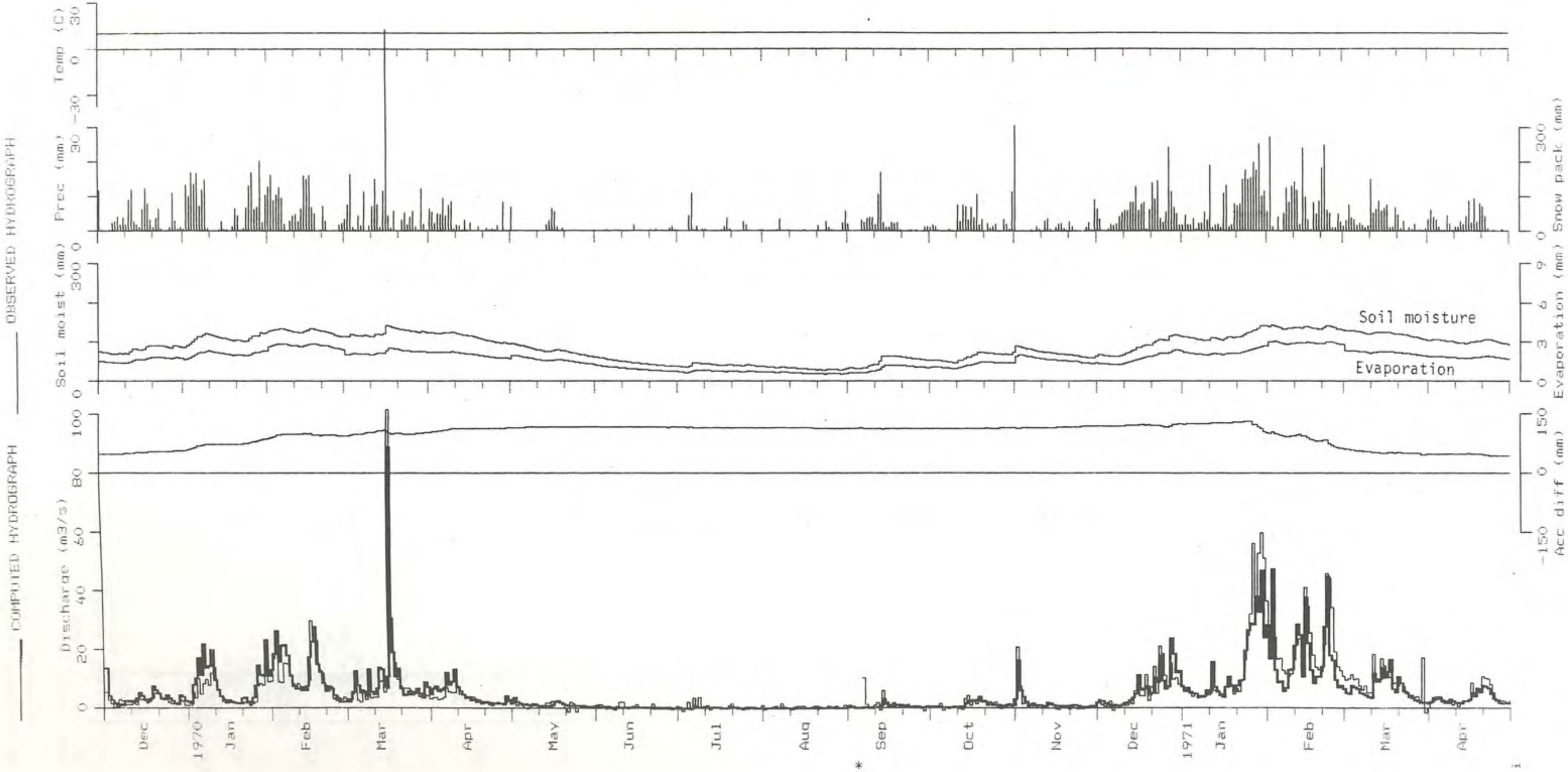


Figure 9a. Model results for Corani. For this period the R^2-value is 0.82.

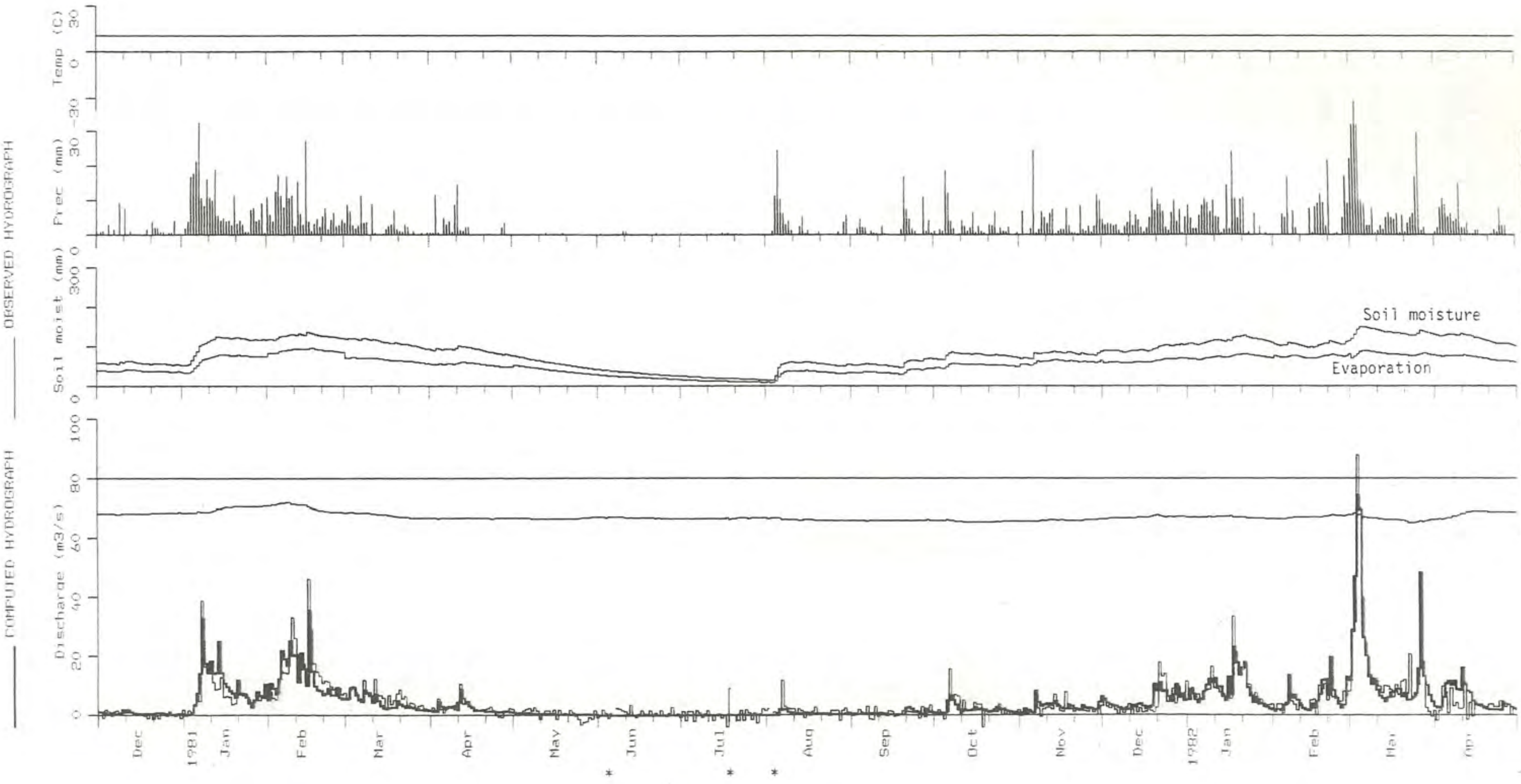


Figure 9b. Model results for Corani. For this period the R^2-value is 0.85.

