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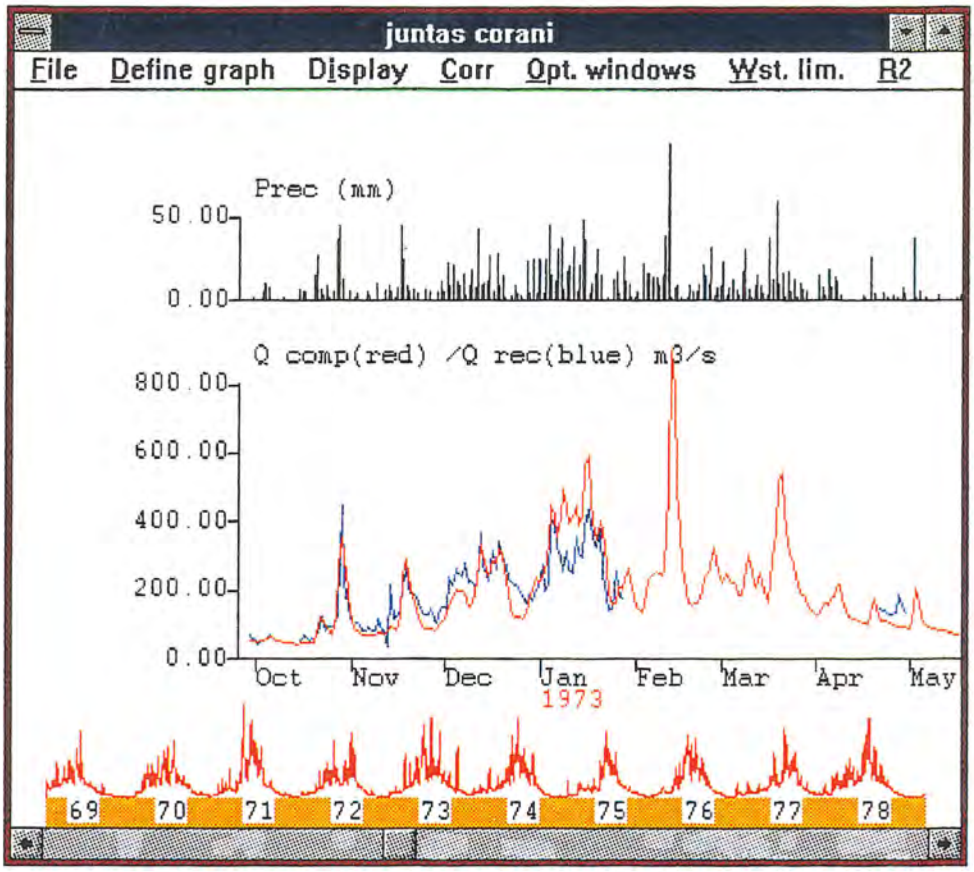

Hydrometeorological Monitoring and Modelling for Water Resources Development and Hydropower Optimisation in Bolivia

SMHI ENDE

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Hydrometeorological Monitoring and Modelling for Water Resources Development and Hydropower Optimisation in Bolivia

Final Report

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1. INTRODUCTION

1.1 General

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

SMHI is the governmental agency in Sweden responsible for collection of meteorological, hydrological and oceanographic data. SMHI also provides weather forecasts as well as hydrological forecasts and warnings to the general public. Approximately 60 % of the annual turnover is from commercial services.

ENDE is a Bolivian national enterprise charged with the study of the National Electrification Plan (NEP). During the project, parts of ENDE have been sold to 50 % according to the national plan of capitalisation. Besides ENDE the new company concerned with this project is named Corani SA.

The main objective of NEP is to identify priorities and to establish executing periods for the construction of works to enhance the electrical supply capacity in Bolivia. The hydroelectric plants account for more than 50% of the total production of electricity in Bolivia. However, hydropower has still a large potential in the country. Within the NEP, hydraulic works are planned at several sites within the project area, the Icona basin, both at existing plants and at new locations.

In order to ensure correct design and optimisation of current and planned hydropower development, basic hydrometeorological information is essential. However, hydrometeorological data in Bolivia in general are of poor quality. Available records often are of short length and have limited geographical coverage. This is also true for the Icona basin.

It is therefore important to improve the availability of hydrometeorological information in the Icona basin, both through improvement of measurements and by hydrological modelling to fill in gaps and extend historical data records. Hydrological modelling also gives possibilities to forecast dam inflows to optimise power production.

This project is a continuation and expansion of the project, Application of the HBV-model to Bolivian Basins, carried out 1986-87 (Johansson et al, 1987). An old version of the HBV-model was then installed for a part of the project area.

This project started in January 1994 and will be finished after a project fulfilment and evaluation visit in December 1995. The Swedish Board for Investment and Technical Support (BITS) contributed to its financing.

1.2 Project objectives

The general objective of this study was to strengthen the capacity of ENDE in water resources assessment and optimisation of hydropower production. This should be made through application of the Integrated Hydrological Model System (IHMS), developed at SMHI, to the Icona watershed and by acquisition and installation of hydrometeorological stations.

The specific objectives of the study were:

- A quality control of available historical hydrometeorological data.
- A database build-up and calibration of the IHMS to the Palca, Corani, Upper Malaga, Locotal and Icona basins.
- An extension of the hydrological records at the existing hydrometric stations.
- A generation of long records of daily runoff at 16 subbasins located within the Icona watershed.
- A computation of flow duration curves at different sites where future hydraulic works will be situated.
- A brief study of the sediment load in the Icona basin.
- A strengthening of the hydrometeorological network by installation of new stations.
- A transfer of knowledge and on-the-job training in the setup, calibration and operational use of IHMS as well as maintenance of the new hydrometeorological stations.

2. THE IHMS

2.1 General description

The Integrated Hydrological Model System (IHMS) is a computerised system for hydrological model computations. The system is based on the HBV model, a conceptual runoff model, which was developed at SMHI in the beginning of the seventies. When the model had been in use for almost twenty years, the need of a more user friendly system was found. In 1990, SMHI started to develop the IHMS. The system has options for calibration, hydrological forecasting, design flood computations and automatic calibration. Different options are included in different versions.

The model program can be run in the VMS operating system, but the complete system, including menus, has been developed for PC using WINDOWS.

2.2 Applications

2.2.1 Hydrological forecasting

The IHMS can be used for both short-range and long-range hydrological forecasting. Before the day of forecast the model is run on observed input data until the time step 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 carefully, 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 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 long range forecast uses precipitation 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.

2.2.2 Quality control, extension of runoff and filling in of gaps

Sometimes it is necessary to check observed data in order to find missing or bad values. In Sweden the HBV model is used for correction of effects of ice-jamming on the records. Other possibilities are that the model helps to identify if a change in observed water level has any relation to snow or rain. There are also examples where the model has helped to identify inhomogeneities in the runoff records.

Problems with too short runoff records can be solved by using a straightforward application of the hydrological model. The methods are very useful in areas where the climatological records are more complete than the hydrological.

2.2.3 Computation of design floods

The IHMS can be used for computing design floods, such as Standard Project Flood (SPF) and Possible Maximum Flood (PMF). For Swedish conditions the system includes routines for combining a design storm with snow melt, reservoir regulation and critical hydrological conditions. The system can be adjusted for tropical conditions and is capable of simultaneous analyses of multi-reservoir systems.

2.3 The HBV-model

There are a large number of hydrological runoff models of varying complexity available in the world today (see for example WMO, 1986). The HBV model belongs to the second generation of computer-based models which are characterised by attempts to cover the most important runoff generating processes by as simple and robust structures as possible. The model was developed at SMHI and the first applications to hydropower developed rivers were made in the early 70-ties (Bergström, 1976).

2.3.1 Model structure and data requirements

The HBV model can best be classified as a semi-distributed conceptual model. It uses subbasins as primary hydrological units, and within these an area-elevation distribution and a crude classification of land use (forest, open, lakes) are made. The subbasin option is used in geographically or climatologically heterogeneous basins.

The HBV model consists of three main components:

- subroutines for snow accumulation and melt, (not applied in the Icona basin)
- subroutines for soil moisture accounting,
- response, river and reservoir routing subroutines.

The model has a number of free parameters, values of which are found by calibration. There are also parameters describing the characteristics of the basin and its climate which, as far as possible, remain untouched during model calibration. The use of subbasins opens the possibility to have a large number of parameter values for a whole basin.

It is usually run with daily time steps, but higher resolution can be used if data are available. Input data are precipitation and in areas with snow, air temperature. The soil moisture accounting procedure requires data on the potential evapotranspiration. Normally monthly mean standard values are sufficient, but more detailed data can also be used. The source of these data may either be calculations according to the Penman formula or similar, or measurements by evaporimeters. In the latter case it is important to correct for systematic errors before entering the data in the model.

Areal averages of the climatological data are computed separately for each subbasin by a simple weighing procedure where the weights are determined by climatological and topographical considerations or by some geometric method like the Thiessen polygons. The climatological input is further corrected for elevation above sea level by constant lapse rates. The temperature lapse rate is usually set to -0.6 °C per 100 meter deviation from station level. The precipitation lapse rates are more site-specific and set by local climatological considerations. All model parameters for correction of input shall be regarded as confined.

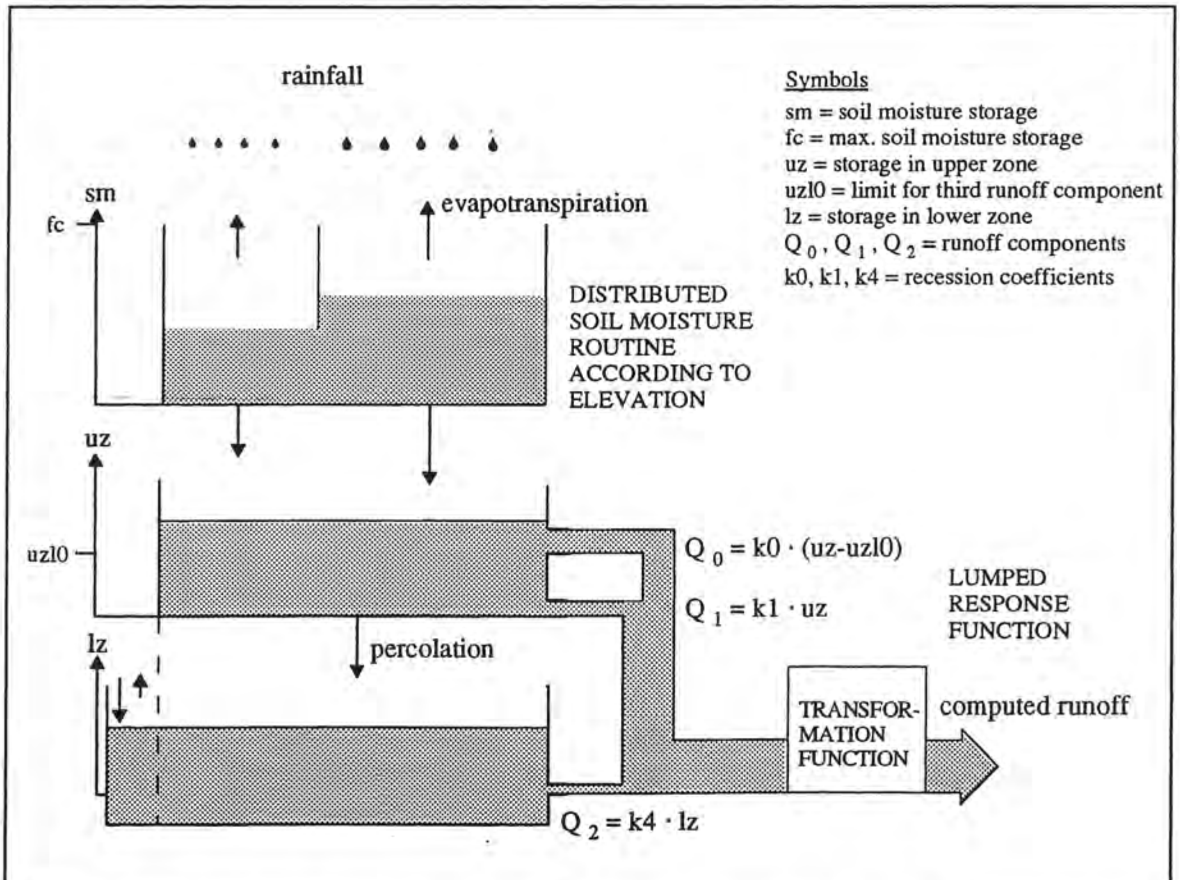

Figure 2.1. The general structure of the HBV model when applied to one subbasin

Soil moisture routine

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 snow melt generate small contributions of excess water from the soil when the soil is dry and large contributions when conditions are wet.

$$Q_s(t) = \left(\frac{S_{sm}(t)}{FC}\right)^{\beta} \bullet P(t) \tag{1}$$

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

Evapotranspiration, is computed as a function of the potential evapotranspiration and the available soil moisture, as:

$$E_a(t) = \begin{cases} \dfrac{E_p \bullet S_{sm}(t)}{LP} & if\ S_{sm} \le LP \\ E_p & if\ S_{sm} > LP \end{cases} \tag{2}$$

where: E_a = actual evapotranspiration,
E_p = potential evapotranspiration, and
LP = S_{sm} threshold for E_p.

Runoff response routine

The runoff response routine transforms excess water (Q_s) from the soil moisture routine and direct precipitation over open water bodies, to discharge for each subbasin (see Fig. 2.1). The routine consists of two tanks with the following free parameters: three recession coefficients, K_o, K_1 and K_4, a threshold, UZL, and a constant percolation rate, PERC. Runoff is generated according to equations (3) and (4).

$$Q_u(t) = \begin{cases} S_{uz}(t) \bullet (K_0 + K_1) - K_0 \bullet UZL & if\ S_{uz} > UZL \\ K_1 \bullet S_{uz}(t) & if\ S_{uz} \le UZL \end{cases} \tag{3}$$

$$Q_l(t) = K_4 . S_{lz}(t) \quad \textbf{(4)}$$

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, and
S_{lz}	= 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 for modelling the damping out of the generated flood pulse.

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.

2.3.2 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 (Nash and Sutcliffe, 1970):

$$R^2 = \frac{\Sigma\,(\bar{Q}_o - Q_o)^2 - \Sigma\,(Q_c - Q_o)^2}{\Sigma\,(\bar{Q}_o - Q_o)^2} \quad \textbf{(5)}$$

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 the graph showing 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.

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 in humid climate 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 are captured. Parameter values are therefore integrated and specific for each catchment and cannot easily be obtained from point measurements in the field.

2.3.3 The use of HBV in the world

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 (see Fig. 2.2). Despite its relatively simple structure, it performs equally well as the best known models in the world (WMO, 1986 and 1987).

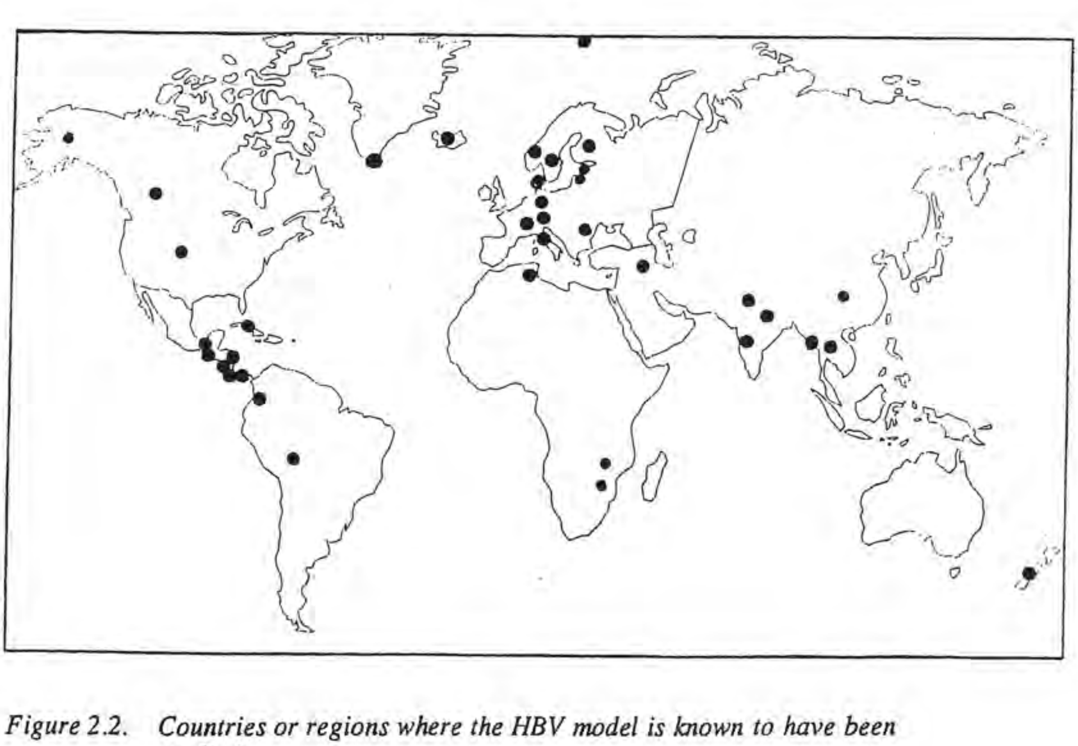

Figure 2.2. Countries or regions where the HBV model is known to have been applied.

Some examples of model applications around the world are:

- inflow and flood forecasting and computation of design floods in totally about 170 basins in Scandinavia (Häggström, 1990; Killingtveit and Aam, 1978; Harlin, 1992; Vehviläinen, 1986),

- modelling the effects of clearcutting in Sweden (Brandt et al., 1988),

- snow melt flood simulation in Alpine regions (Renner and Braun, 1990; Braun and Lang, 1986), and

- flood forecasting in Central America (Häggström et al., 1990).

3. GENERAL DESCRIPTION OF THE ICONA BASIN

The Icona basin is situated in a geographical zone with large climatological variations. The basin is located in one of the most important regions regarding hydroelectric exploitation. The high rates of precipitation combined with large differences in altitude, makes the hydroelectric potential of this region one of the highest in Bolivia.

The location of the catchment is shown in Fig. 3.1.

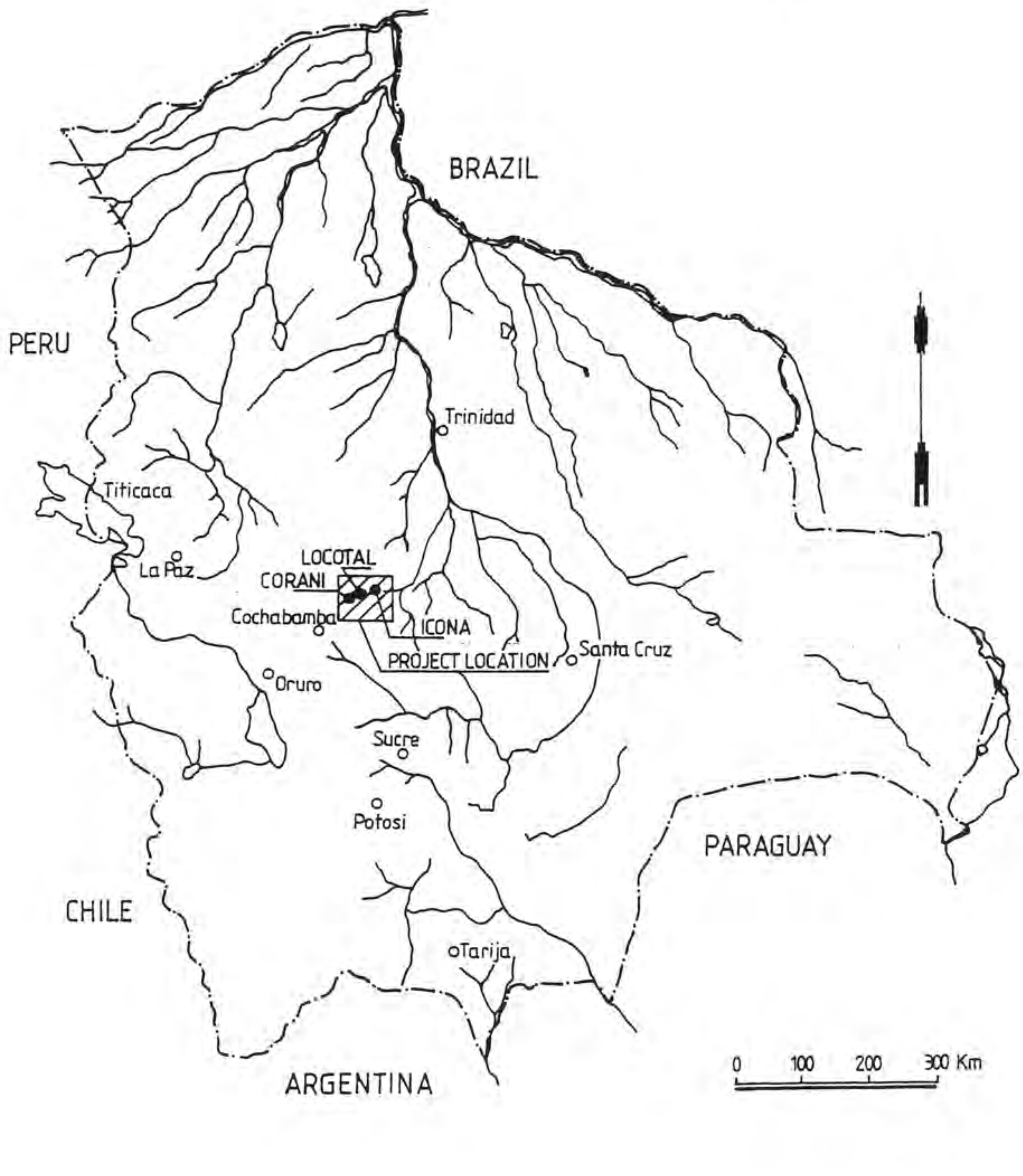

Figure 3.1. Map of Bolivia with location of the project area.