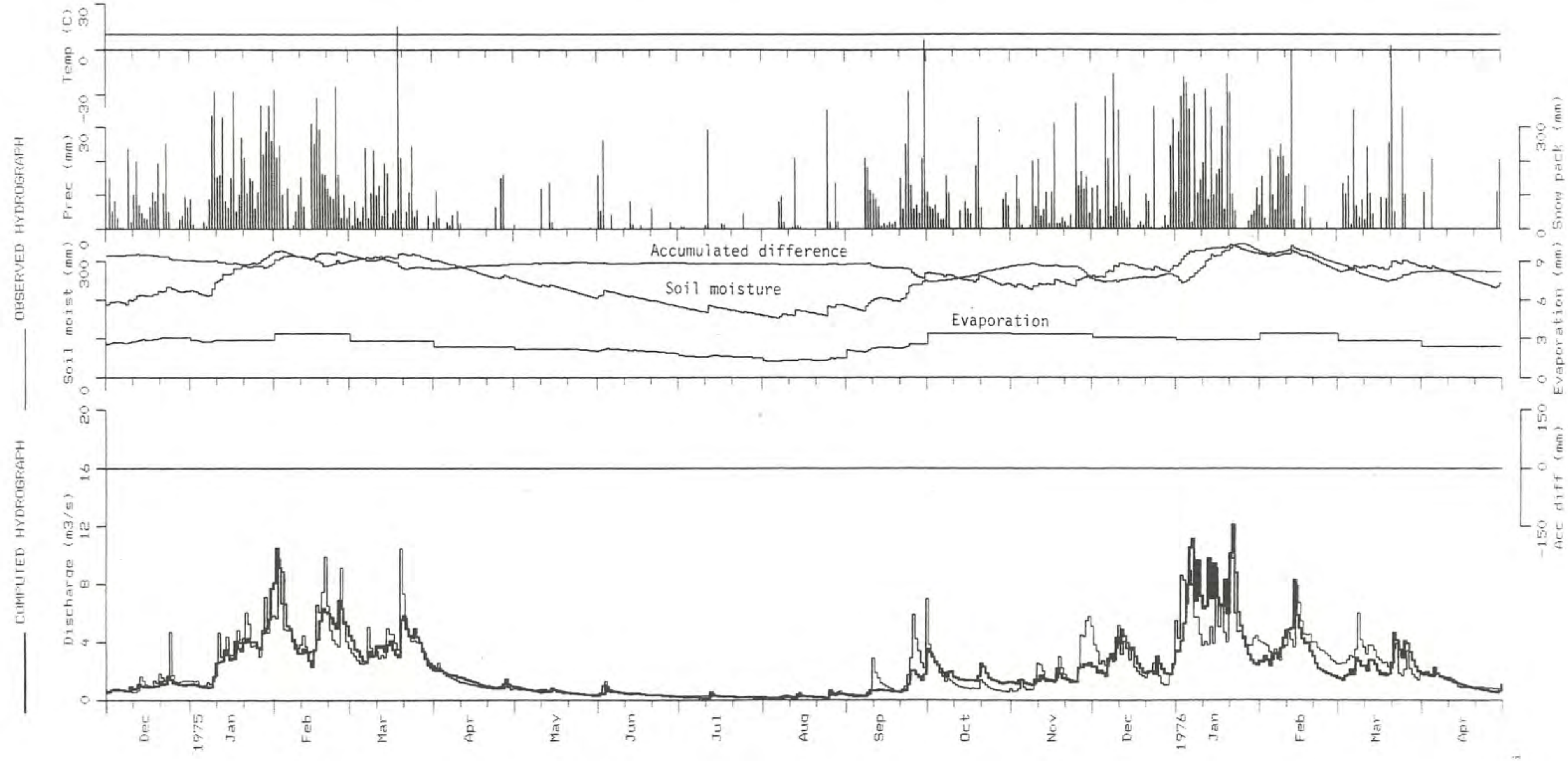


Figure 10a. Model results for Málaga 3200. For this period the R^2-value is 0.72.