The Juntas Corani river has a drainage area of approximately 2140 km^2 measured at Icona site. It is located in the Cochabamba region, between 16°50' and 17°23' south latitude, and 65°49' and 66°10' west longitude. The catchment presents a mountainous drainage with steep slopes and elevations between 580 and 4300 m.a.sl. Juntas Corani river has a length of approximately 83 km measured from its origin to the Icona site.

According to Thornthwaite climate classification, the lower zone is classified as belonging to a megathermic climate with a pluviometric index PI of 255, typically a jungle zone with high temperatures and high precipitation. The upper zone corresponds to a mesothermic climate with PI equal to 337, where the mountains are bare and have low temperatures, occasionally with snow.

4. AVAILABLE DATA AND DATA QUALITY CONTROL

4.1 Available data

Records from totally 21 pluviometric stations were used, all of them including frequent gaps. The locations of the stations are shown in Fig. 4.1 together with the average annual isohyets. The spatial distribution of the stations is very irregular. Most stations are located in the Corani subbasin, while there are almost none in the north-western part of the watershed.

In Fig. 4.1 the locations of the hydrometric stations are also shown as well as the existing and planned hydroelectric plants.

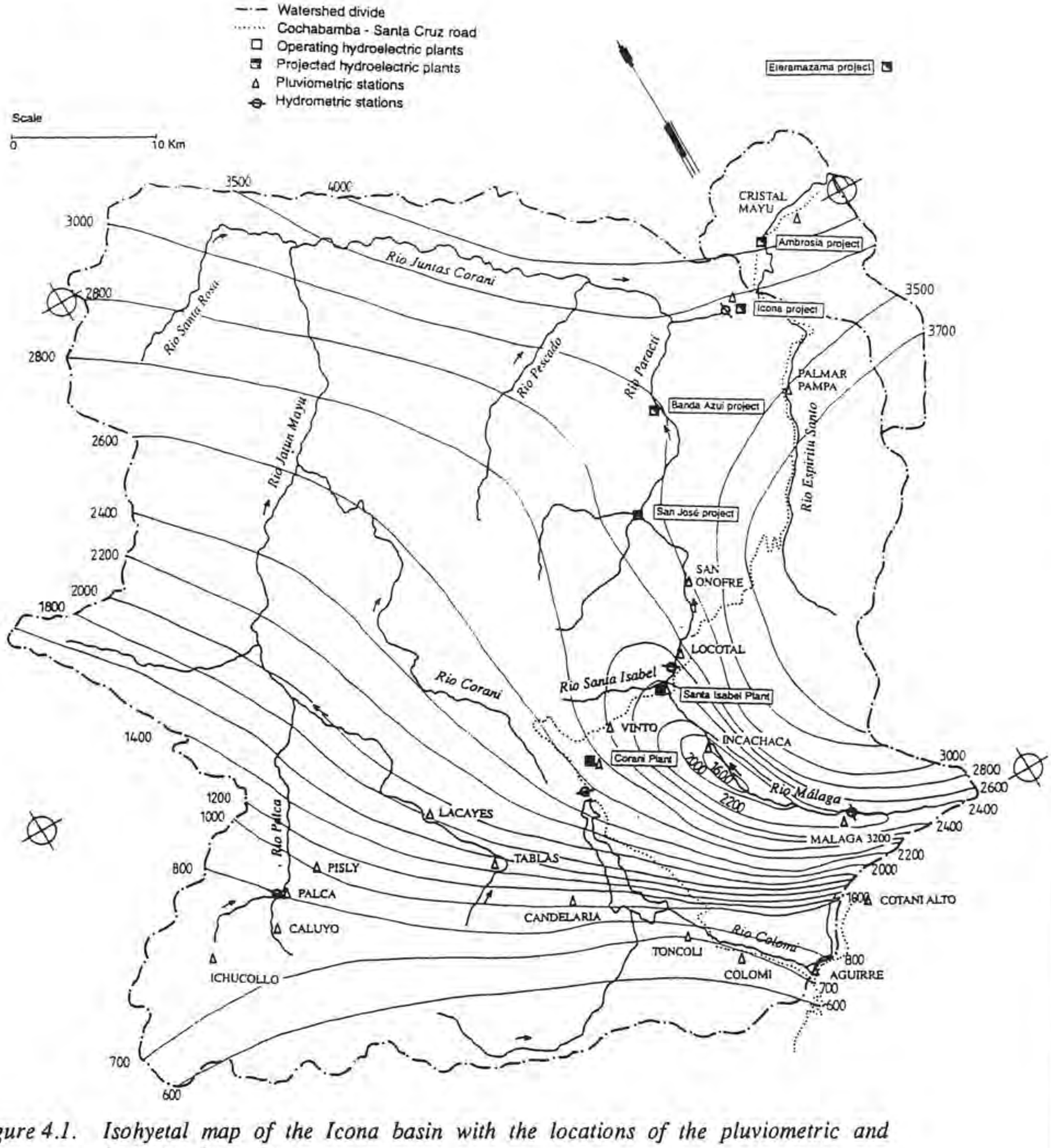

Figure 4.1. Isohyetal map of the Icona basin with the locations of the pluviometric and hydrometric stations.

Evaporation records are available at three stations within the Corani subbasin for a reduced number of years. For the lower region, data are available at Chipiri, located north of Icona site.

Recorded daily runoff is available at the Corani dam site for the period 1952 to 1966. After the dam construction 1966, reservoir levels, release, and energy production are available. The Corani dam was raised five meters in 1983, leading to an increase of energy production at Corani plant and at Santa Isabel plant. In 1984 intake works at Malaga River were constructed to divert this river into the Corani reservoir.

For the Malaga River, recorded discharge is available at two sites: Locotal hydrometric station for the period 1966 to 1981 and some months in 1983, and at Malaga 3200 hydrometric station with recorded runoff covering the period 1969 to 1981.

At Palca river the recorded runoff covers the period 1970-1978, 1981-1983 and 1993 including frequent gaps.

At the Icona site on the Juntas Corani River, runoff was measured during the period 1971-1982 and partially 1993-1994. These records also include frequent gaps.

In App. A the periods of available data used in this study are presented chronologically.

Other available information is volume-elevation curves at the Corani reservoir as well as energy production data at Santa Isabel hydroelectric plant.

4.2 Quality control of data

4.2.1 Precipitation data

Precipitation data were controlled mainly through comparison of monthly sums and by double mass analyses.

The double mass technique was used to check the homogeneity of the precipitation records. The 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 sum at each station is plotted against the mean sum of a number of stations in the vicinity. An inhomogeneity is showed by a change in the slope of the line. Examples of the double mass plots are shown in App. B.

The plots indicate that some records have slight inhomogeneities. The two stations that according to these tests were the most unreliable, were Aguirre and Palca. All stations have, however, been used since the inhomogeneities were judged to be minor and since stations with long records are few.

4.2.2 Discharge data

Discharge data were mainly checked through comparison of mean values and through plotting of the records.

In general the discharge data were judged to be of fair quality. However, the frequent gaps considerably limit the length of the continuous runoff records.

The individual records were plotted and unreasonable values were controlled and corrected.

5. SETUP AND CALIBRATION OF THE IHMS

5.1 Basin subdivision

The Icona basin was divided into 16 subbasins for the calibration. The subbasins are shown in Fig. 5.1 and the catchment areas and mean areal precipitation are presented in Tab. 5.1.

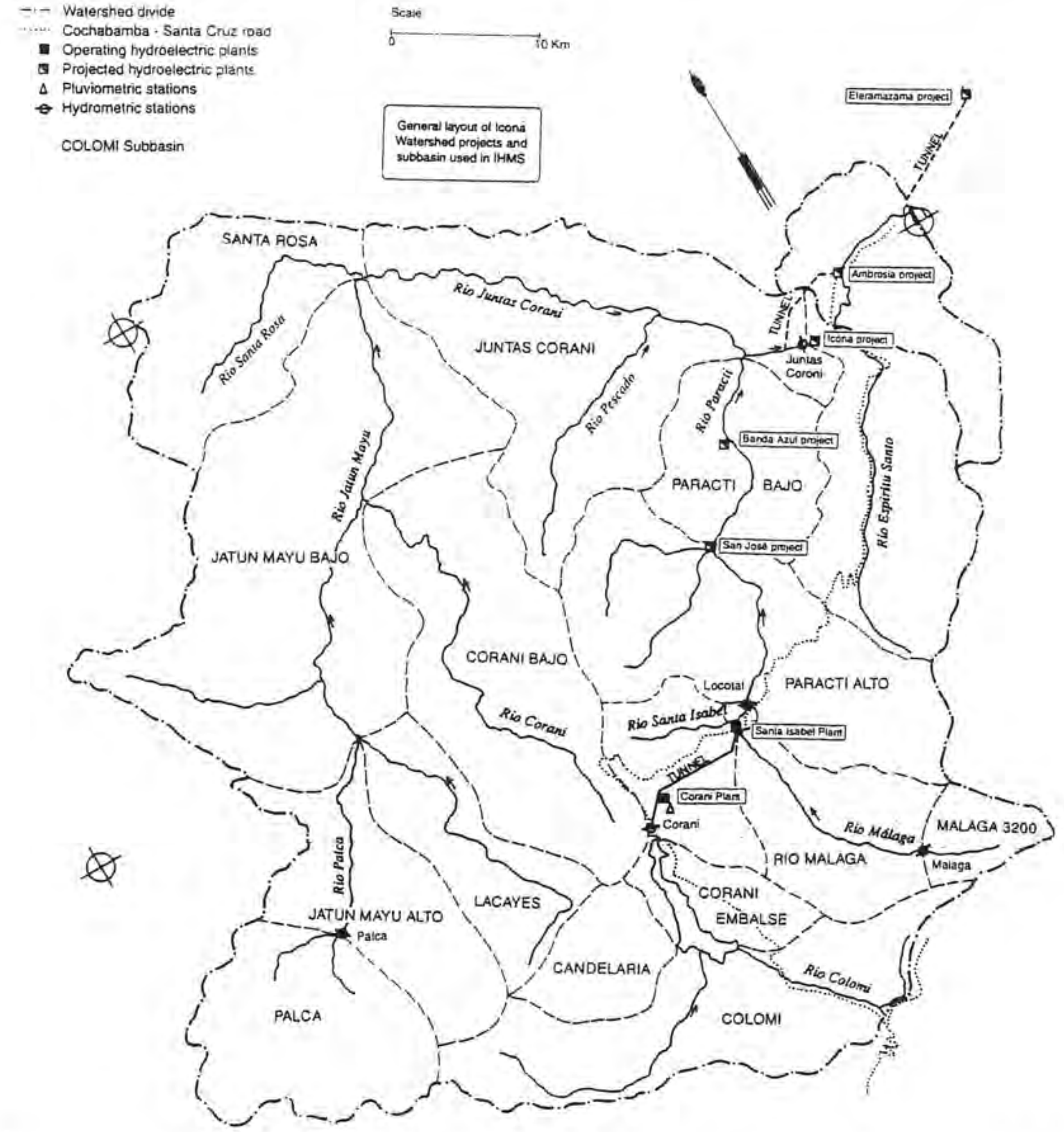

Figure 5.1. Subbasin division of the Icona basin. The subbasin divides are shown as dashed lines.

The upper basins, above 3000 m.a.sl., as Corani, Palca, Upper Malaga and the upper zones of Jatun Mayu Alto and Lacayes consist mostly of bare soil, have small precipitation amounts, low temperature and sometimes temporal snow on the peaks. Some peaks are located around 4500 m.a.sl.

The lower subbasins are located at elevations down to 600 m.a.sl. at Icona. These subbasins generally have high precipitation amounts and high temperatures. The soil is mostly covered with jungle.

Subbasin	Drainage Area (km^2)	Annual Precipitation (mm)
Candelaria	59	1400
Colomi	176	700
Corani dam	52	2200
Palca	138	700
Upper Malaga	38.7	2600
Rio Malaga	96.3	2200
Santa Isabel	58	2800
Locotal	7	2800
Jatun Mayu Alto	119.6	1200
Lacayes	90	1800
Jatun Mayu Bajo	378.8	2500
Corani Bajo	228	2808
Paracti Alto	212	3120
Paracti Bajo	88.6	3417
Santa Rosa	135.1	3204
Juntas Corani	280.7	3715

Table 5.1. Drainage area and average precipitation of the subbasins. The average annual areal precipitation shown in the table have been estimated from the isohyethal map (ENDE, 1993).

5.2 Calibration methodology

Each catchment with a discharge record was calibrated separately. For this purpose the links between the subbasins were determined so that observed runoff output from the considered basin was decreased with the observed runoff into the basin. Through this it was possible to perform local calibrations for the different subbasins.

Once the parameters for each subbasin were locally determined, a model run including all the upstream subbasins was carried out to validate the calibrated model parameters.

5.3 Corani

Corani reservoir, located at 3245 m.a.sl. regulates Corani river flows for hydro-electricity. The drainage area is located between 3245 and 4200 m.a.sl. The catchment area is 287 km^2 and the basin consists mainly of bare soil and agricultural areas.

The model setup for Corani basin is basically the same adopted as in (Johansson et al, 1987). The basin has been subdivided into three subbasins, which are shown in Fig. 5.2.

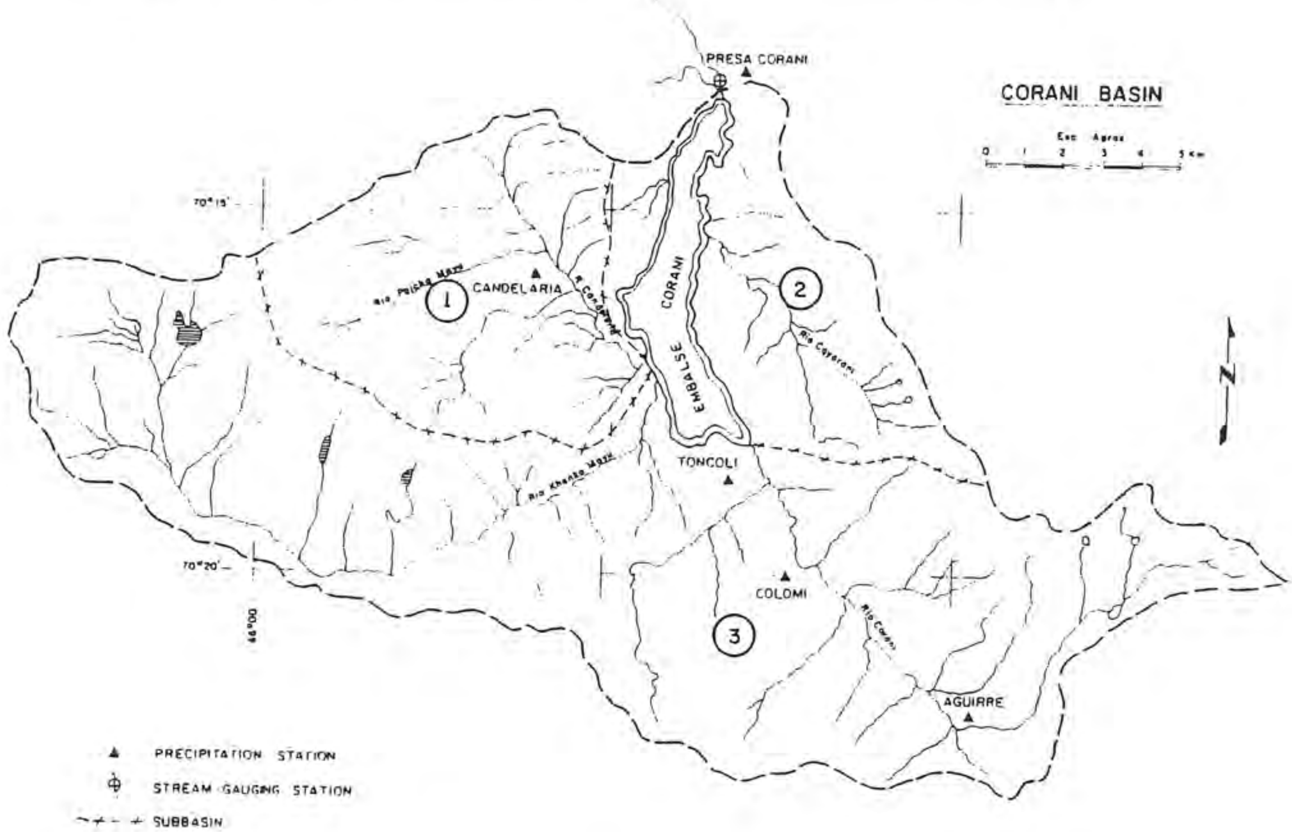

Figure 5.2. Map of the Corani basin with subbasins.

Precipitation data were used from five precipitation stations. The stations and corresponding elevation and mean annual precipitation are presented in Tab. 5.2.

Station	Elevation (m.a.sl.)	Annual precipitation (mm)
Aguirre	3350	830
Candelaria	3380	920
Colomi	3300	670
Presa Corani	3250	2560
Toncoli	3280	680

Table 5.2. Precipitation stations used for Corani

For the potential evapotranspiration, monthly averages from observations at Toncoli station were used. These are presented in Tab. 5.3.

Jan	Feb.	March	April	May	June	July	Aug.	Seep	Cot	Nov.	DEC
3.3	3.7	3.1	3.1	3.6	3.4	3.2	3.3	3.3	3.5	3.9	3.5

Table 5.3. Monthly mean values of evaporation for Corani basins (mm/day)

Flows through the Corani turbines together with reservoir levels and spilling, were used to calculate the inflow to the reservoir. Since 1984, diversion works (design value of 10 m^3/s) are in operation, discharging water from the upper Málaga river into the Corani watershed. This diversion was included in the model setup.

There are only few measurements made since 1985, except at the Corani station. Therefore an additional calibration with new data was not done and the model parameters chosen in (Johansson et al, 1987) were used. Some parameters, however, had to be converted to the new model system.

The calibration for 1969-1985 gave a goodness of fit-value, R^2, equal to 0.74 and a small volume error. Parts of the model run are shown in Fig. 5.3.

The model outputs plotted in Fig. 5.3 are mean areal precipitation, soil moisture, evaporation, accumulated difference between the computed and observed hydrographs, observed and simulated inflow to the Corani dam.

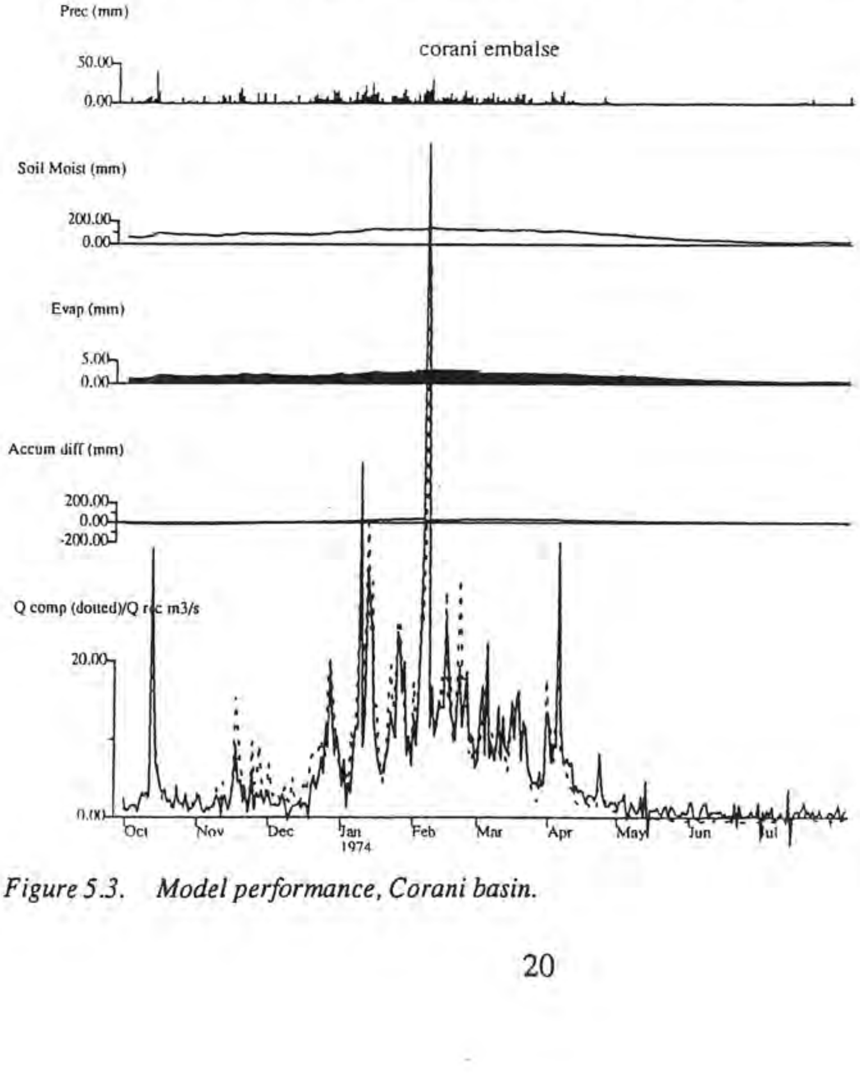

Figure 5.3. Model performance, Corani basin.

An attempt was also made to calibrate only with the three precipitation stations that existed after 1985, Presa Corani, Aguirre and Corani Alto. The reason was that a change in water balance for the catchment was suspected for the last ten years. The model with new parameters based on a calibration for this period would give possibility to simulate the long term mean runoff with the new conditions. The estimate of the areal precipitation was, however, not sufficient with these stations and a satisfactory model fit was not reached.