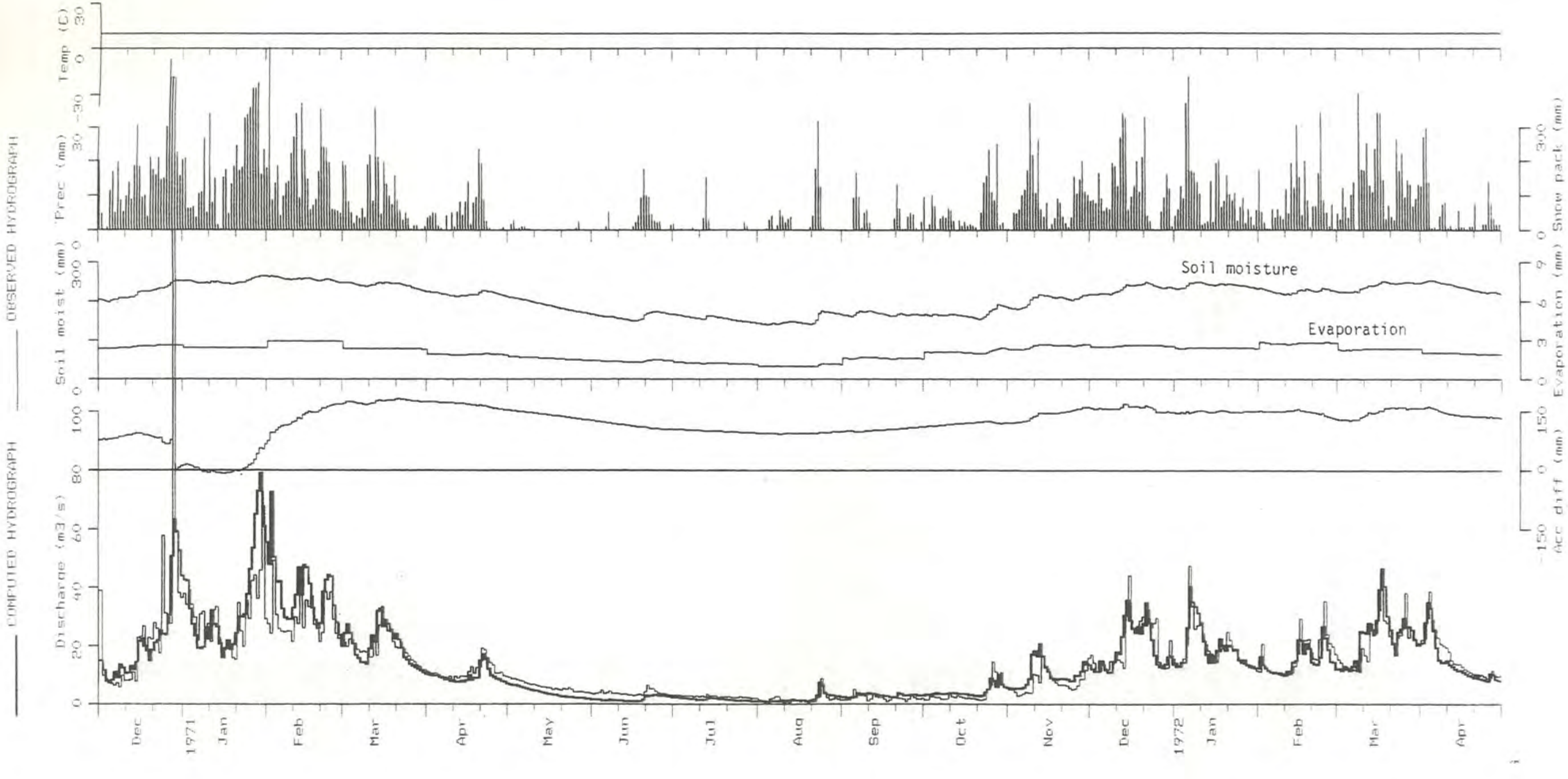


Figure 10b. Model results for Locotal. For this period the R^2*-value is 0.61.*

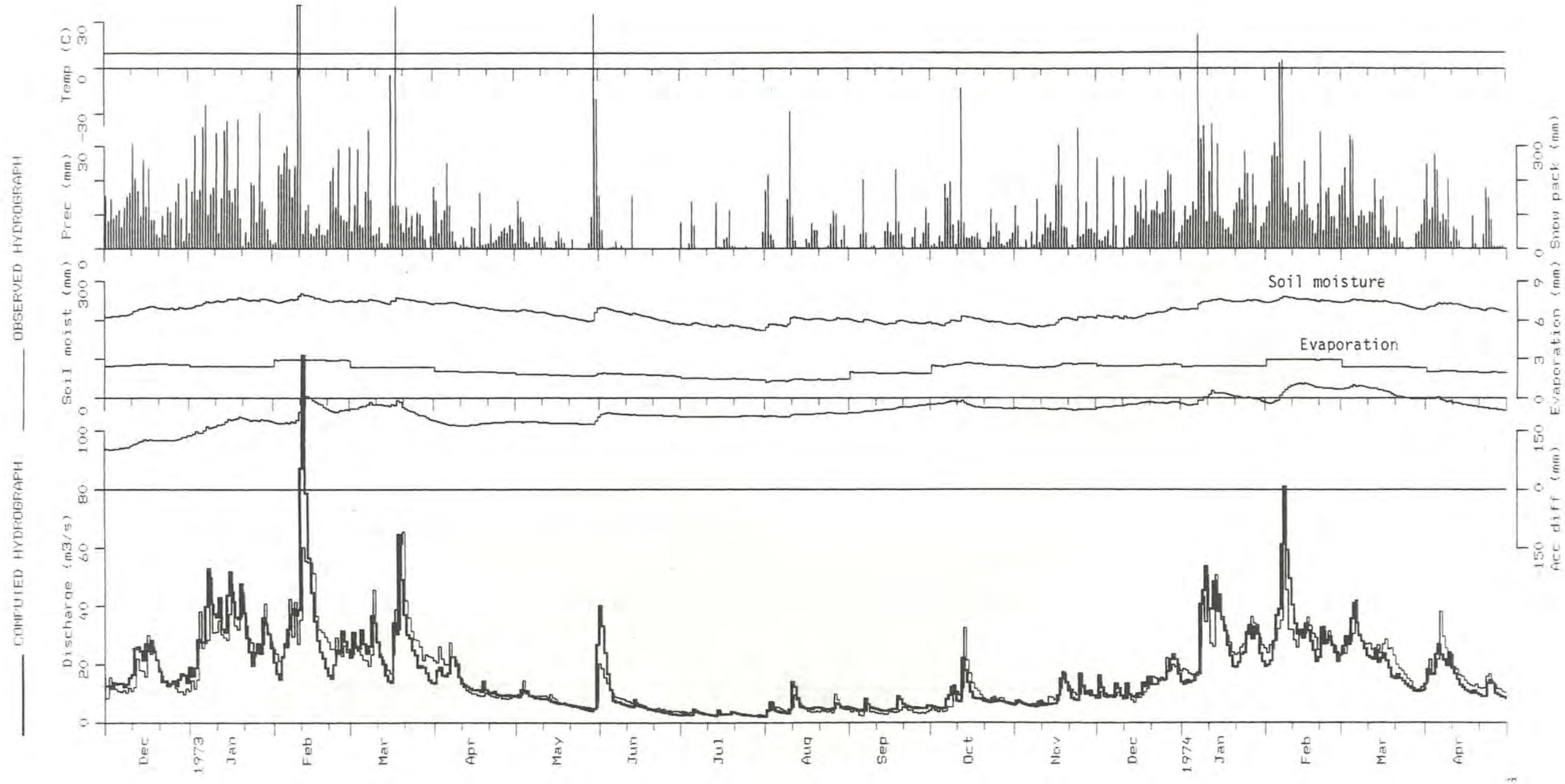


Figure 10c. Model results for Locotal. For this period the R^2-value is 0.68.

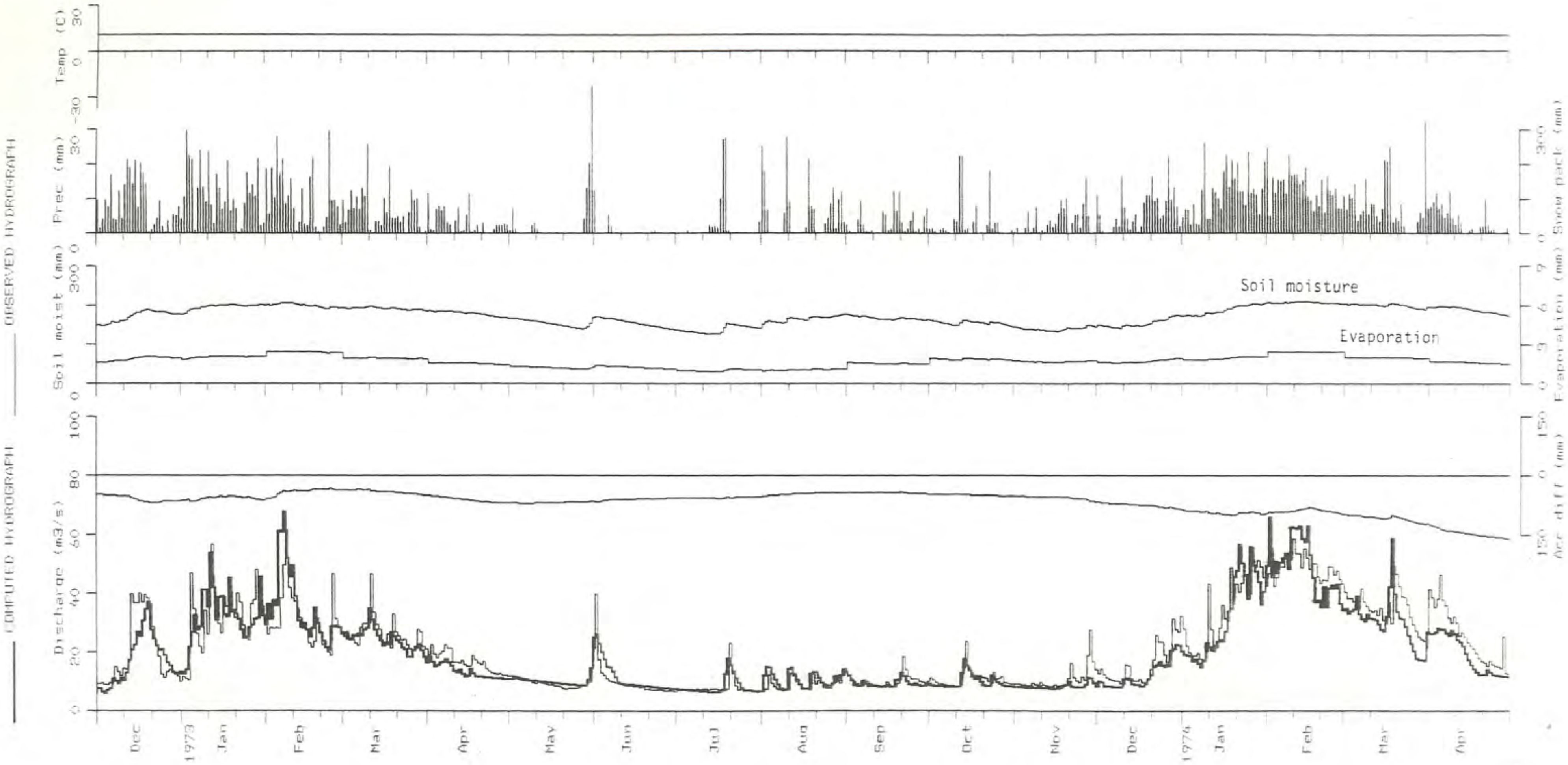


Figure 11a. Model results for Miguillas. For this period the R^2-value is 0.81.