5.3 Upper Malaga

The catchment area of Malaga river at the hydrometric station located 3200 m.a.sl. is 38.7 km^2. The elevation is between 3200 m.a.sl. and 4600 m.a.sl. The soil is bare with very sparse vegetation consisting of grass and bushes.

A rain gauge located at the hydrometric station was in function during the period 1969-1975 and 1977-1984. The observed runoff covers the period 1969-1981. Evaporation values measured at Corani and Toncoli were used.

A calibration was performed for the period 1969-1975. The years 1977-1981 were used for validation of the model parameters. The R^2-value for the whole period 1969-1981 was 0.59.

Rainfall data for some years had to be adjusted with a correction factor in order to achieve good results. This was done because of the existing inhomogeneities mainly due to changes of observers at the station.

An example of the model performance is given in Fig. 5.4.

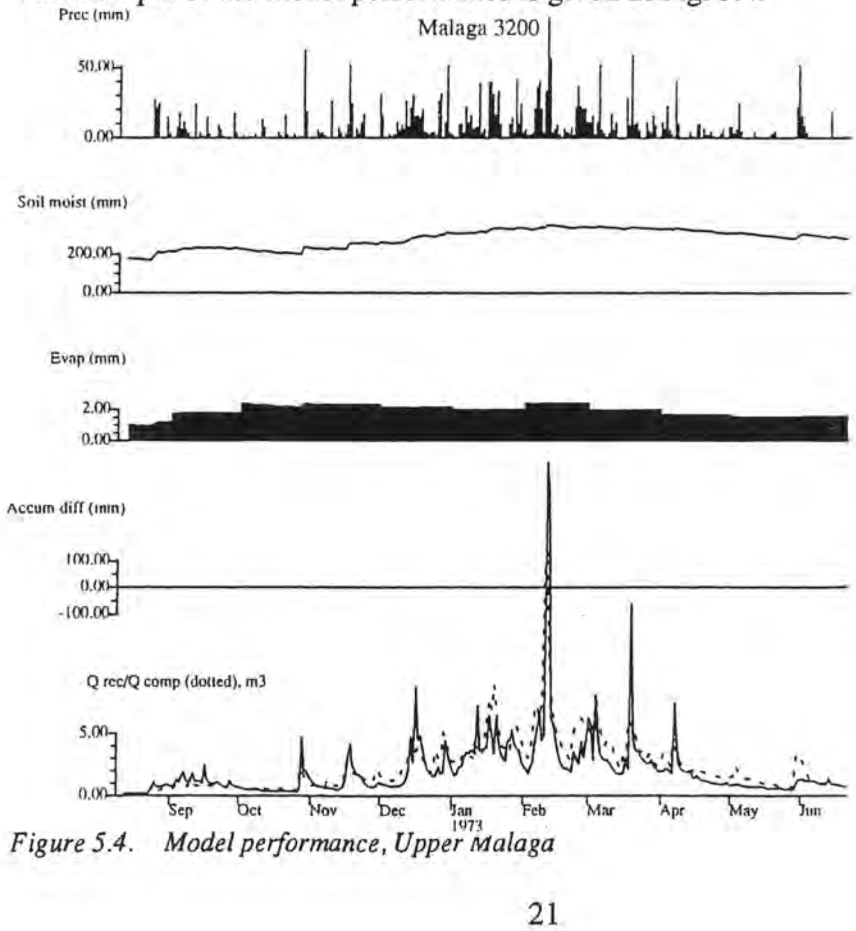

Figure 5.4. Model performance, Upper Malaga

5.5 Locotal

The Locotal basin has an area of 200 km^2 with altitudes between 1700 and 4200 m.a.sl. Vegetation covers most parts of the area but diminishes with increasing altitude.

For performing the calibration, the watershed was divided into four subbasins: the upper (38.7 km^2) and the lower part (96.3 km^2) of the Malaga River, the Santa Isabel river (58 km^2) and the remaining part down to Locotal (7 km^2). The subbasin division is shown in Fig. 5.5.

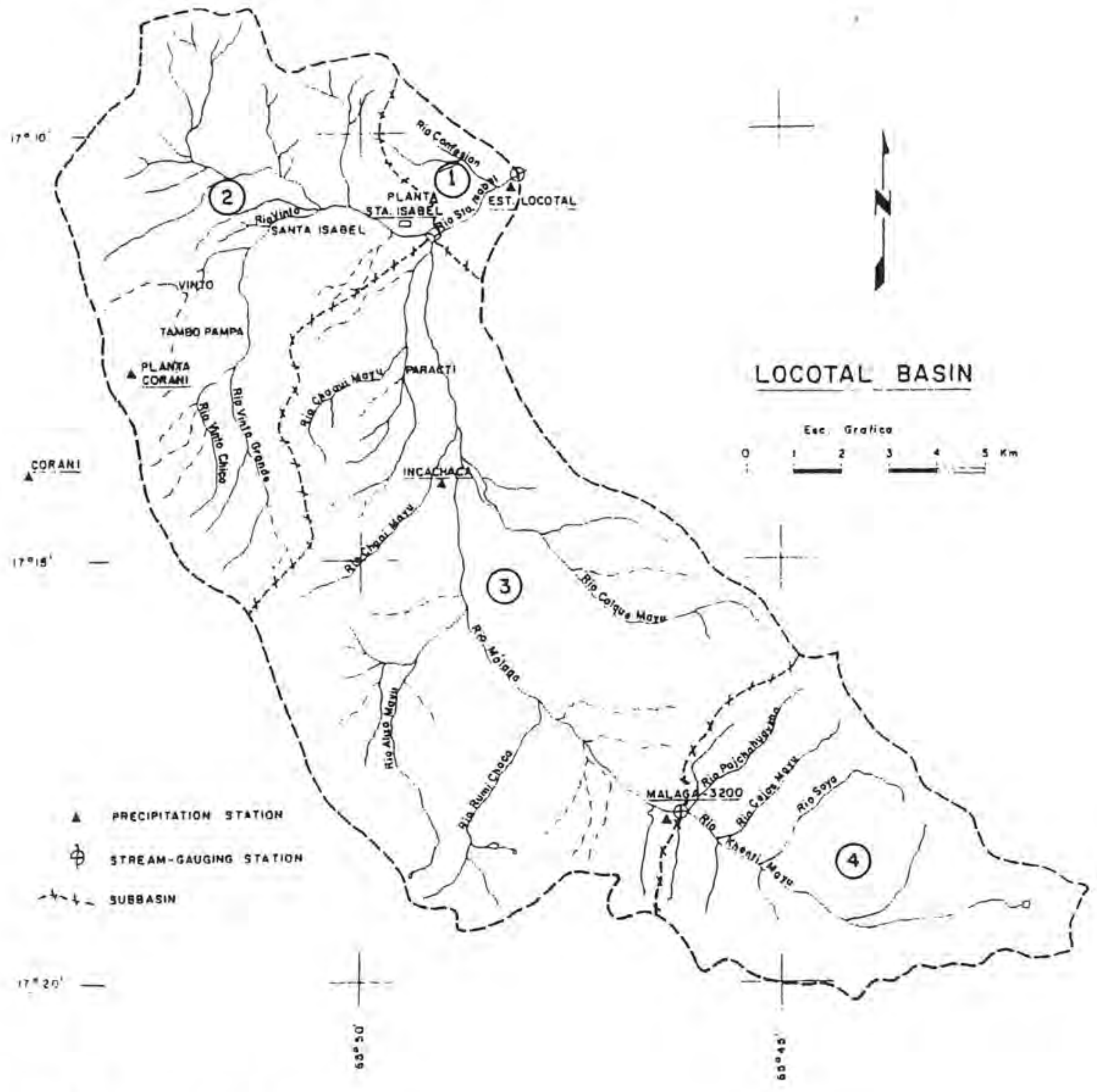

Figure 5.5. Map of Locotal with subbasin

The upper Malaga basin was calibrated separately (see Chapter 5.4).

The runoff records at Locotal covers the period 1966-1981. The observed runoff at Locotal includes the turbine flows coming from the Corani reservoir. These flow values were added to the simulated runoff at Locotal to obtain an accurate comparison between simulated and observed runoff.

The areal precipitation was estimated based on the stations in Tab. 5.4.

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

Table 5.4. Precipitation stations used for Locotal.

The potential evapotranspiration used by the model was determined from observations at Corani and Toncoli as follows in Tab. 5.5.

Jan	Feb.	March	April	May	June	July	Aug.	Seep	Cot	Nov.	Dec.
2.1	2.4	2.0	1.7	1.6	1.6	1.5	1.3	1.8	2.4	2.4	2.2

Table 5.5. Monthly mean values of evaporation for Locotal basins (mm/day).

Model calibration and validation for the entire basin were performed for the period 1967-1981. For the period a R^2- value of 0.72 was achieved. The volume error was fairly small. In Fig. 5.6 parts of the model run for Locotal are shown.

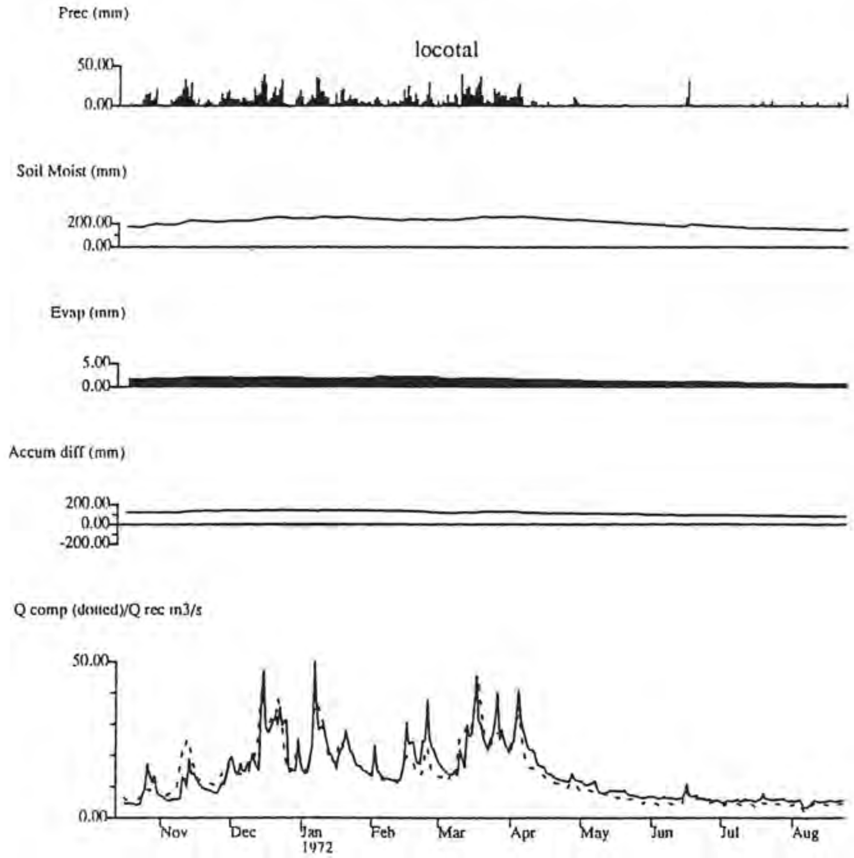

Figure 5.6. Model performance, Locotal.

5.6 Palca

The area of the Palca basin is 138 km^2, with elevations ranging from 3200 to 4500 m.a.sl. A brief map of the basin is shown in Fig. 5.7. The surface mostly consists of bare soil. At the outlet of the basin an intake work is designed for energy and drinking water supply.

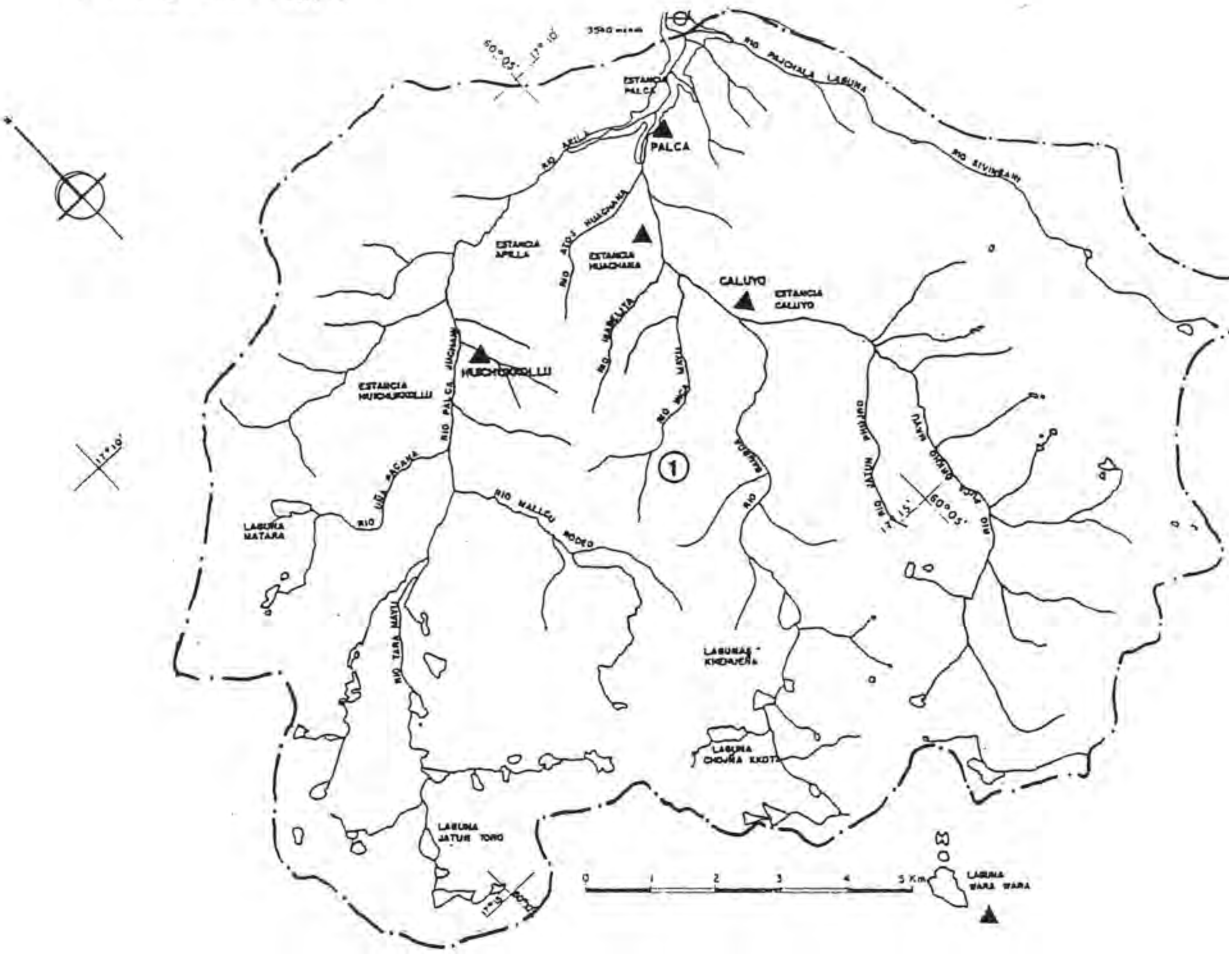

Figure 5.7. Map of Palca basin.

The period of reliable observed runoff covers only ten months: January to October 1993. For this period precipitation data at nearby stations are available at Palca and Presa Corani stations, the latter outside the basin. The stations Caluyo and Ichucollu have data for the period 1979-80, 1984-88 and 1971-84 respectively.

Tab. 5.6 resumes the mean annual precipitation at these stations:

Station	Elevation (m.a.sl.)	Annual precipitation (mm)
Presa Corani	3250	2560
Palca	3500	920
Caluyo	3700	506
Ichucollu	3600	750

Table 5.6. Precipitation stations for Palca basin.

Potential evaporation values were estimated based on monthly averages observed at Misicuni and Corani stations.

To estimate the model parameters for Palca, the following runs were made: a first run based on precipitation at Palca station, a second, based on Corani data and a third, based on both Palca and Corani stations. During the ten months calculation period, the precipitation record from Palca do not seem to represent the average areal precipitation of the watershed.

Simulation based on Corani precipitation gave the best results with an R^2 value of 0.71. Using the Corani station also has the advantage of having a long precipitation record in order to extend the Palca discharges. The alternative using Palca was, however, finally chosen since the period with reliable data was to short to conclude that Corani was more representative then Palca. A more reliable parameter estimation should be performed when future data are obtained.

5.7 Icona

The total area of Icona watershed is approximately 2140 km^2, based on 1:100 000 topographical maps. According to the hypsographic curve of Icona, 17% of this area is situated above 3400 m.a.sl. and the mean elevation is 2390 m.a.sl.

The basin was divided into subbasins as shown in Fig. 5.1. The upper basins, Corani, Palca and Locotal were calibrated separately (see corresponding chapters).

The recorded runoff at Icona, Juntas Corani hydrometric station, covers the years 1971-1975, 1982 and 1993-1994. The record includes several periods with missing data.

The precipitation data available at 21 pluviometric stations were used. All of them having different recording periods, which also include frequent gaps. Stations with the longest observed periods are Locotal, San Onofre and Corani dam. These were often used as replacing stations.

Since there exist no precipitation data at the northern part of the Icona watershed the following procedure was adopted:

- For the subbasins Jatun Mayu Bajo, Santa Rosa and Corani Bajo, the corresponding hypsographic curves were used combined with an altitude-precipitation correction factor, which considers the decreasing rain amount with increasing altitude that is appropriate for this region.
- For the remaining lower subbasins the areal precipitation was reproduced with the existing precipitation data together with precipitation correction factors.

Through applying this procedure it is possible not only to reproduce the flow values at the existing hydrometric stations at Icona, but also to reproduce the existing precipitation pattern as established in the isohyethal map of the watershed.

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6. RESULTS

6.1 Simulation of runoff series

Using the calibrated model parameters long continuous runoff series were simulated for all the 16 subbasins in the Icona basin. The period 1968 to 1987 was chosen as during this period, there are available data at the most important precipitation stations.

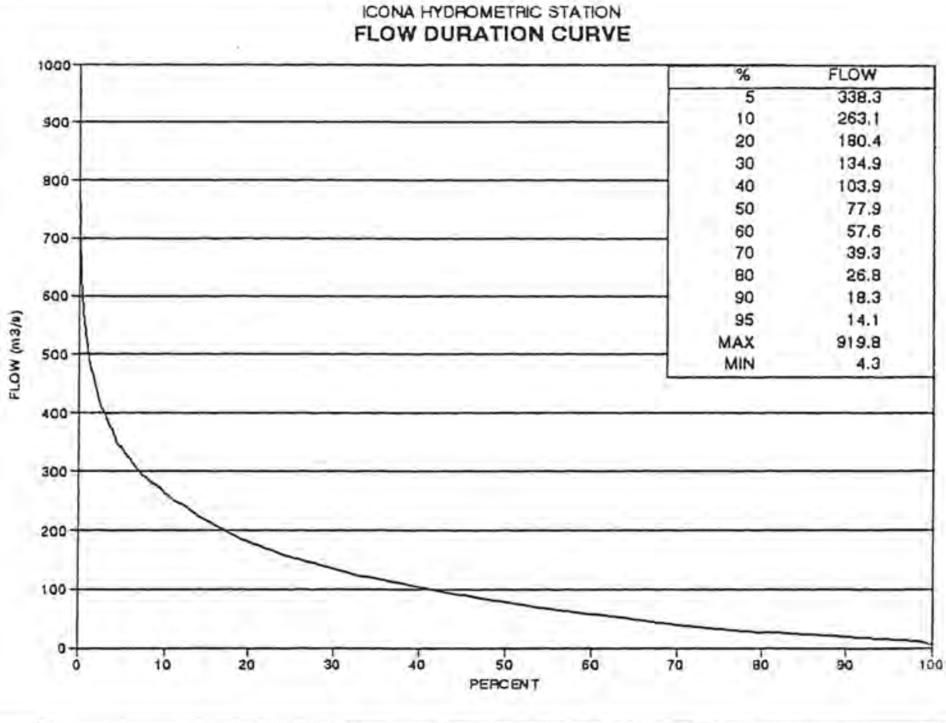
For Locotal the simulated runoff was used to extend the observed record. The retrieved 20 years of runoff data at Locotal, thus, contain observed values 1968-1981 and simulated values 1981-1987. At Icona and Paracti Alto the retrieved runoff series consist only of computed values.

In App. C the series of monthly mean runoff at Icona, Locotal and Paracti Alto (intake of the planned San José hydroelectric plant) are presented.

6.2 Long term flow duration curves

The long series of daily runoff, 1968-1987, were used to compute the duration curves for Icona, Locotal and Paracti Alto. The obtained duration curves for the three sites are presented below in Fig. 6.1-6.3.

The long term mean runoff is 114.5 m^3/s at Icona, 12.8 m^3/s at Locotal and 29.1 m^3/s at Paracti Alto. It should be noted that the maximum value at Locotal, 131.8 m^3/s, is a recorded value that is uncertain. The modelled value at the same occasion is much lower and may be a more realistic estimate since the precipitation at this occasion is not extremely high.



%	FLOW
5	338.3
10	263.1
20	180.4
30	134.9
40	103.9
50	77.9
60	57.6
70	39.3
80	26.8
90	18.3
95	14.1
MAX	919.8
MIN	4.3

Figure 6.1. Flow duration curve (1968-1987), maximum and minimum flow at Icona.