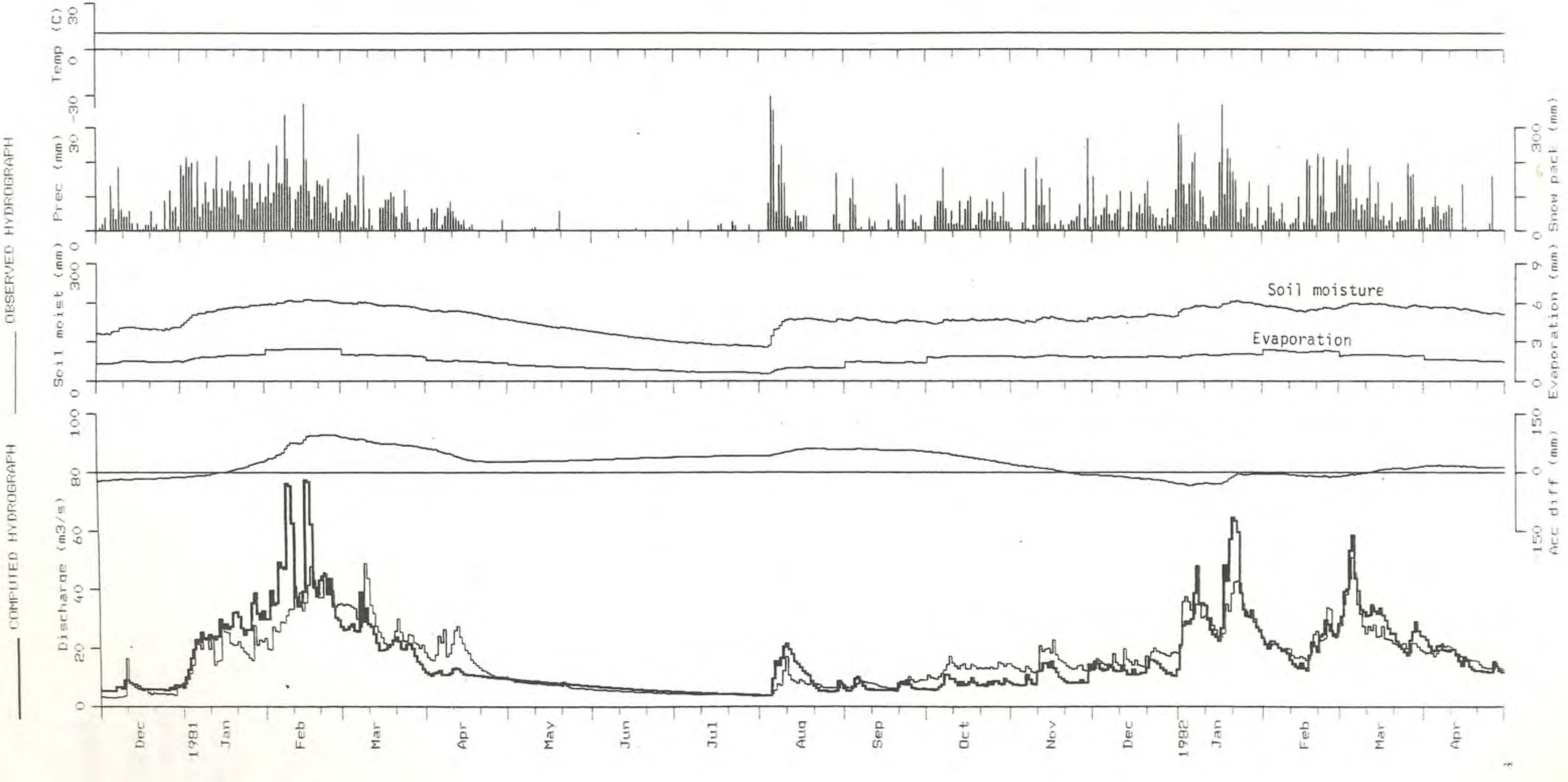


Figure 11b. Model results for Miguillas. For this period the R^2*-value is 0.58.*

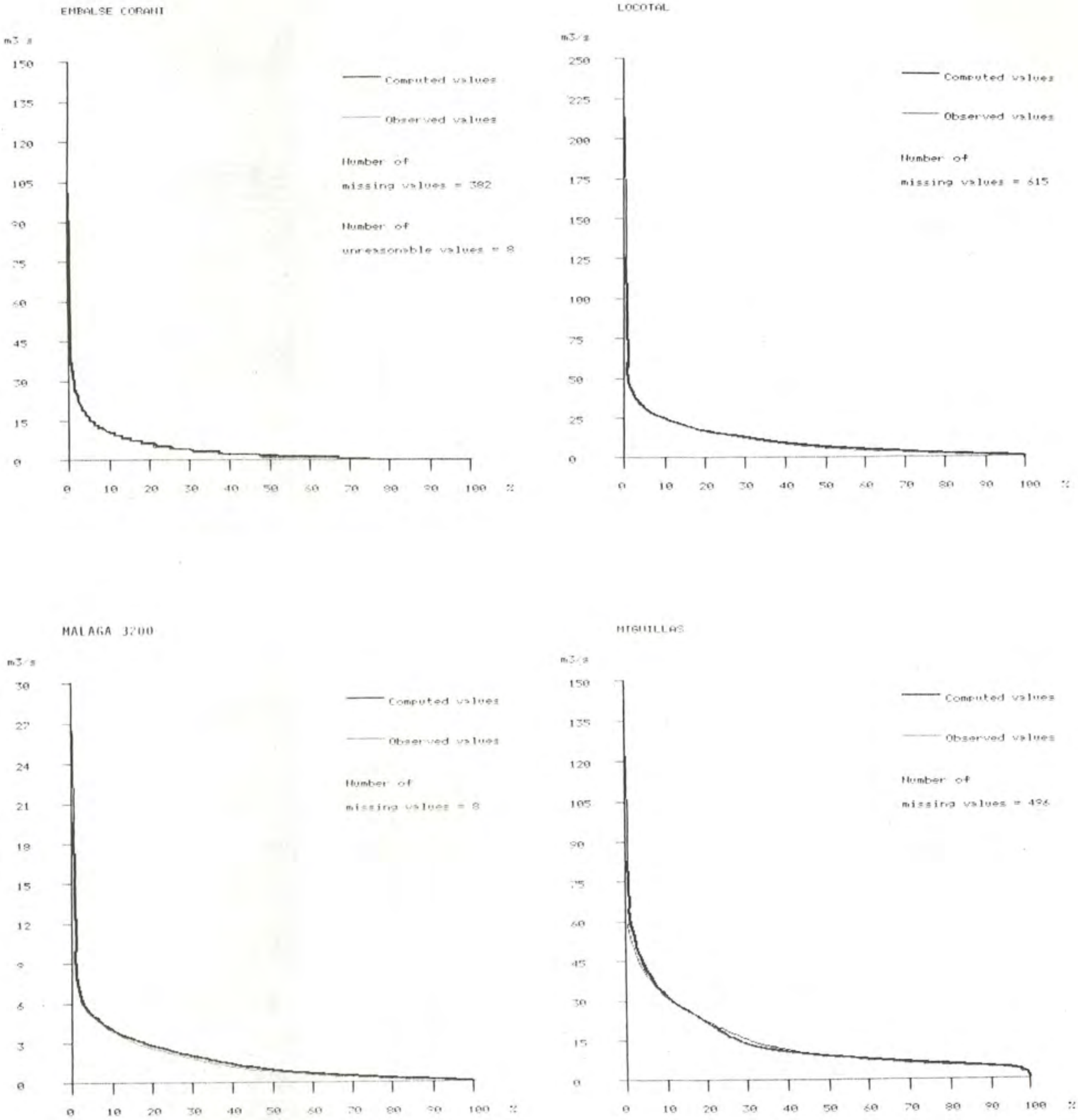


Figure 12. Duration curves of computed and observed hydrograph. Days with missing observations have been omitted.