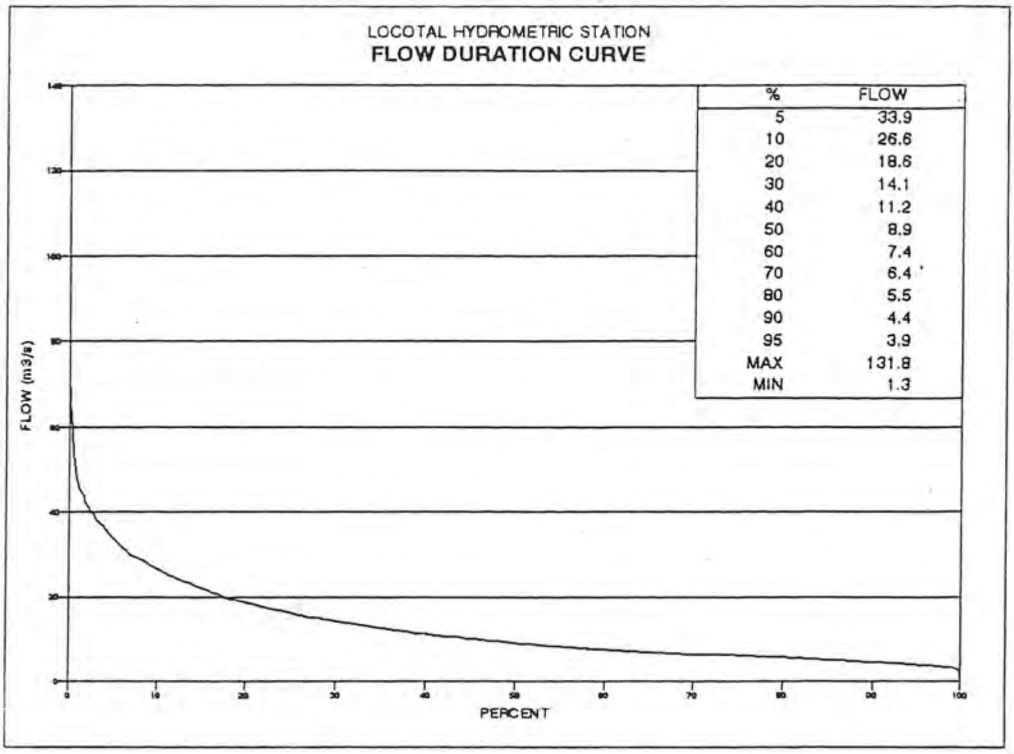


Figure 6.2. Flow duration curve (1968-1987), maximum and minimum flow at Locotal.

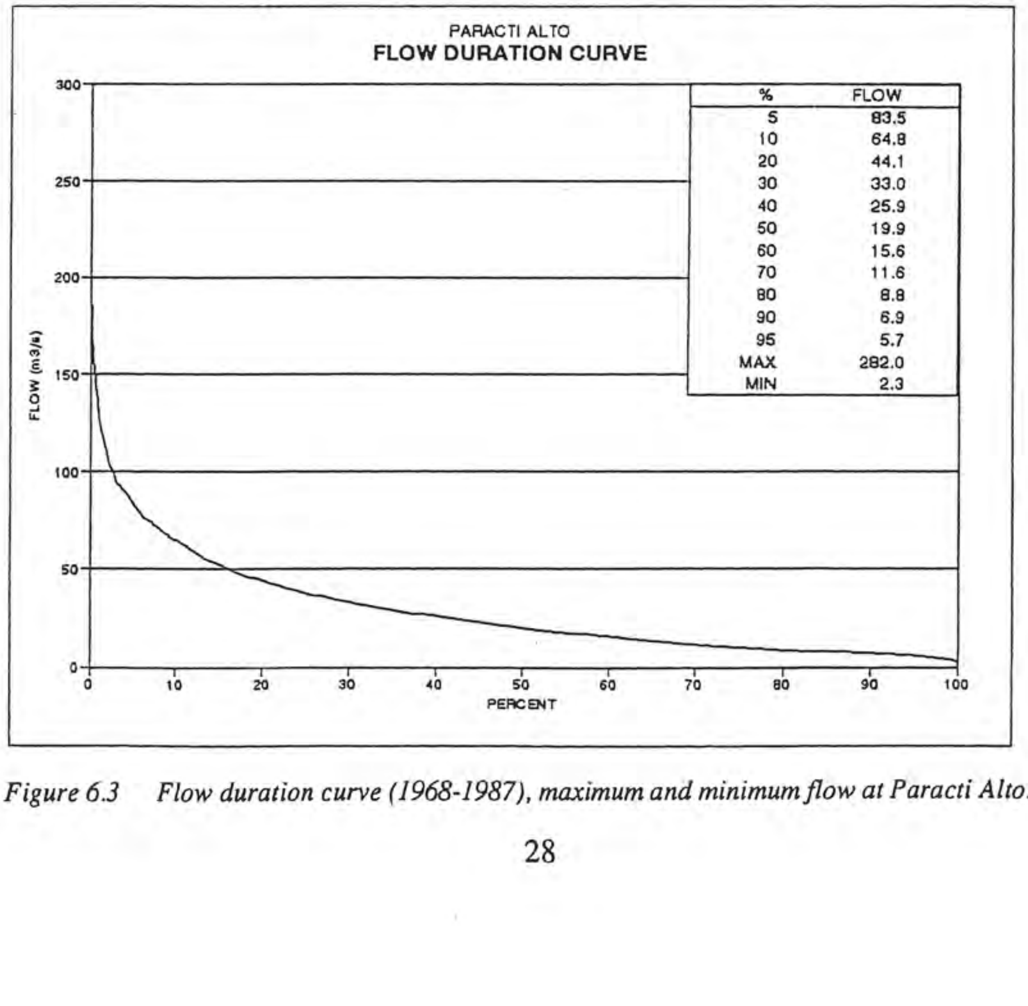


Figure 6.3 Flow duration curve (1968-1987), maximum and minimum flow at Paracti Alto.

7. ACQUISITION AND INSTALLATION OF HYDRO-METEOROLOGICAL STATIONS

The hydrometeorological information in Bolivia generally is of poor quality. Available records often are of short length and have limited geographical coverage. In areas where hydroelectric projects are planned it is therefore very important to increase the number of hydrometeorological stations as well as to improve the quality of the observations.

To improve the availability of hydrometeorological data of high quality in the Icona basin, three meteorological and three hydrological stations have been purchased and installed within the project.

The meteorological stations were placed in Colomi, Locotal and Icona, while the hydrological stations were placed at the Corani dam, Locotal and Icona. Both the meteorological and hydrological stations are located close to the sites of the old pluviometric and hydrometric stations (see Fig. 4.1).

The specifications for the purchased stations, the technical solutions and installations as well as the operational use of the stations, are described in more detail in App. D.

8. SEDIMENT STUDY

As a complement to the hydrological study of the Icona basin a sediment study has been performed. The study is described in detail in App. E. Below the methods and results are summarised.

The objectives of the sediment study were to quantify the annual sediment yield at Locotal hydrometric station and to make an evaluation of the sediment yield in Juntas Corani at the Icona site. The study mainly consisted of a review of previous literature, collection of data and the set up of a supply-based sediment yield model, developed by SMHI, for the Locotal basin.

Available sediment samples at Locotal were judged to be of good quality. The samples were used to calibrate the sediment yield model, which performed satisfactorily. Daily rainfall and runoff, from the hydrological study were then used as input to the sediment model to simulate the sediment yield from 1967 to 1987. Complementary studies of extreme storm flood events were also carried out.

The results from the sediment modelling verified the dimension of the previous retrieved estimates and gave modified values of the mean annual sediment yield. More specific the sediment study led to the following conclusions:

- the long-term mean annual sediment yield at Locotal is estimated to 400 000 tonnes/year. Previous studies gave an estimate of 600 000 tonnes/year. This figure can not be neglected but is probably a conservative estimate.

- based on the areal estimate of sediment yield in the Locotal basin, the long-term mean annual sediment yield at the Icona site is estimated to 3 700 000 tonnes/year. However, the areal sediment load in the Icona basin as a whole is probably less than the areal load in the Locotal basin. Thus, the achieved value is possibly on the high side.

9. 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 the Icona basin through quality control of historical hydrometeorological data and extension of the existing data records as well as through computation of long term mean and duration curves at three sites, which are of interest for future hydroelectric development.
- The Integrated Hydrological Model System (IHMS) has successfully been applied to the Icona basin. The IHMS gives possibilities to compute long continuous 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 forecast inflow to the existing Corani reservoir as well as forecast runoff in future hydroelectric plants.
- The HBV-model, included in the IHMS, performs well in the Icona basin. When representative precipitation data is available, the model performance is very good. Even when there is no available precipitation data for parts of the catchment, it is possible to have a fair model performance.
- For future development and operation of the hydropower in the region of the Icona basin, an improvement of the hydrometeorological data is essential. Thus, within the project, three hydrometeorological stations have been purchased and installed in the Icona basin. The stations are in operation and are working well.
- The transfer of knowledge within the project, both in the use of the hydrological model system as well as in the maintenance of the new stations, has been very successful. The ENDE personnel is now capable to operate the IHMS as well as setup and calibrate the system for new basins of interest.
- The sediment study has provided new valuable information regarding the erosion and sediment yield in the Icona basin.

The following recommendations are made:

- New hydrometeorological data from the installed stations should continuously be inserted into the IHMS and the model parameters should be regularly updated. The results from the HBV-model could considerably be improved if the quality and consistency of the hydrometeorological data are increased.
- The knowledge of operating the IHMS-system should be spread further among the ENDE personnel and be maintained trough operational use and new applications.

10 ACKNOWLEDGEMENTS

Appreciation is expressed to the ENDE staff in Cochabamba and the SMHI personnel at the division of Environment & Energy Services in Norrköping, for help and assistance during the project. Special thanks to Mr Daniel Zambrana for valuable geological information, Ms Anna Amrén for contributions to the report and to Dr Joakim Harlin for useful advises. Ms Eva-Lena Ljungqvist has drawn the figures and assisted in the layout of the report.

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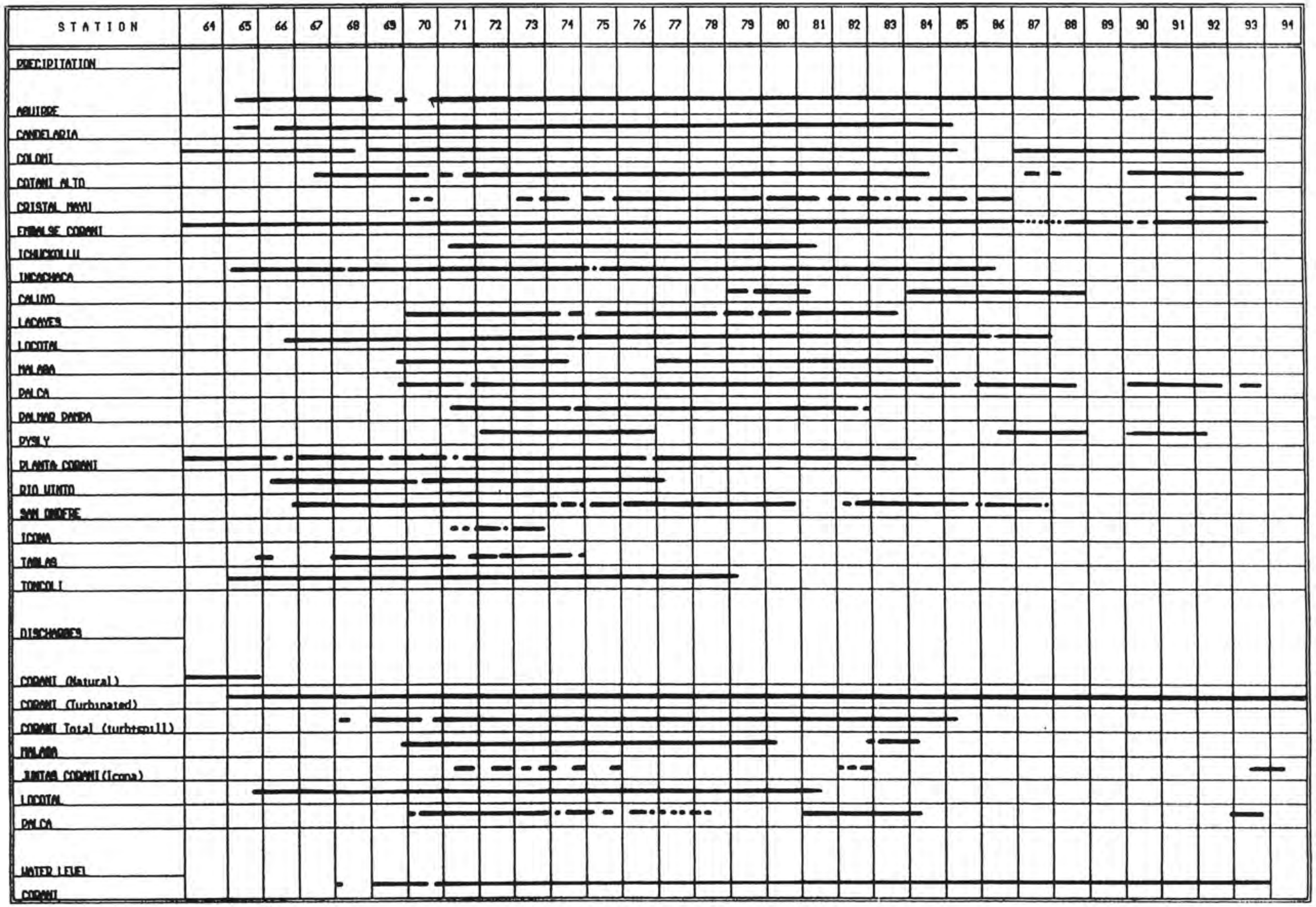
Appendix A

Chronological table of the available hydrometeorological data in the Icona basin

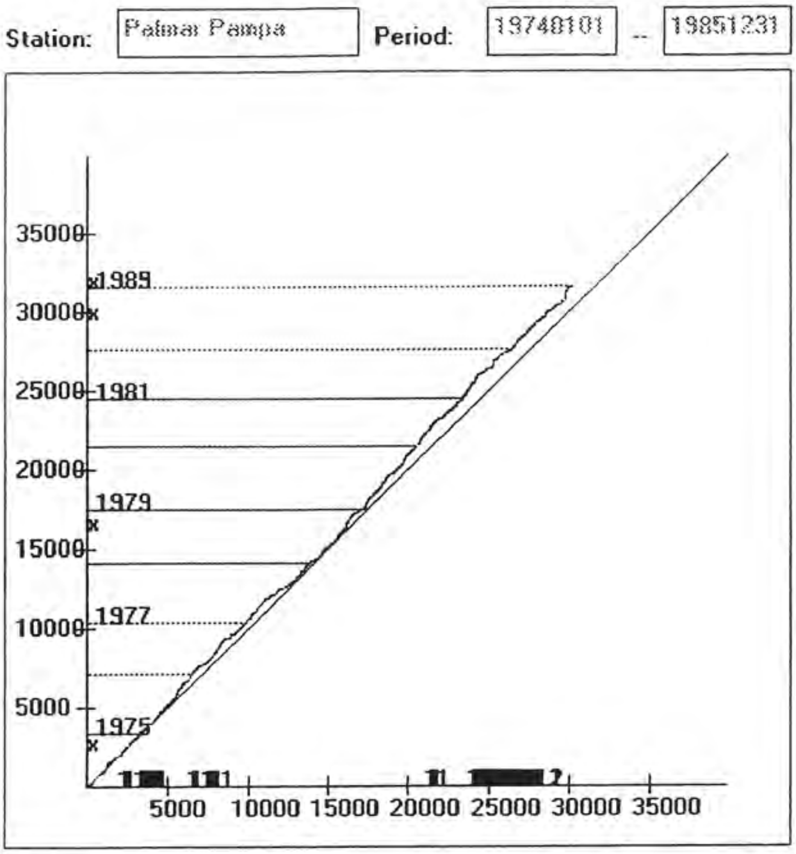
ICONA BASIN

AVAILABLE RECORDED DAILY DATA

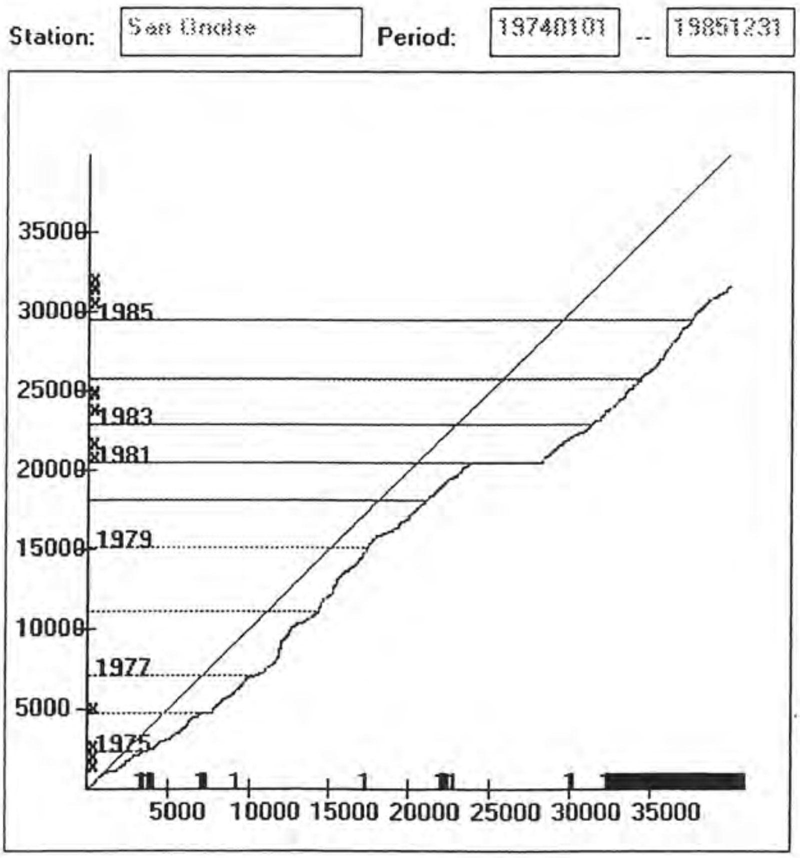


Appendix B

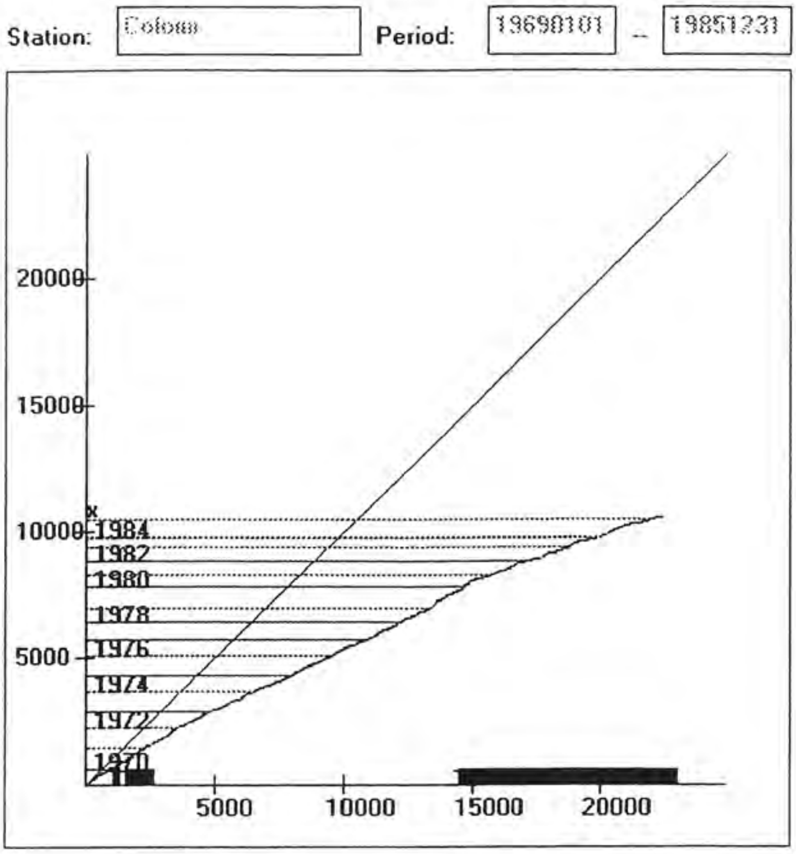
Double mass plots of precipitation data



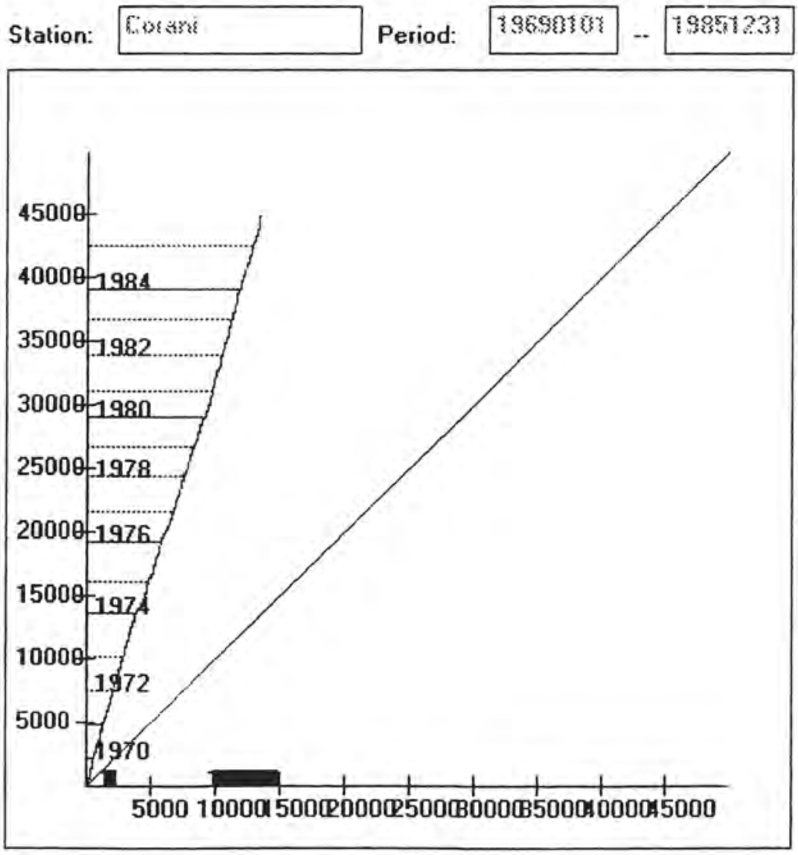
Palmar Pampa, 1974 to 1985, plotted against Cristal Mayu, Locotal and San Onofre.