5. CONCLUSIONS

The application of the HBV-model to three Bolivian rivers shows that the model accounts for between 70 and 80 % of the variance of the observed runoff from these basins. The volume errors are small for two of the basins, Corani and Miguillas, but will for Locotal, for some periods, be of a higher order of magnitude.

The numerically greater errors in Locotal can partly be explained by the higher precipitation in this basin than in the others. Sometimes there are also obvious errors in the observed discharges. But it is probable that the model behaviour would be improved if more precipitation data were available. The amount of precipitation differs considerably between the four stations used and no geographical pattern could be found.

As the coverage of precipitation stations for Miguillas is not satisfactory, the good results for this basin were a little unexpected. Knowledge of the basin characteristics where here essential to perform the calibration. This made it possible to choose station weights and precipitation correction factors in an optimum way.

The general conclusion, is that the HBV-model works well for Bolivian conditions and is a tool that can be used for hydropower planning in Bolivia.

6. ACKNOWLEDGEMENTS

This project was supported by the Swedish Agency for Technical and Economic Co-operation (BITS).

Thanks are also due to Mr. Arne Forsman, the project leader, and Mr. Ola Grahn for valuable assistance in computer techniques.

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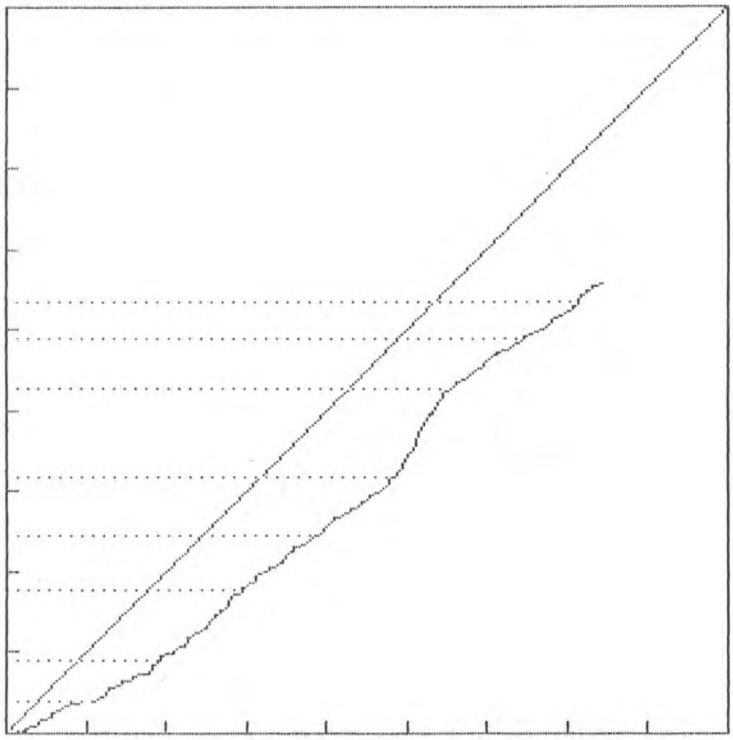
APPENDIX

Double mass plots of precipitation data

B A S I N : EMBALSE CORANI



STATION 1

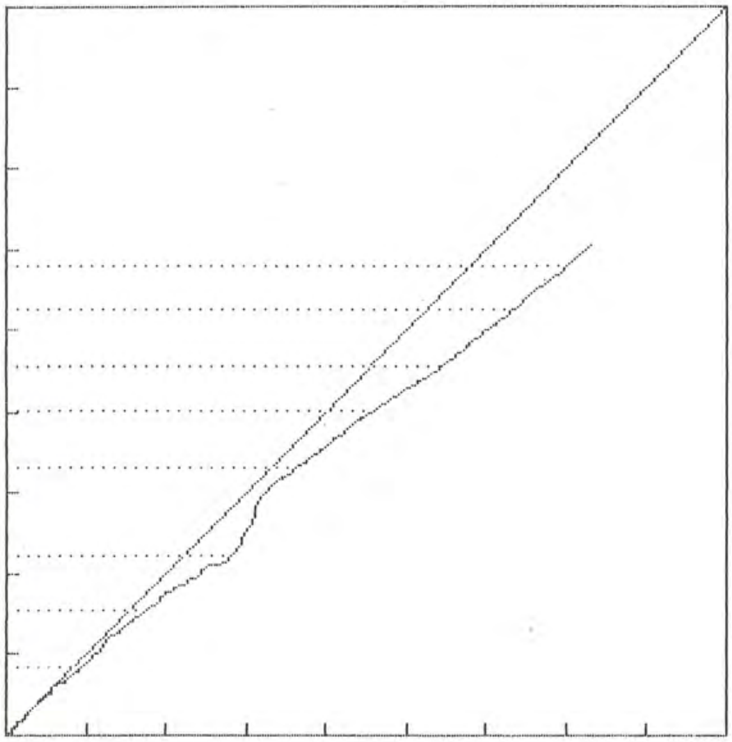
AGUIRRE

PERIOD:

1970 11 1 - 1979 2 28

SCALE UNIT: 1500 MM

B A S I N : EMBALSE CORANI



STATION 2

CANDELARIA

PERIOD:

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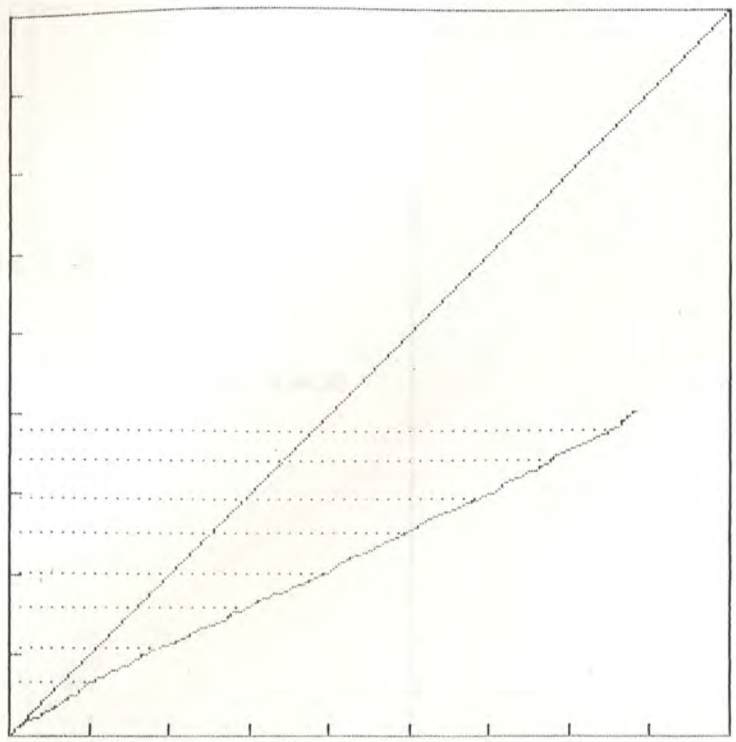

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COLOMI

PERIOD:
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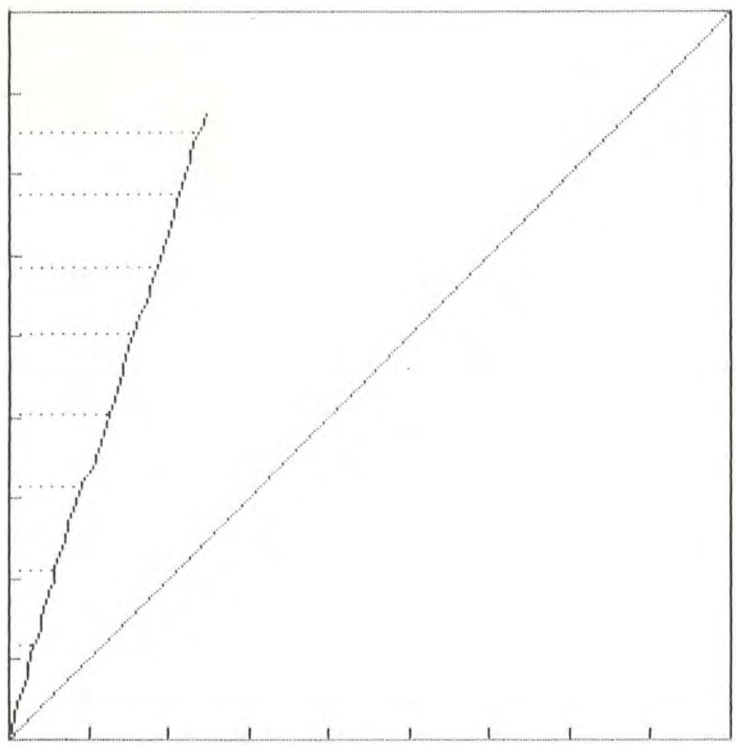