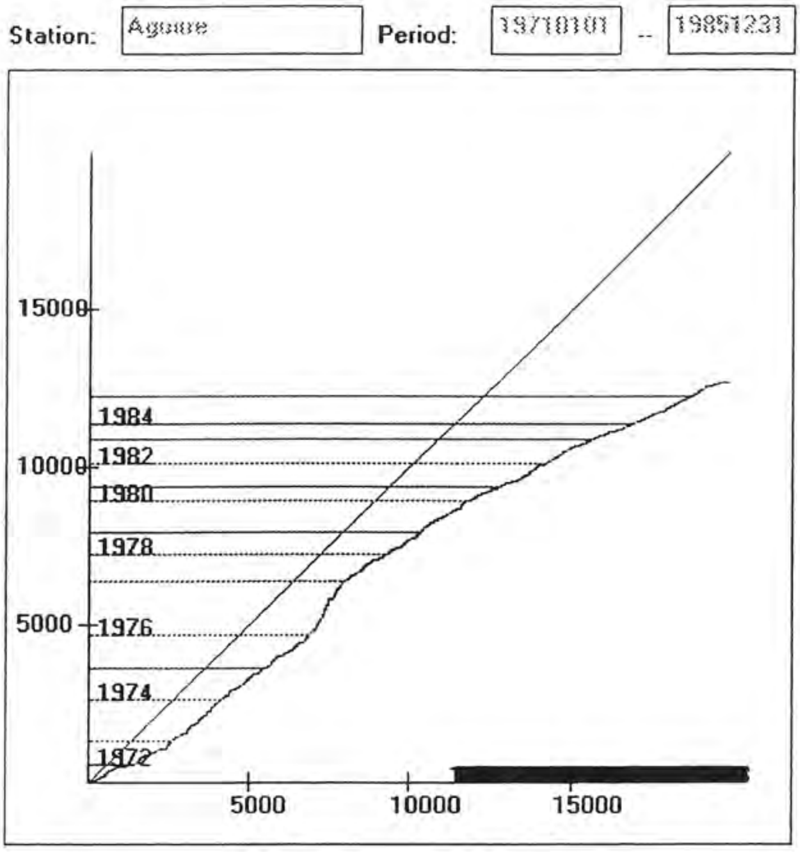
San Onofre, 1974 to 1985, plotted against Cristal Mayu, Locotal and Palmar Pampa.



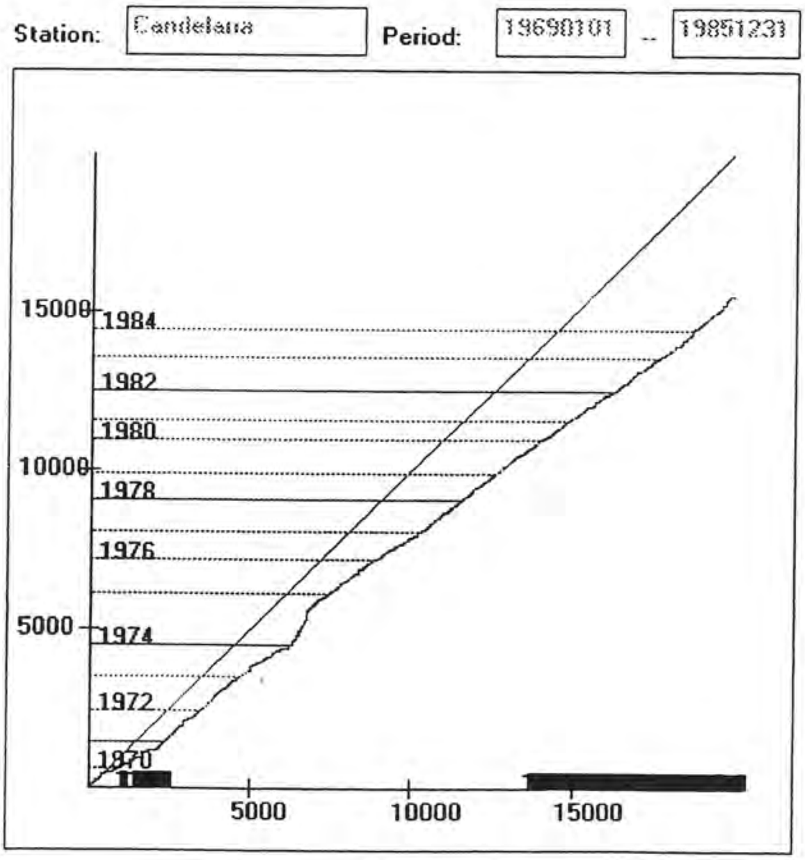
Colomi, 1969 to 1985, plotted against Aguirre, Candelaria, Corani, Cotani alto and Toncoli.



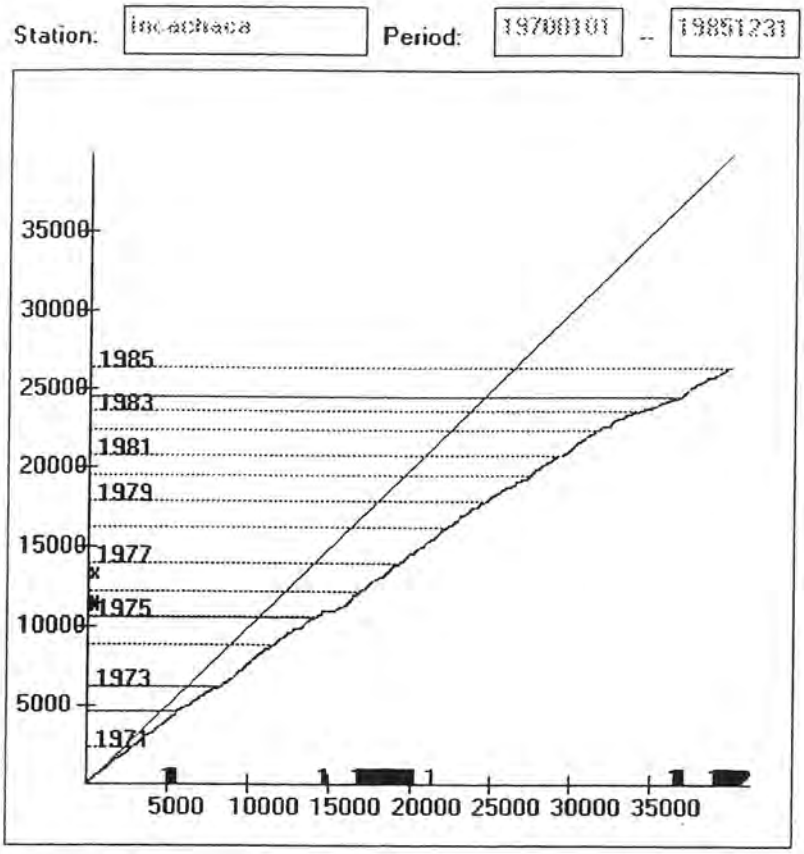
Corani, 1969 to 1985, plotted against Aguirre,Candelaria, Colomi, Cotani alto and Toncoli.



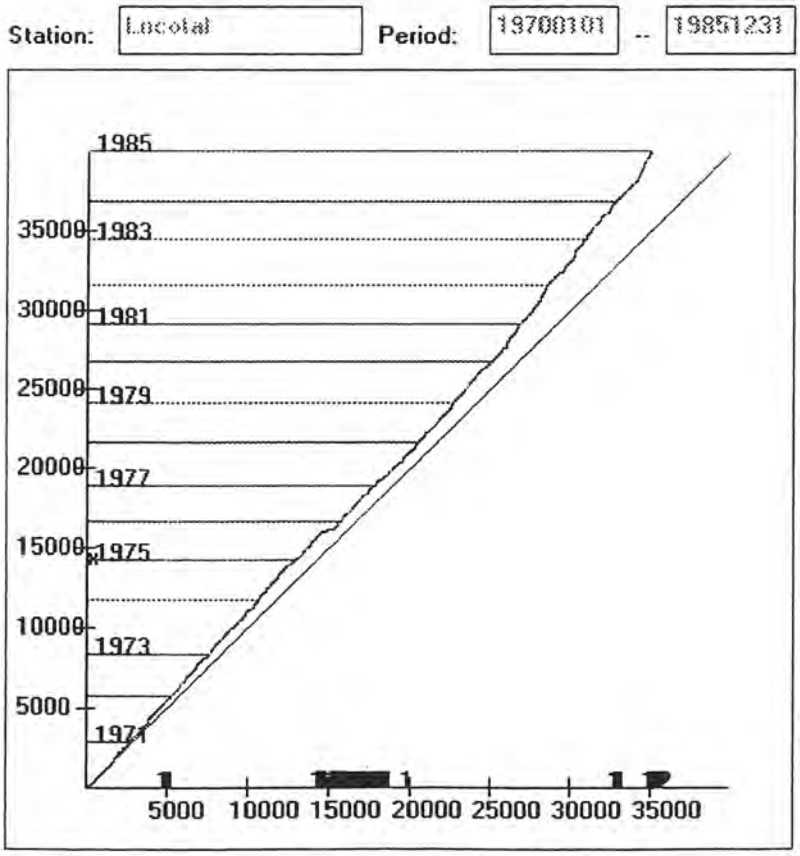
Aguirre, 1971 to 1985, plotted against Candelaria,Colomi, Corani, Cotani alto and Toncoli.



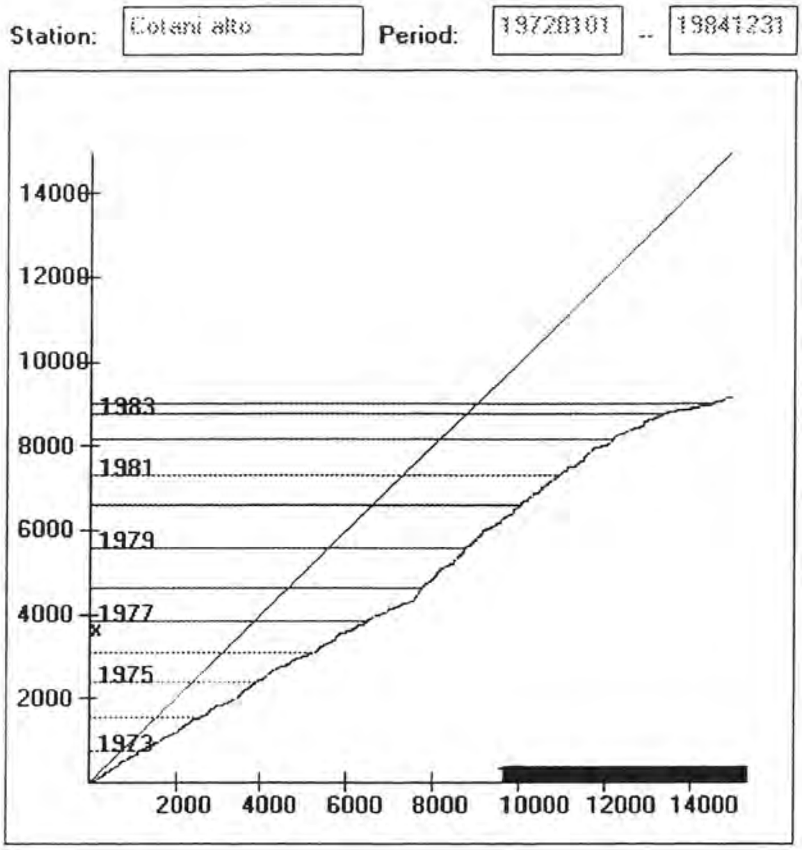
Candelaria, 1971 to 1985, plotted against Aguirre,Colomi, Corani, Cotani alto and Toncoli.



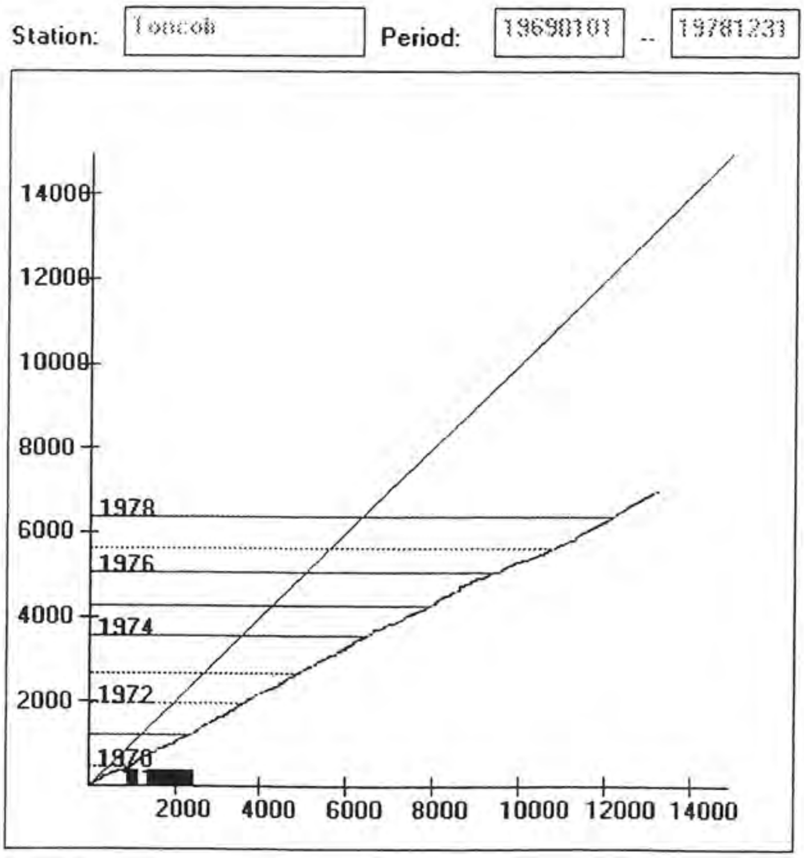
Incachaca, 1970 to 1985, plotted against Locotal, Planta Corani and Malaga 3200.



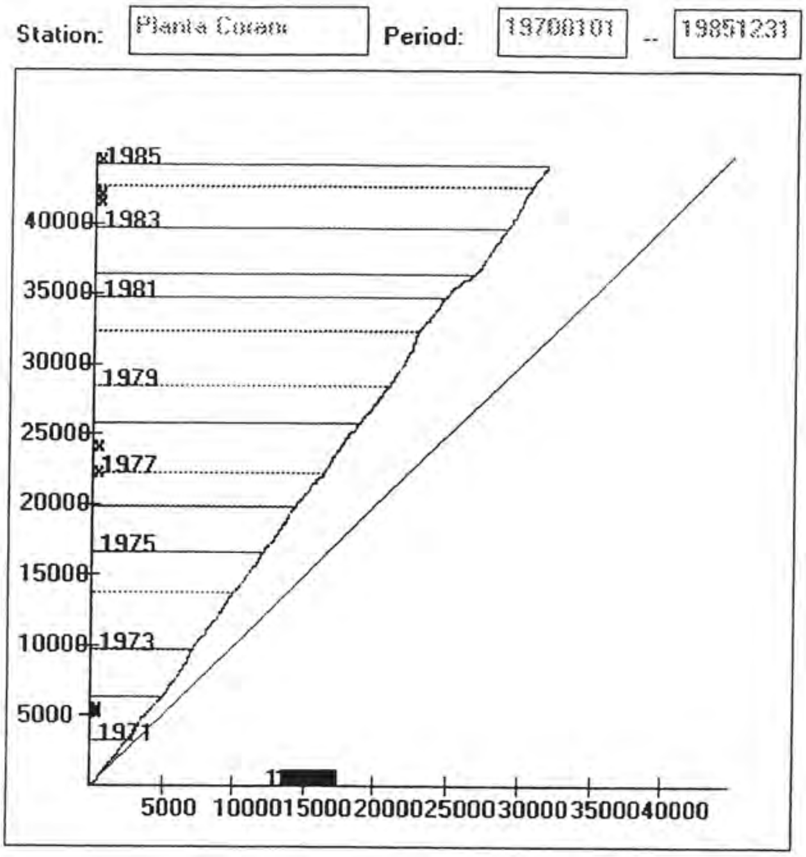
Locotal, 1970 to 1985, plotted against Incachaca, Planta Corani and Malaga 3200.



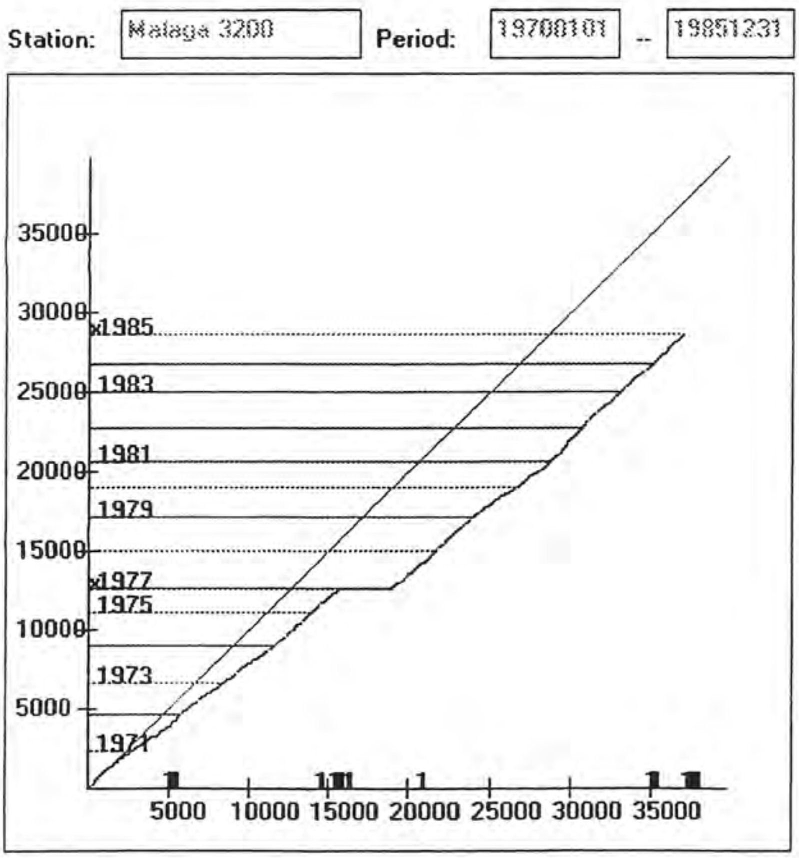
Cotani alto, 1972 to 1984, plotted against Aguirre, Candelaria,Colomi, Corani and Toncoli.



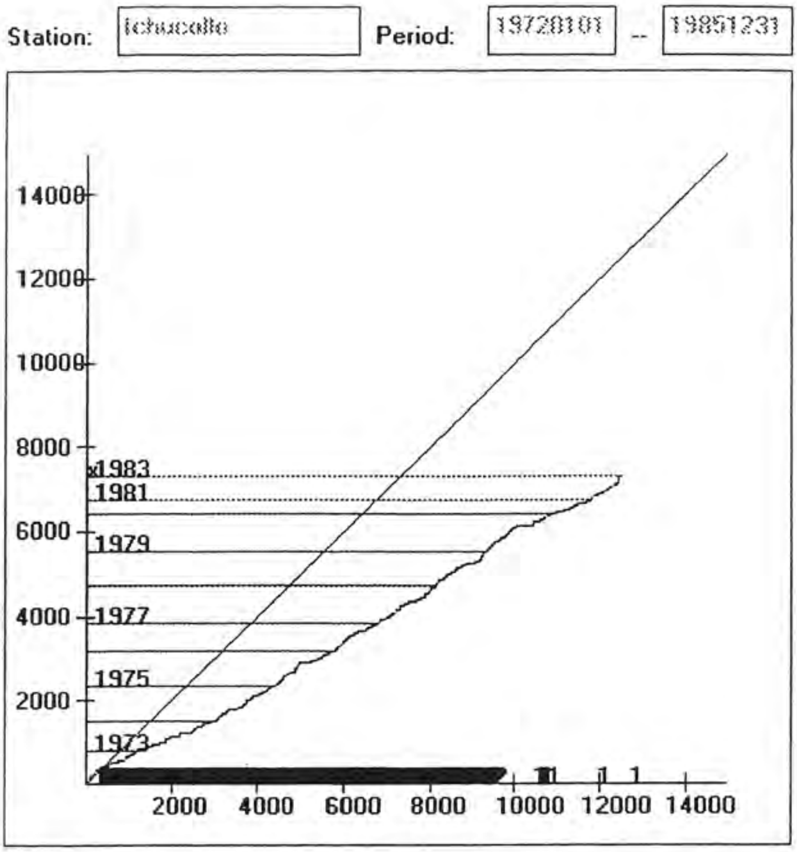
Toncoli, 1969 to 1978, plotted against Aguirre,Candelaria,Colomi, Corani and Cotani alto.



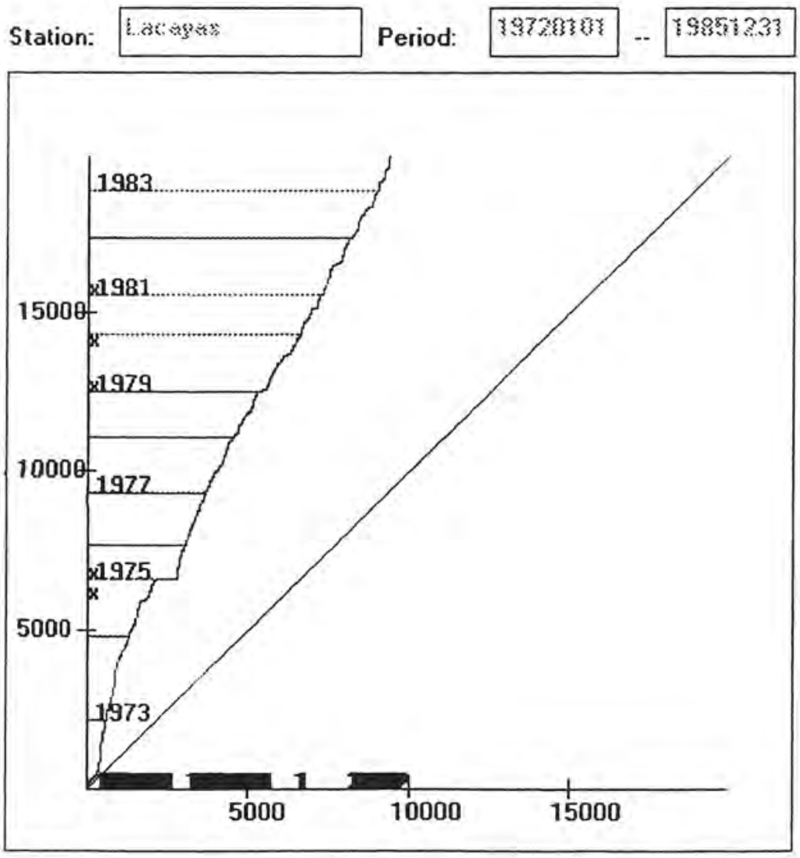
Planta Corani, 1970 to 1985, plotted against Incachaca, Locotal and Malaga 3200.



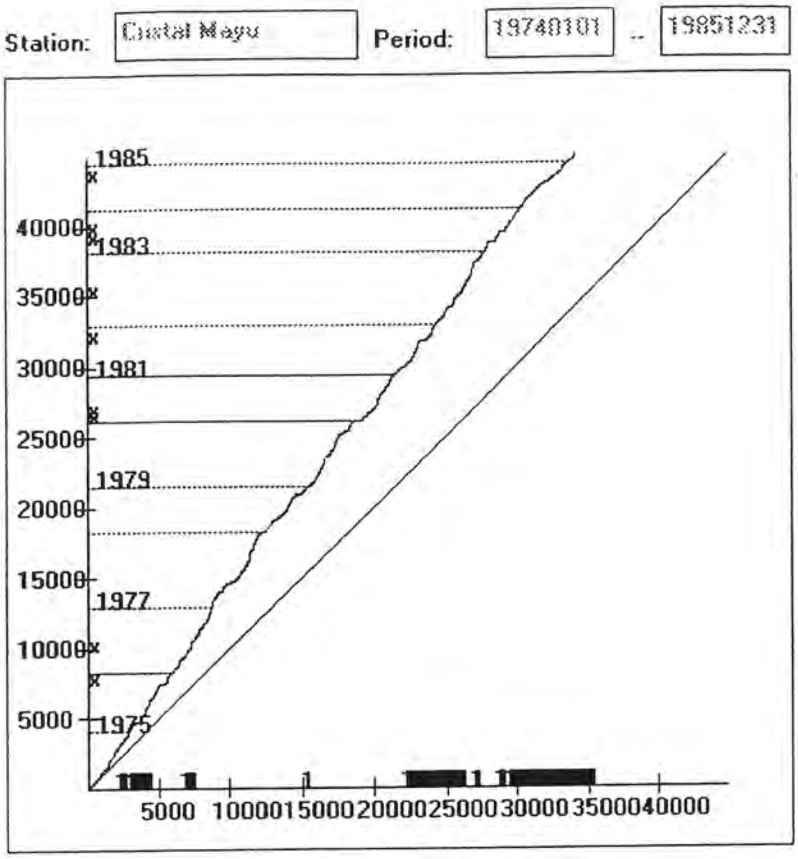
Malaga 3200, 1970 to 1985, plotted against Incachaca, Locotal and Planta Corani.



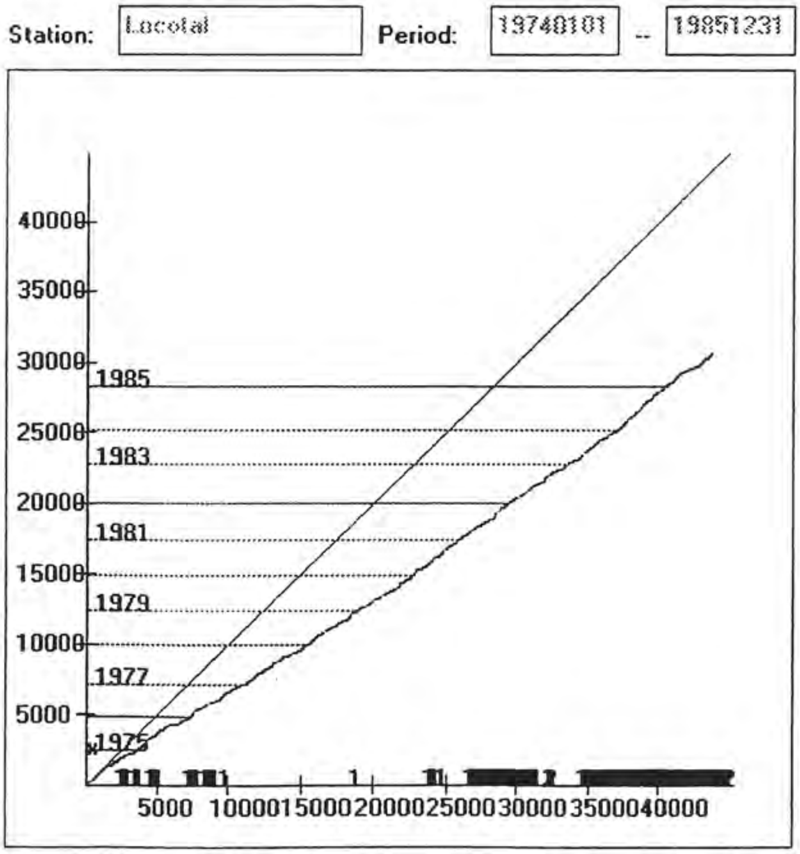
Ichucollo, 1972 to 1985, plotted against Lacayas and Palca.



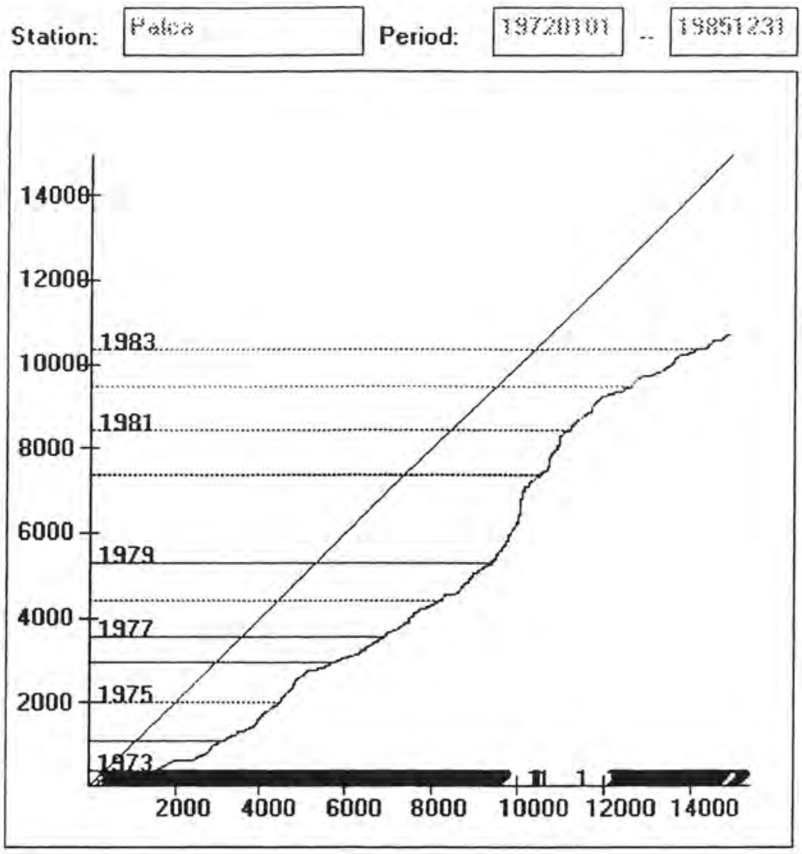
Lacayas, 1972 to 1985, plotted against Ichucollo and Palca



Cristal Mayu, 1974 to 1985, plotted against Locotal, Palma Pampa and San Onofre.



Locotal, 1974 to 1985, plotted against Cristal Mayu, Palmar Pampa and San Onofre



Palca, 1972 to 1985, plotted against Ichucollo and Lacayas.

Appendix C

Monthly tables of discharge at Icona, Locotal and Paracti Alto

JUNTAS CORANI AT ICONA
SIMULATED FLOWS (M3/S)

AÑO	ENE	FEB	MAR	ABR	MAY	JUN	JUL	AGO	SEP	OCT	NOV	DIC	MED
1968	162.94	365.93	138.77	97.22	41.49	21.25	11.11	9.35	17.28	41.71	101.00	144.33	96.03
1969	187.93	278.21	122.35	80.07	46.04	27.56	13.69	6.19	9.88	34.09	114.72	146.26	88.92
1970	186.17	221.84	228.78	144.94	91.76	36.80	28.75	20.30	40.51	78.66	79.96	224.33	115.23
1971	324.54	386.64	223.51	99.29	50.96	25.72	20.05	20.20	31.34	48.85	108.01	194.60	127.81
1972	200.87	168.13	252.33	147.23	57.20	29.03	17.93	21.52	51.91	95.46	110.90	207.22	113.31
1973	345.42	289.94	256.41	132.73	94.75	91.72	31.93	41.35	61.78	99.67	88.85	147.11	140.14
1974	286.38	337.84	204.46	178.49	57.14	22.39	15.21	20.84	32.14	61.78	74.80	85.33	114.73
1975	175.65	335.16	235.34	97.94	57.94	37.75	21.91	18.27	43.57	59.65	101.38	168.57	112.76
1976	336.25	286.26	208.35	104.42	50.38	22.57	13.80	42.80	51.92	48.99	68.86	110.41	112.08
1977	164.05	274.59	270.87	172.45	80.18	40.39	26.57	43.36	133.89	120.39	188.21	150.91	138.82
1978	369.05	311.86	163.63	103.37	48.42	23.99	15.03	13.36	21.39	37.71	101.82	246.76	121.37
1979	272.35	206.08	280.18	152.27	88.93	41.85	30.05	19.29	22.67	64.72	122.69	246.75	128.99
1980	187.45	174.31	265.81	128.08	60.40	31.01	25.34	40.50	52.91	72.13	85.47	88.41	100.98
1981	212.70	269.66	135.33	75.19	44.56	23.80	14.67	18.65	34.62	62.03	88.95	128.78	92.41
1982	206.68	205.59	270.45	159.34	65.69	29.59	16.82	21.29	26.87	104.00	225.15	195.95	127.28
1983	143.13	173.81	273.94	95.22	81.49	38.76	30.01	32.12	48.76	62.72	133.20	115.85	102.42
1984	295.30	315.55	441.60	149.03	58.57	25.23	13.53	13.31	18.08	52.27	130.53	141.73	137.89
1985	197.34	239.13	146.28	154.81	68.21	37.80	23.27	22.61	94.48	103.66	105.75	104.49	108.15
1986	137.11	254.26	311.59	138.71	61.97	32.26	21.58	14.53	30.95	53.89	103.43	175.78	111.34
1987	312.54	167.03	102.68	84.54	58.70	31.70	19.10	11.31	27.52	66.51	162.55	118.82	98.58
MEDIA	235.19	264.09	226.63	124.77	63.24	33.56	20.52	22.56	42.62	68.44	114.81	157.12	114.46
DES.EST.	74.21	66.08	79.18	32.22	16.10	15.17	6.46	11.41	28.82	24.40	38.68	49.17	15.42
C.V.	0.3	0.3	0.3	0.3	0.3	0.5	0.3	0.5	0.7	0.4	0.3	0.3	0.1

LOCOTAL HYDROMETRIC STATION
RECORDED + SIMULATED FLOWS

AÑO	ENE	FEB	MAR	ABR	MAY	JUN	JUL	AGO	SEP	OCT	NOV	DIC	MED
1968	20.19	28.44	20.09	10.37	5.56	4.29	3.52	3.10	3.04	4.55	8.94	10.13	10.19
1969	19.54	20.36	9.55	8.17	4.62	3.98	3.42	3.55	3.51	5.42	15.53	13.90	9.30
1970	18.99	23.54	23.23	18.27	8.79	4.96	4.88	3.63	4.80	6.33	15.43	25.65	13.21
1971	32.80	31.68	21.58	13.49	8.43	6.71	5.52	4.02	4.78	6.37	9.96	23.00	14.03
1972	21.59	18.84	23.68	18.48	8.69	6.58	5.76	6.41	8.10	8.92	12.41	17.89	13.11
1973	33.42	36.10	30.89	16.58	11.37	10.51	6.40	7.91	6.59	11.74	11.17	15.06	16.48
1974	31.20	33.19	25.32	20.11	9.04	6.17	6.00	5.38	4.93	9.36	6.67	8.45	13.82
1975	21.66	34.80	27.51	12.08	6.14	5.05	4.45	4.21	8.25	8.52	16.74	18.87	14.02
1976	44.19	26.00	19.57	9.03	5.34	4.07	4.16	4.81	6.28	4.56	4.93	8.04	11.75
1977	15.41	30.51	25.93	13.32	9.05	7.51	6.39	7.16	10.34	10.64	16.69	17.46	14.20
1978	29.25	25.35	14.30	8.86	6.10	5.00	4.56	4.07	5.05	4.68	7.54	15.67	10.87
1979	19.05	18.96	19.44	12.27	6.91	5.83	6.07	4.42	4.19	6.39	7.61	16.35	10.62
1980	17.83	11.87	20.38	13.06	7.43	5.82	4.78	6.21	6.41	8.42	7.27	9.43	9.91
1981	26.39	38.71	21.33	14.00	5.85	5.26	5.01	5.67	5.80	8.66	9.95	14.56	13.43
1982	25.06	19.66	30.45	18.26	9.64	7.15	6.69	7.46	5.26	10.22	17.34	25.28	15.21
1983	14.61	23.22	33.05	13.55	10.36	8.38	7.40	7.93	9.61	8.26	10.74	11.52	13.22
1984	32.45	37.90	34.23	15.93	7.96	5.29	5.46	5.98	6.42	9.29	11.22	13.34	15.46
1985	17.77	20.57	14.23	13.69	8.87	7.17	6.29	6.95	10.73	10.83	9.07	10.47	11.39
1986	15.32	22.80	32.43	15.34	9.41	6.88	6.19	5.22	6.83	7.25	13.69	19.57	13.41
1987	28.99	17.71	11.37	10.52	8.21	6.85	6.20	5.76	6.81	10.90	12.54	12.35	11.52
MEDIA	24.29	26.01	22.93	13.77	7.89	6.17	5.46	5.49	6.39	8.07	11.27	15.35	12.76
DES.EST.	7.83	7.57	7.19	3.43	1.82	1.58	1.08	1.50	2.14	2.26	3.69	5.25	1.98
C.V.	0.32	0.29	0.31	0.25	0.23	0.26	0.20	0.27	0.33	0.28	0.33	0.34	0.15

PARACTI ALTO
SIMULATED FLOWS (M3/S)

AÑO	ENE	FEB	MAR	ABR	MAY	JUN	JUL	AGO	SEP	OCT	NOV	DIC	MED
1968	50.32	84.45	32.68	21.90	10.46	6.79	4.24	3.80	5.77	10.98	26.55	38.58	24.71
1969	49.54	64.56	27.43	19.87	11.70	8.16	4.97	3.15	4.18	11.30	30.44	36.22	22.63
1970	50.30	57.11	59.61	36.53	22.78	10.35	9.82	7.18	13.62	23.87	22.65	62.36	31.35
1971	83.46	90.54	52.85	24.71	12.76	7.94	7.21	6.90	10.90	15.17	31.33	50.37	32.85
1972	50.66	44.23	62.59	35.49	13.93	8.66	6.67	8.17	15.79	23.29	27.99	46.75	28.68
1973	85.25	79.07	64.61	33.10	26.48	20.52	10.47	13.91	14.62	24.55	22.41	38.38	36.12
1974	72.81	79.28	48.44	40.41	14.23	6.47	5.80	7.80	8.80	16.79	17.90	20.50	28.27
1975	44.55	83.90	50.23	23.21	13.79	10.01	6.50	5.79	11.46	11.92	19.00	38.07	26.54
1976	86.03	65.23	39.59	24.37	13.29	6.23	5.12	14.80	15.90	14.00	19.58	23.70	27.32
1977	35.40	70.45	68.08	40.19	21.16	11.80	8.75	13.20	34.03	26.46	37.28	42.10	34.08
1978	91.86	76.17	41.87	23.53	11.94	7.37	5.91	5.87	7.54	10.55	26.10	61.20	30.82
1979	61.36	46.19	58.73	35.23	19.53	9.42	9.14	6.40	8.09	19.77	31.97	67.24	31.09
1980	49.82	38.65	70.42	27.07	15.29	9.28	8.79	14.98	16.81	20.95	20.11	19.58	25.98
1981	49.58	60.61	29.37	19.72	10.79	7.24	5.95	7.13	7.62	16.96	23.42	32.83	22.60
1982	52.61	46.26	69.03	39.79	18.27	10.67	8.28	10.01	8.06	27.89	43.19	47.33	31.78
1983	34.09	45.02	69.32	24.94	22.05	12.66	11.18	12.19	16.07	17.55	31.16	28.49	27.06
1984	76.89	81.29	97.98	35.16	15.21	8.37	6.69	7.28	8.76	18.40	33.22	35.74	35.42
1985	48.01	59.21	35.20	33.96	17.00	11.40	8.52	9.34	27.81	27.32	25.89	27.37	27.59
1986	37.03	68.21	74.93	34.86	17.30	10.66	8.62	6.68	12.31	16.10	32.10	49.05	30.65
1987	77.28	45.24	25.23	23.23	16.68	11.09	8.44	6.76	10.95	23.29	39.23	30.23	26.47
MEDIA	59.34	64.28	53.91	29.86	16.23	9.75	7.55	8.57	12.96	18.86	28.08	39.80	29.10
DES.EST.	18.44	16.13	19.04	7.20	4.37	3.15	1.92	3.51	7.22	5.64	7.02	13.62	3.88
C.V.	0.31	0.25	0.35	0.24	0.27	0.32	0.25	0.41	0.56	0.30	0.25	0.34	0.13

Appendix D

Acquisition and installation of hydrometeorological stations

B. SPECIFICATION

PRIMARY SPECIFICATION OF HYDROMETEOROLOGICAL STATIONS

After discussions on July 12, 1994 and August 2, 1994 between ENDE and SMHI it was found that it was impossible to meet requested measurements with a technical solution consisting of three local hydrometeorological measuring stations. In fact it was necessary to separate the hydrological and meteorological measurements a certain distance from each other from both meteorological reasons as well as from practical reasons.

This required a technical solution with six separate logging units, one at each individual measurement site.

This change from initial plans also resulted in a change of economical conditions, that necessary had to imply a restriction of the quantity and/or quality of the stations. We agreed to accept, if necessary, a minor reduction from first plan, in the parameters to be measured, especially evaporation and radiation, that are not of primary interest to the IHMS model, but more of general value.

We also had to see what quotations we should receive, to be able to optimise stations and their equipment. To make this easy, we asked for detailed quotations with specified costs for all individual components.

The basis for the quotations was a list of requirements, station by station, produced on two EXCEL-forms together with the *INVITATION TO TENDER*, see, in italics, below.

Appendix D

ACQUISITION AND INSTALLATION OF HYDROMETEOROLOGICAL STATIONS

A. General

B. Specification

C. Technical solution

D. Installation

E. Operation

- **Function**
- **Field routines**
- **Data collection**

A. GENERAL

In the co-operation between Empresa Nacional de Electricidad, ENDE, Cochabamba, Boliva and the Swedish Meteorological and Hydrological Institute, SMHI, Norrköping, Sweden an essential project part was to strengthen the **hydrometeorological network in the Icona basin.**

From the specific project objectives, that is described in Chapter 1.2 , there is specified that SMHI should assist in the purchase and installation of three hydrometeorological stations. They should be placed at Corani, Locotal and Icona.

The primary discussions, before the procurement process was initiated, dealt with how to meet ENDEs requirements of stations and measuring parameters with the investment money deposited for a technical system, totally SEK 369000:-, two thirds of which supplemented by SMHI:s funds and one third by ENDE, that was specified in the agreement dated June 1994.