STATION 4

CORANI REP

PERIOD:
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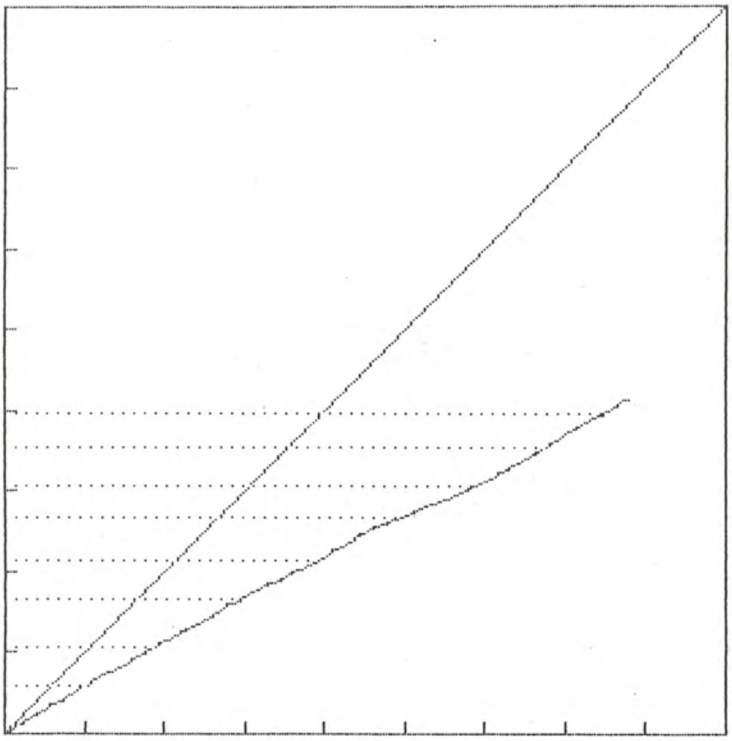
B A S I N : EMBALSE CORANI



STATION 5

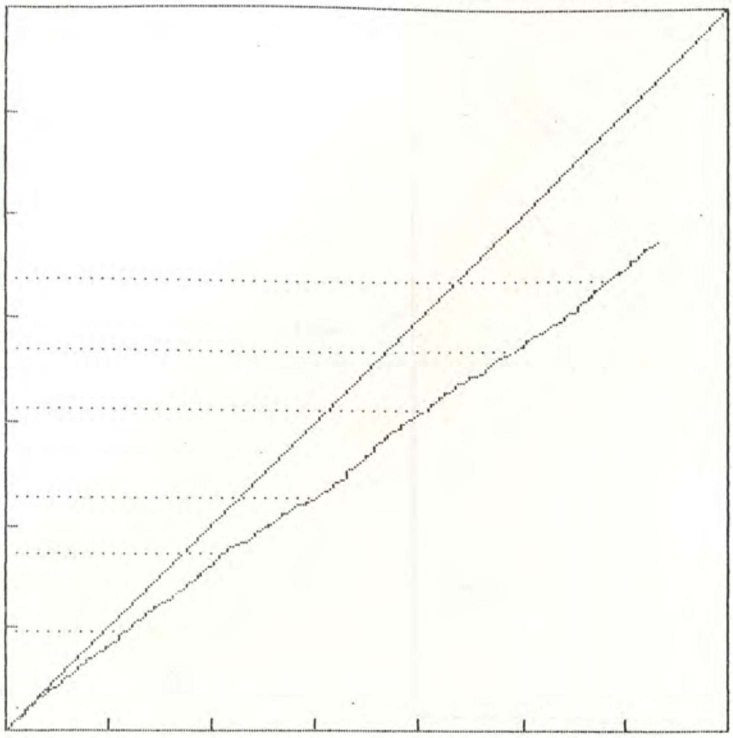
TONCOLI

PERIOD:

1970 11 1 - 1979 2 28

SCALE UNIT: 1500 MM

B A S I N : LOCOTAL



STATION 1

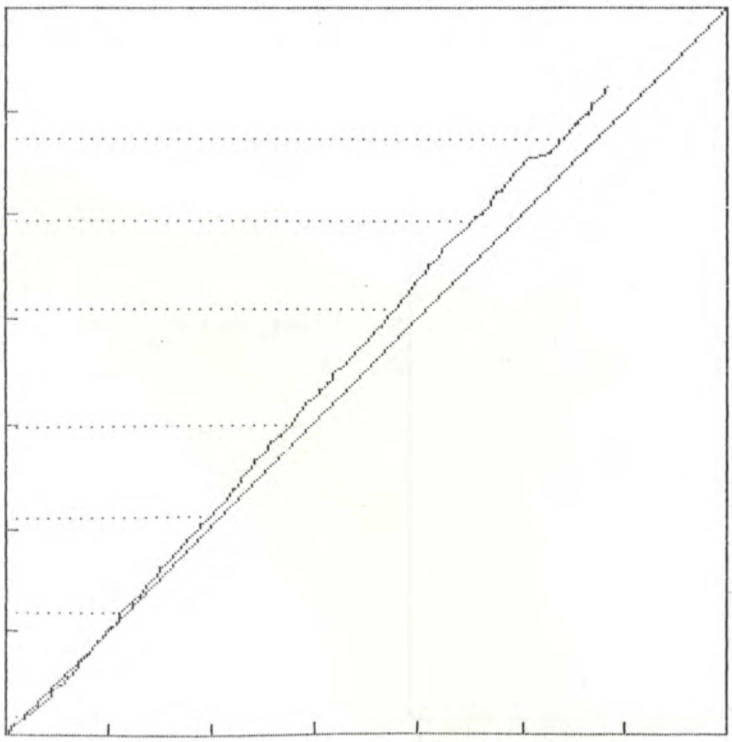
INCACHACA

PERIOD:

1969 11 1 - 1976 7 31

SCALE UNIT: 3000 MM

B A S I N : LOCOTAL



STATION 2

LOCOTAL

PERIOD:

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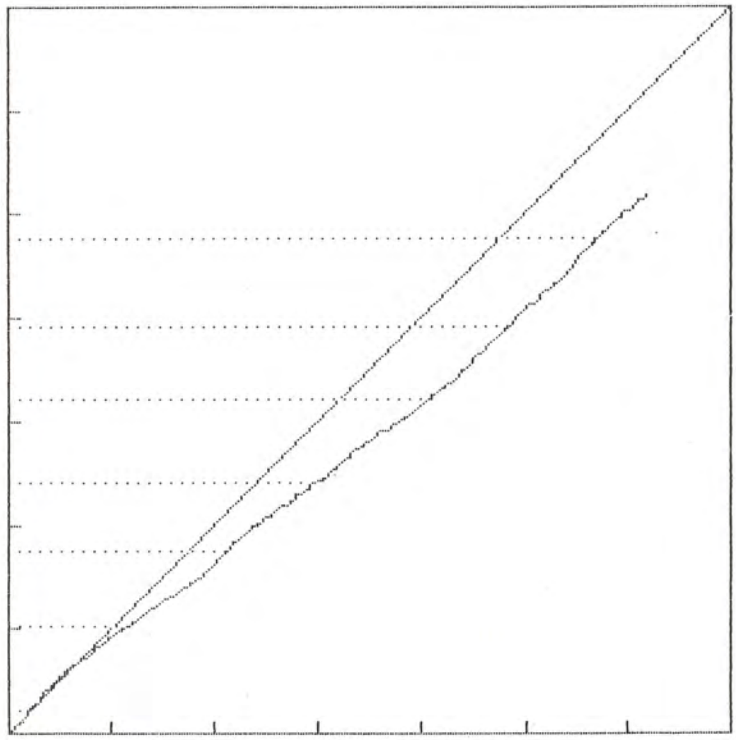

STATION 3

MALAGA3200

PERIOD:

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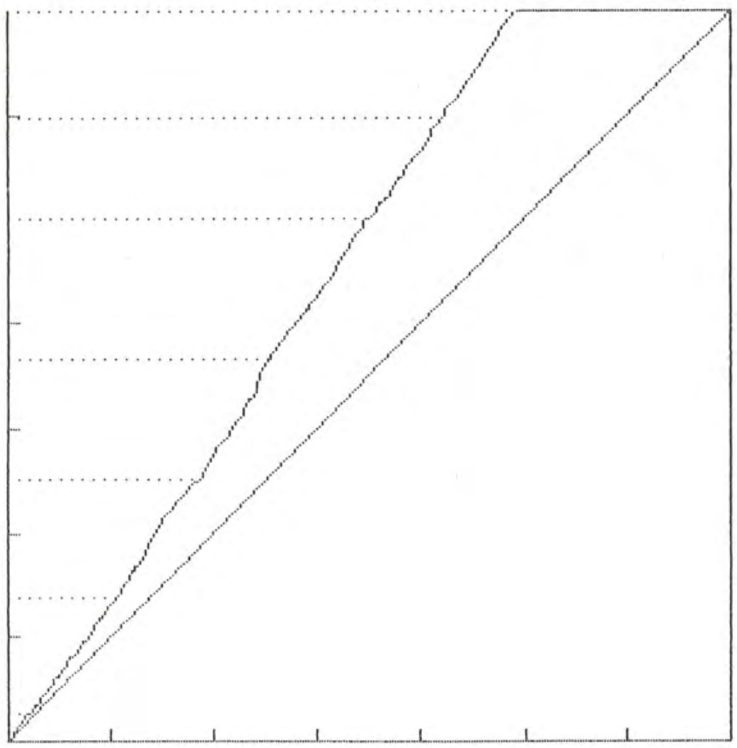
SCALE UNIT: 3000 MM

B A S I N : LOCOTAL



STATION 4

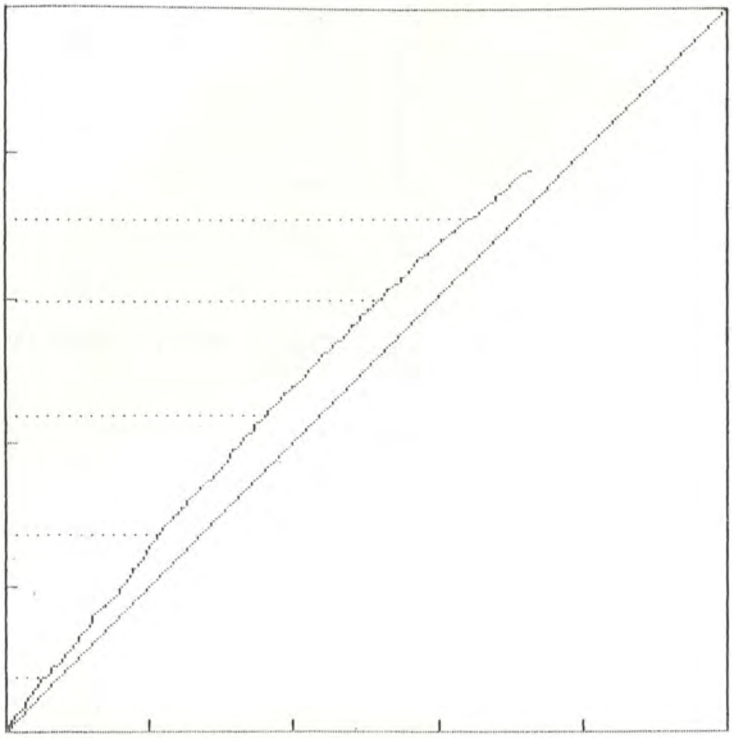
PL CORANI

PERIOD:

1969 11 1 - 1976 7 31

SCALE UNIT: 3000 MM

B A S I N : MIGUILLAS



STATION 2

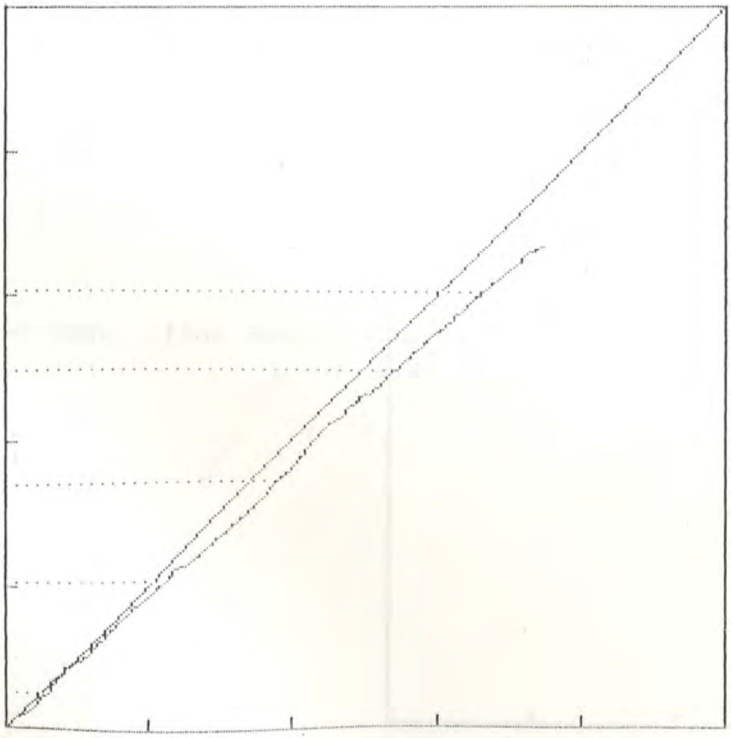
CALACHACA

PERIOD:

1972 7 1 - 1977 5 31

SCALE UNIT: 2000 MM

B A S I N : MIGUILLAS



STATION 3

CARABUCO

PERIOD:

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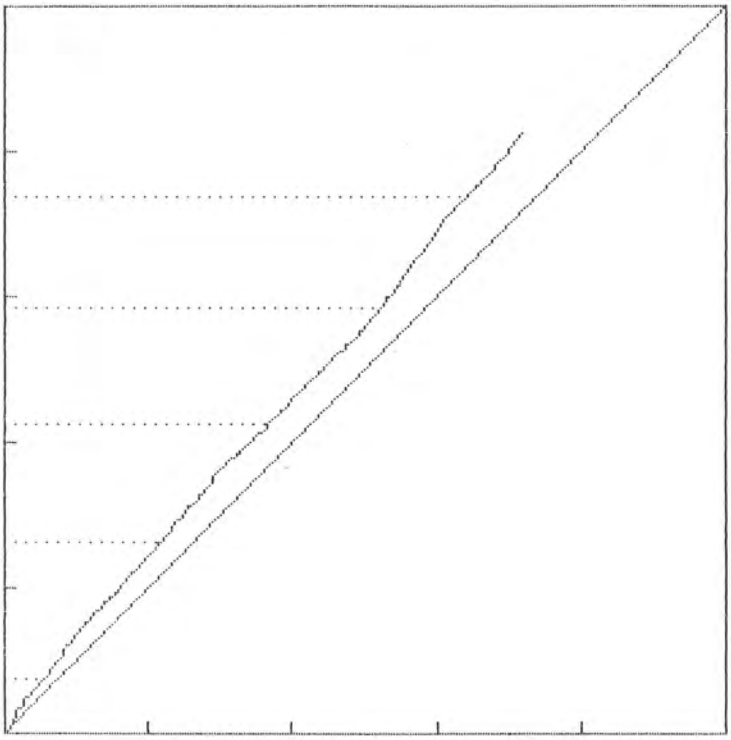