SMHI/loh/Nils Sjödin | 940816

COCHABAMBA

Station/Site	automatically recorded parameters	range	accuracy	resolution	suggested measuring frequency	pow.supply	remarks
Met station Colomi h.a.s.l 3300 m	wind velocity	0 - 40 m/sec	"+/- 2 m/sec"	1 m/sec	every 10 min	electrical network	wind sensors could be installed 4 m above ground
	wind direction	0 - 360 degr.	"+/- 5 degrees"	2 degrees	every 10 min		
	air temperature	"-10 to + 50 C"	"+/- 0,2 C"	0,1 C	every 1 hour		sensor shield neccessary
	relative humidity	0 - 100 %	"+/- 5 %"		every 1 hour		sensor shield neccessary
	precipitation	0 - 300 mm/d	0,5 mm	0,2 mm	continous event record		
	evaporation	all	0,5 mm	0,2 mm	every 3 hour		Type Class A pan
Met station Locotal h.a.s.l. 1700 m	wind velocity	0 - 40 m/sec	"+/- 2 m/sec"	1 m/sec	every 10 min	Solar panel and/or batteries for at least 3 months autonomy	wind sensors could be installed 4 m above ground
	wind direction	0 - 360 degr.	"+/- 5 degrees"	2 degrees	every 10 min		
	air temperature	"-10 to + 50 C"	"+/- 0,2 C"	0,1 C	every 1 hour		sensor shield neccessary
	relative humidity	0 - 100 %	"+/- 5 %"		every 1 hour		sensor shield neccessary
	precipitation	0 - 300 mm/d	0,5 mm	0,2 mm	continous event record		
	evaporation	all	0,5 mm	0,2 mm	every 3 hour		Type Class A pan
Met station Icona h.a.s.l. 600 m	wind velocity	0 - 40 m/sec	"+/- 2 m/sec"	1 m/sec	every 10 min	Solar panel and/or batteries for at least 3 months autonomy	wind sensors could be installed 4 m above ground
	wind direction	0 - 360 degr.	"+/- 5 degrees"	2 degrees	every 10 min		
	air temperature	"-10 to + 50 C"	"+/- 0,2 C"	0,1 C	every 1 hour		sensor shield neccessary
	relative humidity	0 - 100 %	"+/- 5 %"		every 1 hour		sensor shield neccessary
	precipitation	0 - 300 mm/d	0,5 mm	0,2 mm	continous event record		
	evaporation	all	0,5 mm	0,2 mm	every 3 hour		Type Class A pan
	solar radiation (pyranometer)	<1100 Wh/m2*)	"+/- 5 %"		every 1 hour (mean value)		*) Energy on diurnal base

SMHI/loh/NSjodin | 940816

COCHABAMBA

Station/Site	automatically recorded parameters	range	accuracy	resolution	suggested measurring frequency	pow.supply	remarks
Hyd station Corani Dam h.a.s.l. 3200 m	water level preferably bubble gauge	0 - 20 m	"+/- 2 cm"	1 cm	every 1 hour (preferably 2 minutes mean value)	electrical network	gas bottles will be supplied by local operator
Hyd station Locotal river h.a.s.l. 1700 m	water level preferably bubble gauge	0 - 10 m	"+/- 2 cm"	1 cm	every 10 min (preferably 1 or 2 minutes mean value)	solar panel and/or batteries for at least 3 months autonomy	gas bottles will be supplied by local operator
Hyd station Icona river h.a.s.l. 565 m	water level preferably bubble gauge	0 - 10 m	"+/- 2 cm"	1 cm	every 10 min (preferably 1 or 2 minutes mean value)	solar panel and/or batteries for at least 3 months autonomy	gas bottles will be supplied by local operator

INVITATION TO TENDER

SMHI, The Swedish Meteorological and Hydrological Institute invites your company to submit a tender for hydrometeorological monitoring equipment to be installed in the vicinity of Cochabamba, Bolivia, see specification enclosed.

The tender shall be sent to SMHI, attention Nils Sjödin, S-601 76, NORRKÖPING, SWEDEN as soon as possible, but latest by 15 September 1994.

The tender shall include a technical specification, information about required civil works before installation, guarantee conditions, technical assistance at installation as well as recommended spares and maintenance for a one and a five years period.

The equipment of interest are in general terms the following:

- *three meteorological stations, with sensors according to specification enclosed. Two of the stations requires solar panels and (or) battery power*
- *three river water stage gauges, of which two requires solar panels and (or) battery power*
- *data loggers at all stations, totally six, capable to store at least three months of data*
- *software to handle and transfer collected data*
- *terminal logger for field service, if necessary*
- *extra data storage packs, if necessary*
- *necessary adapters, parts, tripods or similar masts (if applicable) and mounting parts for a good and long term function.*
- *service manuals for all equipment*

All measurement records shall be direct related to local time or UTC.

Civil works, as well as local transports in Bolivia for equipment and installation staff shall not be included in the tender.

Climatic environmental conditions for the stations are:

- Temperature range	*0^o to + 40^o C*
- Annual precipitation	*< 3000 mm*
- Height above sea level	*500 to 3000 m*
- Climate	*humid to semi-arid*

The solar and (or) battery powered stations, two meteorological and two hydrological stations, are to be installed in remote areas. The remaining two stations will be installed in populated areas.

Costs shall be specified for each item in the tender.

Delivery terms shall be included in the tender. The installation of the monitoring stations shall preferably be done within two months from order.

C. TECHNICAL SOLUTION

After communications between SMHI and the different companies, that had given quotations, we found that only two of them could offer a complete measuring system of a configuration that was requested for the Icona basin project. It was Campbell Scientific, Inc., Utah, USA and Handar Inc., California, USA, both with well qualified equipment and with documented references from among others US Geological Survey.

The price level gave us, however, in fact no chance to consider the Handar quotation, unless a reduction of the number of stations, so we decided to go further with the Campbell solution.

At a discussion on SMHI November 24, 1994 the Swedish representative, FDS Mätteknik AB, informed ENDE and SMHI about the Campbell system, how it could meet the requirements and be the solution for actual measuring application.

The basic unit in the hyd-met stations is a compact datalogger CR 10, that has been used extensively in many places around the world. All sensors in suggested system are of good standard quality and can be used together with the logger without any interfaces.

At the meeting, on November 24, we also cleared out the management, procurement and payment responsibilities for SMHI and Ende to the different parts of the hydrometeorological measurement project.

The agreements from this meeting were of both economical and practical sort:

The cost for the basic equipment will be shared with 1/3 paid by ENDE and 2/3 by SMHI, all in accordance with the document "Cost summaries for the Cochabamba-Project with a Campbell system" dated 11 December, 1994.

SMHI will pay the evaporation equipment and the PC that will be bought in Bolivia.

SMHI will pay the air ticket for FDS Mätteknik's agent Mr Ekman, who will install the equipment.

ENDE will pay for the basic site constructions at the stations.

ENDE will cover all local costs including transports for Mr Ekman during his stay during the installation session in Boliva.

ENDE will pay costs for the transportation of instruments within Bolivia.

The finally chosen technical solution was the Campbell system that in detail is descried in the annex to our order No. 531, dated 1995-01-20. In italics, see next three pages.

Specification of order No. 531 from SMHI, The Swedish Meteorological and Hydrological Institute.

The ordered equipment is in coincidence with your quotation of 1994-11-29 and are in general terms:

- ***three meteorological stations**, complete with sensors, data logging unit, energy supply, cabinet and mounting equipment, according to specification below.*
- ***three hydrological stations**, complete with sensors, data logging unit, energy supply, cabinet and mounting equipment according to specification below.*

Specification in detail as follows:

***Colomi** Met station*

-Campbell datalogger CR 10
-Wind monitor 05103
-Humidity sensor MP 300
-Temperature sensor 107
-Radiation shield 41004
-Rain gauge ARG100

-Power backup by lead accumulator 3,6 Ah, connected via recharger from 220 VDC network.
-Lightning protection on mains connection.
-Cabinet 40 x 40 cm with mounted connectors for sensors.
-Mounting equipment for attaching cabinet to 1,5" pole.

***Locotal** and **Icona** Met stations*

-Campbell datalogger CR 10
-Wind monitor 05103
-Humidity sensor MP 300
-Temperature sensor 107
-Radiation shield 41004
-Rain gauge ARG100

-Power supply by lead accumulator 3,6 Ah, recharged by solar cell MSX 10.
-Cabinet 40 x 40 cm with mounted connectors for sensors.
-Mounting equipment for attaching cabinet to 1,5" pole.

*Specific for the **Icona** station:*

-Pyranometer LicCor with mounting equipment to ¾ - 1" horizontal rod and necessary connectors.

***Corani Dam** Hydrological station*

-Campbell datalogger CR 10
-Bubbler level gauge DB1

-Power backup by lead accumulator 3,6 Ah, connected via recharger from 220 VDC network.
-Lightning protection on mains connection.
-Cabinet 40 x 60 cm prepared for installing of bubbler tubes and mains cable.
-Mounting equipment for attaching cabinet to 1,5" pole.

Locotal and Icona Hydrological stations

-Campbell datalogger CR 10
-Bubbler level gauge DB1

-Power backup by lead accumulator 3,6 Ah, recharged from solar cell MSX10.
-Cabinet 40 x 60 cm prepared for installing of bubbler tubes and mains cable.
-Mounting equipment for attaching cabinet to 1,5" pole.

Common equipment

-Software MS-DOS PC208
-RS232 Interface, 2
-RS232 Cable 5 m
-Keyboard display

Spare parts

Spare parts in accordance to following list:

1 Rotronic Rh probe
1 Calibration chamber
1 Set calibration ampoules 35 %
1 Set calibration ampoules 80 %
1 Temperature sensor No 107
1 Bearingmounting Wind speed sensor
6 Bearings
1 Potentiometer, Wind direction sensor.
1 Set of working tools
1 Rechargeable lead accumulator 6 Ah
1 Rechargeable lead accumulator 3 Ah
20 Desiccant bags

Systemizing work

The contractor, FDS, has a system responsibility that means.
- *to produce a menusystem for the operator.*
- *to produce a software for the measuring routine (including functions for control of battery voltages, battery saving and evaporation measuring system and bubbler gauge control).*

The contractor has also to provide documents over system, software and outcoming data. This should be included in a practical and useful handbook over the system.

The contractor guaranties an one year consulting service over (telephone or mail) on the system, misfunctions, system development and assistance at interchange of spare parts.

The stations should first be assembled at FDS, Sweden for a test run, before shipped to ENDE, Bolivia.

Installation

Installation should be done as early as possible, preferably in March 1995, and after agreement between contractor FDS, SMHI and ENDE.

The installation work is scheduled to five (5) days work at site in the Cochabamba area, and two (2) days travelling. Within this order is included cost for air travel from Sweden to

Cochabama, Bolivia and return, for one person to be supervisor at the installation and responsible for local education according to schedule above.

Allowances and cost for accommodation at an international standard hotel is to be paid by ENDE. All local transports from Cochabamba to installation sites is also supplied by ENDE.

Terms:

Delivery: Cochabamba	*60 days after order + time for transport from Sweden to Bolivia; CIF*
Warranty:	*12 months after delivery to final customer (ENDE)* *36 months on CR10 datalogger.* *FDS repairs in Sweden, or arranges from Sweden for interchange of such parts that are faulty.* *All transport cost, for any part from Bolivia to FDS, Sweden and by return, in connection with warranty repair is to be dealed with and paid by customer.*

D. INSTALLATION

After the decision of the equipment to be procured the proceeding work were done parallel at SMHI as well as at ENDE.

SMHI had to fulfil the procurement of technical equipment.
ENDE had to prepare actual measuring sites to get them in order for the installation.

The basic hardware part of the measurement system was ordered January 20, 1995 from FDS, Mätteknik, Skara, Sweden, that is the Swedish representative for Campbell Scientific, Inc.

During the early spring 1995 the system, except for the evaporation unit, was put together at the FDS office and prepared for installation in Bolivia. This equipment was sent from Sweden April 6, 1995 and the evaporation measuring equipment from NovaLynx, USA, April 12.

The installation at the sites in Bolivia was first planned to March-April 1995, but was delayed until June 17 - 24, mainly depending on late delivery of basic hardware 0components, but to part also due to delayed customs action in Bolivia.

ENDE informed on March 8, 1995 that they had constructed the three platforms necessary for the meteorological stations at Colomi, Locotal and Icona. ENDE had also, at the river level stations at Locotal and Icona, arranged for pipes, to which the gas tubes from the water level measuring system should be fitted. These stations were constructed at places that there already existed older stations. The water level station at the reservoir at Corani was given place to be installed in an existing room within a building at the reservoir.

The installation was performed during a concentrated period under supervision from Mr Ekman from FDS Mätteknik. This resulted in an almost complete installation, summarised station by station to following status on June 24, 1995:

Colomi Met station:	Physical installation complete. Software complete with latest version, including daily and hourly mean values.
Locotal Met station:	Physical installation complete. Upgrading of software to latest version including daily and hourly mean values remains.
Icona Met station:	Physical installation complete. Upgrading of software to latest version including daily and hourly mean values remains.
Corani dam Hyd station	Temporary, shallow installation, of tubes for the bubbler level gauge. To be modified at low water in reservoir. Software complete, with latest version.
Locotal Hyd station	Physical installation completed, but with a very small distance between the two pipe orifices. This gives a higher uncertainty at higher levels. Ought to be considered by some complementary technique. Software complete, with latest version.
Icona Hyd station:	Physical installation not complete, depending on stolen tubing´s for the bubble gauge level measuring system. Function not tested.

E. OPERATION

The installed data collection system is a compact modular system that has been procured as the optimum solution for the actual project. Parts, as sensors, dataloggers and power supply units within the system, are interchangeable without any complicated procedures. They should be found on the market for a certain future amount of years, depending on the wide spread of Campbell loggers. The system has also a great flexibility in that it is possible to change and/or add components to it and also change data collecting schedule, as raising or lowering the frequency in the measurements.

The routines of operation, field service and data recovery follows basically local schedules, that SMHI basically do not have to consider. These have been first established under supervision by the Campbell representative in direct connection to the installation of the equipment on site in Bolivia. The schedules can easily be changed if necessary.

- function

For the operation of the hydrometeorological stations there have been supplied the manufacturers **CR10 MANUAL** and a **HANDBOOK , Ver. 1.2, 950617** especially written for ENDE´s Campbell stations.

An essential part of the system is the **power supply.** The dataloggers needs constantly external power from the lead battery. Those are in turn, to minimise power supply breaks, backed up by solar cells alternatively mains power.

The principles for the measurements, sensor functions, data logging, data retrieval, operational time and data processing is also described in the **MANUAL** and the **HANDBOOK.**

- field routines

At the time of installation the first recommendations of field routines for servicing the stations were encountered. To get the best data recovery from the six new stations there should be established an operational and service program for each station.
Such a program should contain

- frequency of data retrieval
- frequency of inspection (just visit)
- frequency of inspection (function control)
- frequency of sensor control and/or calibration

The handbook gives information of the stations individual capacity, that is depending on the number of sensors installed and rate of data collection. The Met stations can store data up to 79 (Locotal) and 98 days (Icona and Colomi) before they must be drained to an external computer. The Hyd stations can operate up to 132 days before their internal storage's are filled up with data.

When the internal data logger storage's are filled up with data, new data will overwrite older, so that some data are lost. The last period will however be available. If the stations, after a first period of operation, are found to work in such a reliable way that technical inspections at the measurements sites could be reduced, it would be possible and an advantage to add extra memory units to the stations.

There should also be established a journal describing events at each station.

- data collection

Data is primary stored in a binary format and transformed into ASCII code when transmitted to a field computer or terminal.

The data collection follows Campbell's standard format, station identification, year, Julian day, hour min "hhmm", parameter values, all comma separated. Each measuring sequence is followed by a CR. and commend.

A Laptop PC, with a processor 486 DX, is bought to the project for the collection of stored data from the dataloggers on the field stations. This computer can also be used when there is need for communication with the stations, i.e. for real time display of data and for downloading of new datalogger programs.

The primary processing of the data is performed via a menu-type instruction that is delivered to ENDE together with the hardware.

Appendix E

Sediment study

Sediment study

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1. Introduction

As an addition to the hydrological study and the hydrometeorological monitoring for water resources development in the Icona basin a sediment study was performed by the Swedish Meteorological and Hydrological Institute (SMHI). A brief summary of the sediment study is presented in Chapter 8 in the main report. Below, the available data, methods applied and concluding results are described in more detail. The work at SMHI has mainly been done by Mr Rikard Lidén.

The general objective of the sediment study was to perform

- a quantification of the annual sediment yield at Locotal, and
- an evaluation of the sediment yield problem for the Icona basin

The sediment study was mainly done trough a review of previous literature, collection of data and the set up of a supply-based sediment yield model, developed by SMHI, for the Locotal basin. A brief evaluation of the sediment yield at the Icona site was also carried out.

2. Geological description

The general description of the Icona basin is presented in Chapters 3, 5.1 and 5.6 in the main report while the Locotal basin is briefly described in Chapter 5.4.

The Icona basin covers an area of totally 2140 km^2 down to the planned Icona site and the altitude ranges from 580 to 4300 m.a.sl. The topographical features are sometimes dramatic with deep gorges, high ridges and very steep slopes. Geomorphological the Icona basin as a whole is judged to be in equilibrium even if some of the upper subbasins are considered as young (Icona Feasibility Report, 1993).

Climatological, most of the project area can be defined as tropical, with high temperatures and high amount of precipitation. Only the very upper parts of the basin have less precipitation and lower temperatures. The precipitation is seasonal with a rainy season between October and April.

Below, the geology, soil and vegetation are briefly described for the Locotal and Icona basins. No detailed maps describing the geology, soil or landuse are unfortunately available for the project area. The information below is, thus, based mainly on oral and visual information gained at site visits to the area.

2.1 Locotal basin

Locotal basin is located in the south corner of the Icona basin. The catchment area is 200 km^2 and the altitude ranges from 1700 to 4200 m.a.sl. Fig. 9 in the main report shows the basin and the major rivers within it.

The geology of Locotal basin is characterised by four types of bed rock; quartzite, sandstone, mudstone and slates. A brief geological map of the Locotal basin is shown in Fig. 2.1. The quartzite is mainly located in the upper parts of the basin near the main

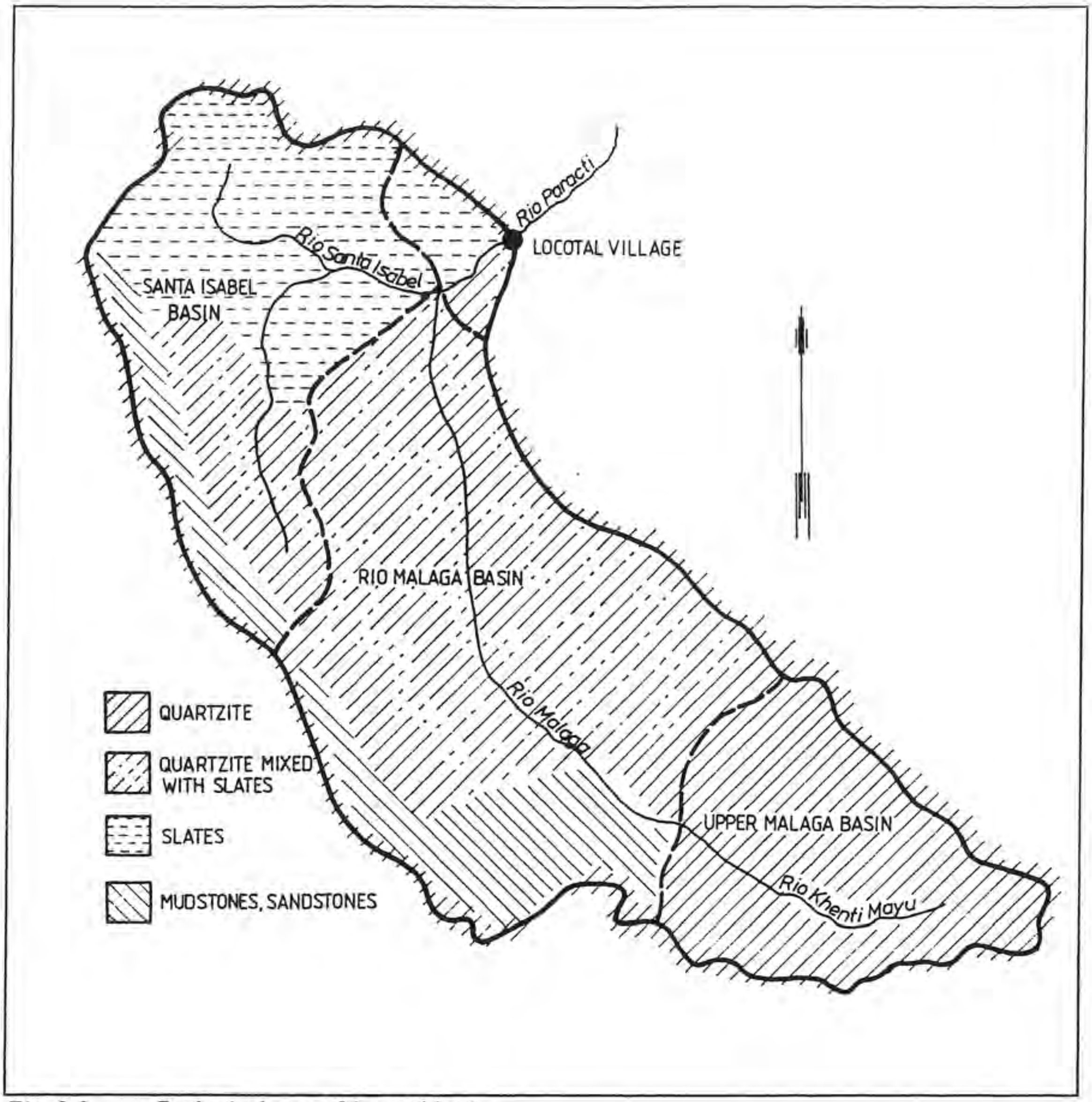

Fig. 2.1. Geological map of Locotal basin.

water divides. The Upper Malaga subbasin with an altitude above 3200 m.a.sl. consists mostly of this quartzite. Mixed with slates the quartzite is also common in the Rio Malaga basin, while the Santa Isabel subbasin mainly consists of slates. In the upper south-west parts of the Rio Malaga and Santa Isabel subbasins, sandstones and mudstones are common.

The soil map of Locotal is basically a result of the underlying bed rock. In the upper parts of the basin where the relative hard quartzite dominates, the overburden is thin and consists mainly of moraine. Further down in the basin, the soil becomes a mixture of glacial and fluvioglacial deposits and, as the altitude decreases, the soil layers get thicker. In the Santa Isabel, where the soft slates dominate, the overburden is thick and fairly unstable. Except glacial/fluvioglacial deposits the soil here also consists of weathered slates. In the bottom of the valleys and in the main stream channels, colluvial and alluvial materials are deposited.