STATION 4

CHICOCHOQ

PERIOD:

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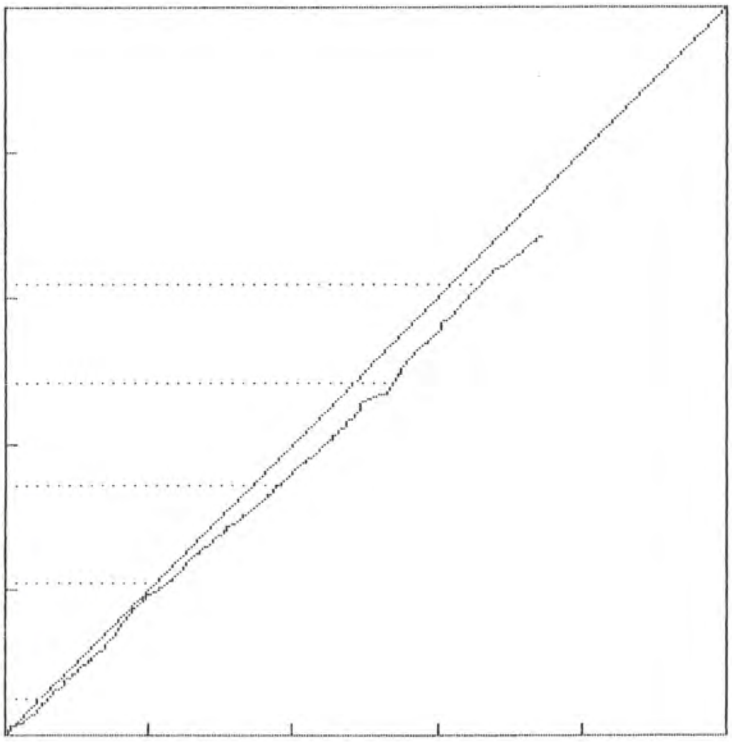

STATION 5

PLCHOQUET

PERIOD:

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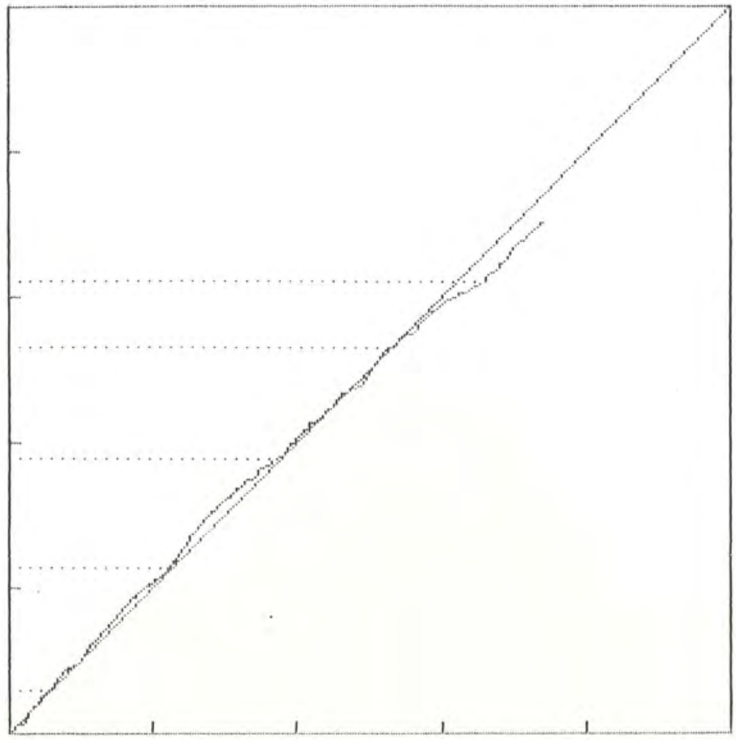

STATION 6

HUMAPALCA

PERIOD:

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SCALE UNIT: 2000 MM

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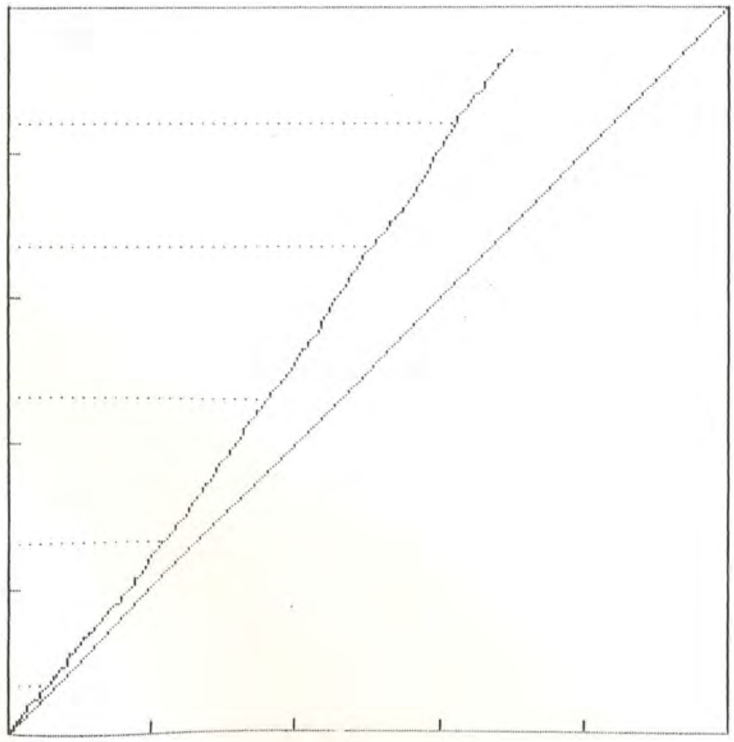

STATION 7

VERTJALAN

PERIOD:

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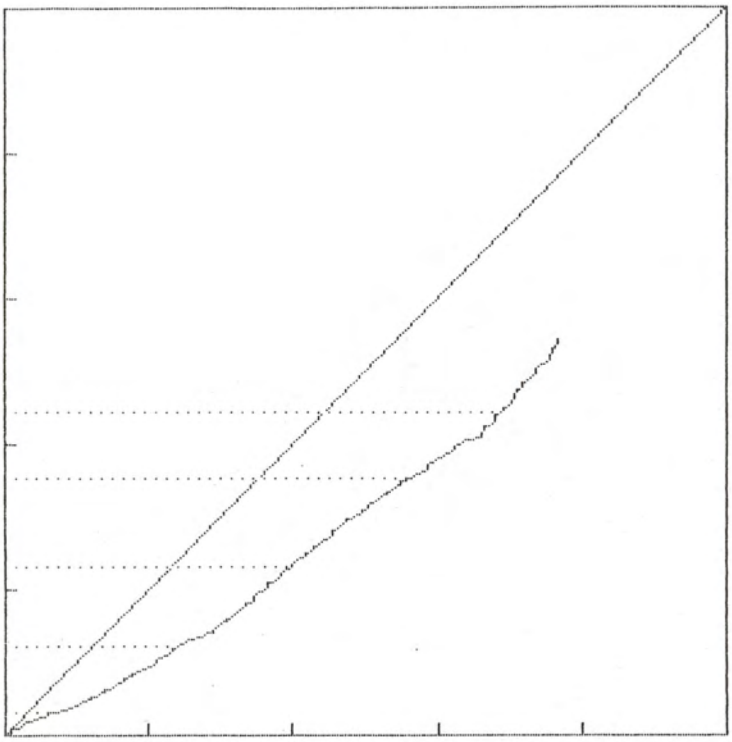

STATION 9

MINANEVADA

PERIOD:

1972 7 1 - 1977 5 31

SCALE UNIT: 2000 MM

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