The vegetation varies from very scarce in the upper Malaga subbasin to dense in the valleys of Santa Isabel. Human impact is very small in the Locotal basin. In the valleys settlements are concentrated to the main road between Cochabamba and Santa Cruz and the Corani and Santa Isabel power plants, while the upper parts are more or less inhabited.

In general the slopes in the Locotal basin are very steep, both in the upper and lower parts. In the Santa Isabel subbasin small landslides often occur due to the steep slopes, thick overburden, soft bed rock and dense vegetation.

2.2 Icona basin

Detailed information regarding geology and soil is limited within the vast areas of the Icona basin. A rough geological map is presented in Fig. 2.2.

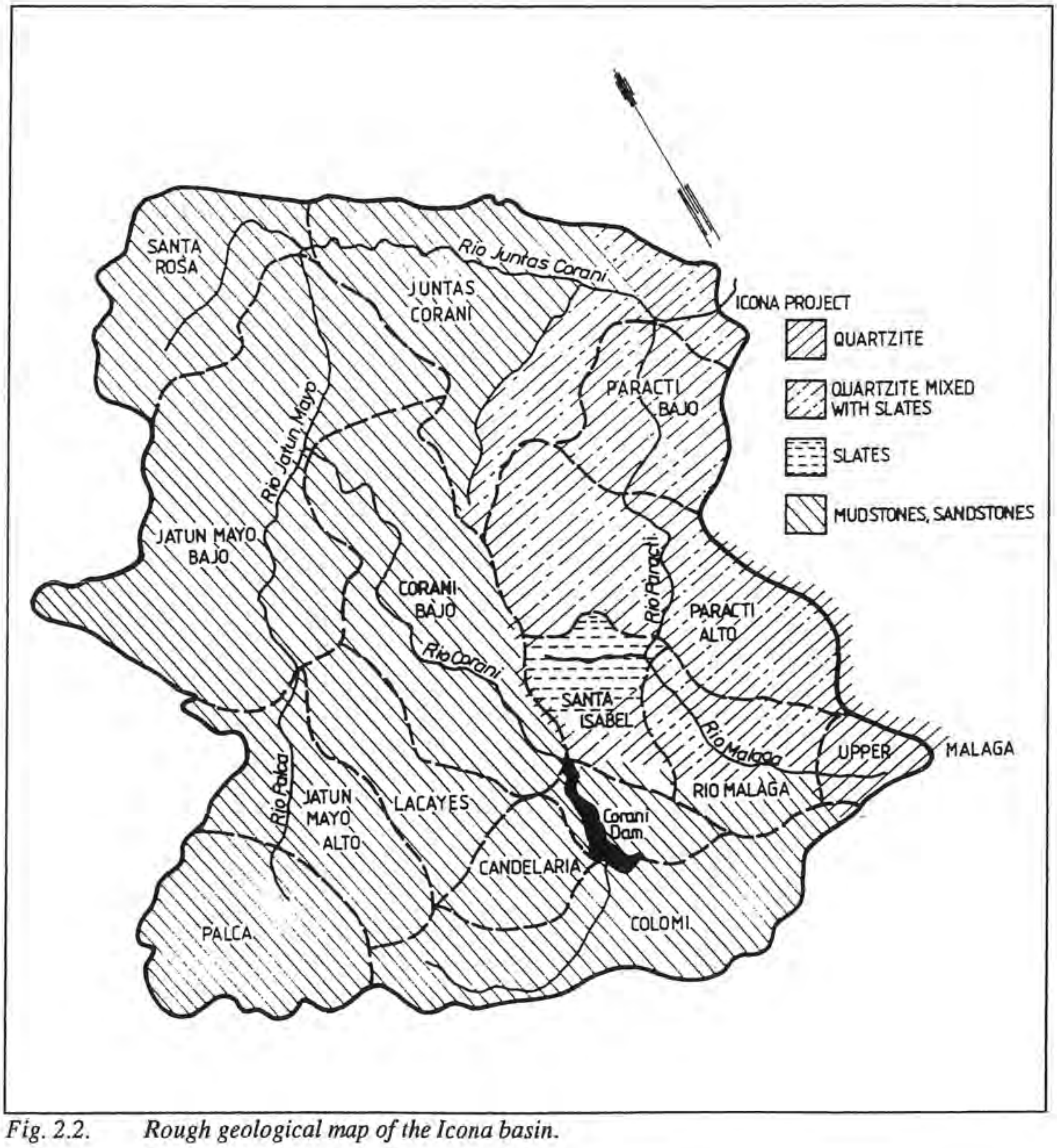

Fig. 2.2. Rough geological map of the Icona basin.

The western and southern parts of the basin are dominated by sandstones and mudstones. The quartzite found in the upper parts of the Locotal basin is also found in the upper parts of Paracti Alto and, mixed with slates and sandstones, in the whole north-west corner of the Icona basin. Slates are dominating in the Santa Isabel basin.

The soil in the upper parts of the basin is mostly moraine, while glacial and fluvioglacial deposits are common in the lower parts. Thick deposits are found in the Santa Isabel and the Corani Bajo basins.

Except the Corani Bajo valley, most parts of the basin north of the Corani Dam are covered with dense, scarcely inhabited jungle. In the south at Colomi, Corani Dam, Candelaria, Lacayes, Jatun Mayo Alto and Palca agriculture is common. The main crop is potatoes and areas that are not cultivated, have scarce vegetation. The most upper parts, and especially the Upper Malaga subbasin, are mainly inhabited mountain areas, with scarce vegetation.

Steep slopes are common in the whole Icona basin even if the southern mountainous areas have the most dramatic topography.

3. Available data

Besides the hydrometeorological data collected for the hydrological study, described in Chapter 4 in the main report, there are also data and information available regarding erosion and sediment for the Locotal and Icona basins. The data and material that have been made available for this study are described below.

3.1 Sediment samples

Suspended sediment samples were taken at the hydrometric station at Locotal between July 1971 and February 1975. Totally 1168 samples were taken during the period. More specifically the measurements were made according to Tab. 3.1.

Data collection period	*Comments*
20/7/1972 - 11/9/1972	
9/10/1972 - 15/1/1973	
16/1/1973 - 9/5/1973	Two samples per day
10/5/1973 - 30/11/1973	
15/12/1973 - 14/3/1974	
29/3/1974 - 31/7/1974	
29/9/1974 - 31/12/1974	Frequent gaps
10/1/1975 - 25/2/1975	Occasional samples

Table 3.1. Suspended sediment samples at Locotal hydrometric station.

The measurements in gram per litre (g/l) were made with an US-D-49 suspended sediment sampler. Corresponding runoff observations were also done at the hydrometric station.

In general the data seem to be of good quality. When samples were taken twice a day during the period January to May 1973, the measured values from the same day generally show good consistency. Also when plotting the suspended sediment samples with corresponding runoff data, the observed concentrations seem to be realistic.

Unfortunately during the recession of the highest observed peak of suspended sediment concentration, observed runoff is missing, 12-14 February 1973. (See further, in 6. Extreme storm flood events.)

3.2 Previous studies, etc.

The following literature includes an evaluation of the sediment yield in Rio Paracti, Locotal and Rio Juntas Corani, Icona;

- Hydrological and Sedimentological study
  in Feasibility Report, San José hydroelectric project, 1983, ENDE.
- Hydrology and Sediment
  Chapter 2 in Feasibility Report, Icona hydroelectric project, 1993, ENDE.

Further information that was used was;

- The results from levelling of the Corani dam at 1973 and 1988. The difference in dam volume gives an estimate of sediment yield into the reservoir.

- 1:50 000 topographical maps for the Icona basin. (Instituto Geografica Militaire)

4. Review of previous studies

4.1 San José Feasibility Report

The site for the planned San José hydroelectric plant is located approximately 10 km downstream of the Locotal hydrometric station in Rio Paracti. In the sediment study within the San José Feasibility Report made 1983 by ENDE an evaluation of the sediment yield has, thus, been made based on the sediment samples taken at Locotal.

The method used to evaluate the suspended sediment yield was the Flow Duration-Sediment Rating Curve Method (p 482, Vanoni, 1975). The method uses the duration curve for runoff together with a runoff-sediment rating curve, which is derived from observed data, to calculate the long-term sediment yield. In the study the runoff duration curve was used for 1966-1981 and the rating curve used, is shown in Fig. 4.1.

The resulting annual suspended sediment yield was 601 000 tonnes/year.

The runoff duration curve based on the years 1968-1987 differs very little from the duration curve for 1966-1981. The same method and runoff-sediment rating curve but with the updated runoff duration curve (see Chapter 6. in the main report) would, thus, give small differences in the calculated annual suspended sediment yield.

More interesting is that Fig. 4.1 shows that the runoff-sediment rating curve is chosen rather conservatively. If the rating curve is instead chosen by linear regression, based on the samples taken when runoff is larger than 30 m^3/s (approximately 90% of the total sediment yield is caused during runoff larger than 30 m^3/s), the resulting annual sediment yield will be approximately 230 000 tonnes/year.

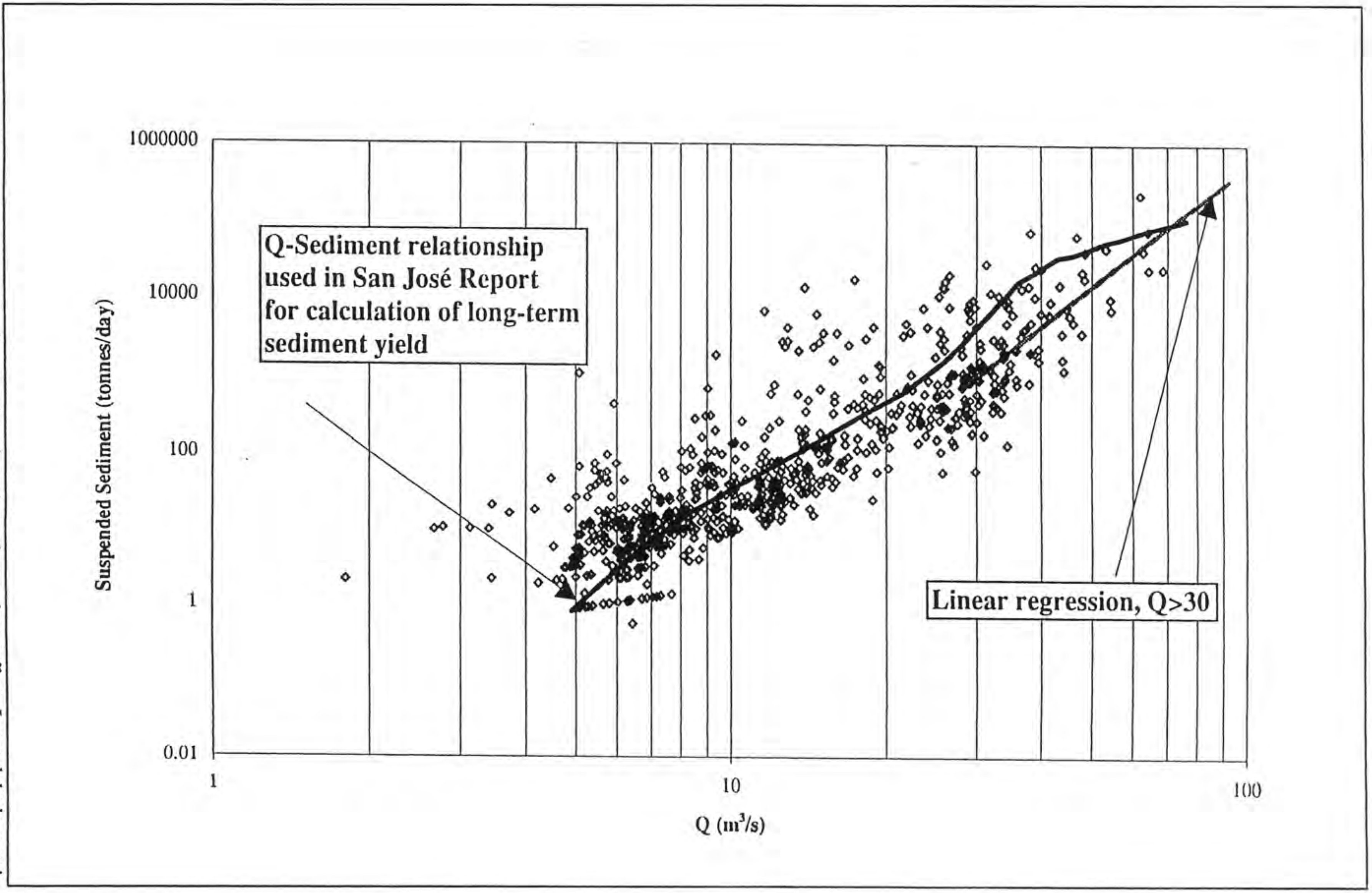

Figure. 4.1. Observed suspended sediment plotted against observed runoff at Locotal hydrometric station.

Also, an evaluation of the annual bed load in Rio Paracti was made in the San José sediment study. The study was based on the Meyer-Peter-Muller equation (p 192, Vanoni, 1975), which computes the bed load from runoff, slope of stream and median size of bed sediment. The resulting annual bed load in Rio Santa Isabel and Rio Malaga was calculated for the hydrological years 1972/73 and 1973/74.

The total calculated bed load for Rio Paracti (sum of results at the two upstream rivers) were for 1972/73, 137 000 tonnes/year and for 1973/74, 66 000 tonnes/year. The year 1973/74 were judged to be an average year based on annual mean runoff and, thus, the figure of 66 000 tonnes/year was used as an estimate of the long-term mean annual bed load.

4.2 Icona Feasibility Report

The Icona hydroelectric plant is planned just downstream of the confluence of Rio Juntas Corani and Rio Paracti. In the feasibility report made 1993, an evaluation of the sediment yield at Icona was carried out.

As no sediment samples exist, except at Locotal hydrometric station, the result in the San José Feasibility Report was used. The retrieved mean annual suspended sediment yield at Locotal was converted into sediment yield per year and km^2, and then utilised for the Icona basin area.

The resulting estimate of sediment yield for Icona was 7 130 000 tonnes/year.

5. Sediment yield model

At SMHI a suspended sediment model, linked to the HBV hydrological model (see Chapter 2.3 in the main report), has been developed. The model uses long continuous series of simulated areal precipitation and runoff, computed by the HBV-model to simulate the suspended sediment yield in a river.

The sediment model has been applied to the Locotal site to estimate the long-term mean sediment yield. The model structure is briefly described below as well as the model setup, calibration and results for the Locotal application.

5.1 Model structure

The suspended sediment model is a conceptual large scale (e.g. a catchment area) model. The model parameters describe the physical properties and processes, in this case erosivity and sediment transport. To calibrate the model, observed sediment concentration and observed runoff are used. The basic model structure is shown in Fig 5.1.

To describe variations in parameters within the total catchment area the model can be distributed into subbasins, which each can be given specific parameters. The model is generally run on a daily basis but other time steps are possible. Input data are areal precipitation and runoff for each subbasin.

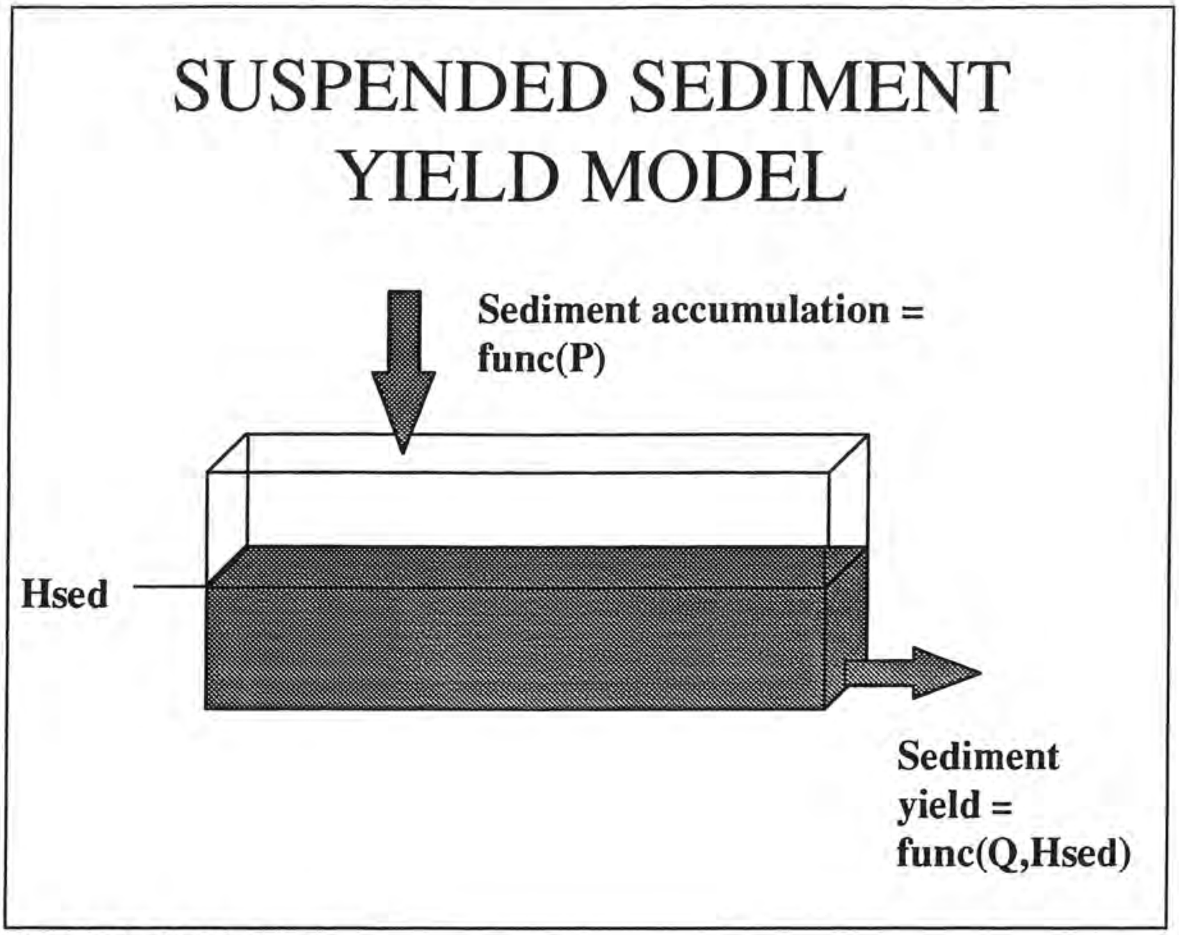

Figure. 5.1. Model structure.

As seen in Fig. 5.1 the model is supply-based. It is basically divided into two routines, the accumulation routine and the yield routine.

The accumulation of available sediment in each subbasin is a function of the areal precipitation in the subbasin. The function parameters, which can be adjusted for each subbasin, are dependant on the erosivity, i.e. dependant on the geology, vegetation, slope and landuse of the subbasin.

The yield of suspended sediment in each subbasin is a function of the areal runoff and the amount of sediment that is accumulated in the sediment box. The function parameters are dependant on the relationship between suspended sediment load and runoff.

The supply-based model gives possibilities to describe the hysteris effect between suspended sediment and runoff, which is very common. The hysteris effect is caused as the sediment concentration most often is much greater during the rise of a runoff peak than during the recession of the same peak. One explanation of this is simply that most of the available sediment is washed away during the rise of the runoff peak.

In the present model version, deposition of sediment in the stream channel is omitted, which limits the use of the model in rivers where deposition is likely to occur.

5.2 Model setup and calibration

The sediment model was setup for the Locotal basin. Division into four subbasins was made according to the division made in the HBV-model (see Chapter 5.4 in the main report). The subbasins and a brief description of their characteristics are presented in Tab. 5.1.

Basin	Area	Bed rock	Soil	Vegetation	Slope
Upper Malaga	38.7	Quartzite	Thin moraine	Scarce	Very steep
Rio Malaga	96.3	Quartzite, slates, mudstones, sandstones	Medium thick deposits	Mostly dense	Steep
Santa Isabel	58	Slates, mudstones, sandstones	Thick deposits	Dense	Steep
Locotal	7	Quartzite, slates	Medium thick deposits	Dense	Fairly steep

Table 5.1. Subbasin characteristics.

Simulated local daily areal precipitation and runoff for the period 1/10/1967 to 30/9/1987 were taken from the HBV-model as input to the sediment model. Each subbasin was given specific parameters regarding erosivity and runoff-sediment relationship. No deposition of suspended sediment in the stream channel was assumed as the slopes of the rivers are large and the water speed in general is high.

The model parameters were then calibrated against observed daily suspended sediment yield at Locotal hydrometric station, calculated from observed sediment concentration and observed runoff, 1971-1975. To get as accurate starting state as possible model runs were made from 1967. The model performance is presented in Fig. 5.2.

5.3 Results

In general the model performance showed fair agreement with observed data. The large sediment peak in February, however, has some uncertainties as observed data are missing (se further in 6. Extreme storm flood events).

The best model results were achieved when the model parameters were adjusted so that the major part of the simulated total sediment yield was produced in the Santa Isabel subbasin. This is also in accordance with the geology (soft slates) and soil (thick deposits) in the Santa Isabel as well as the fact that during floods the larger concentration of suspended sediment in Rio Santa Isabel, compared to Rio Malaga, can visually be observed.

Using the calibrated parameters a model run was then made for the period 1967 to 1987. The resulting yearly suspended sediment load is presented in Fig. 5.3.

Mean annual suspended sediment load was 375 000 tonnes/year or 1875 tonnes/year and km^2.

Approximately 65% of the simulated total sediment yield originated from the Santa Isabel subbasin.

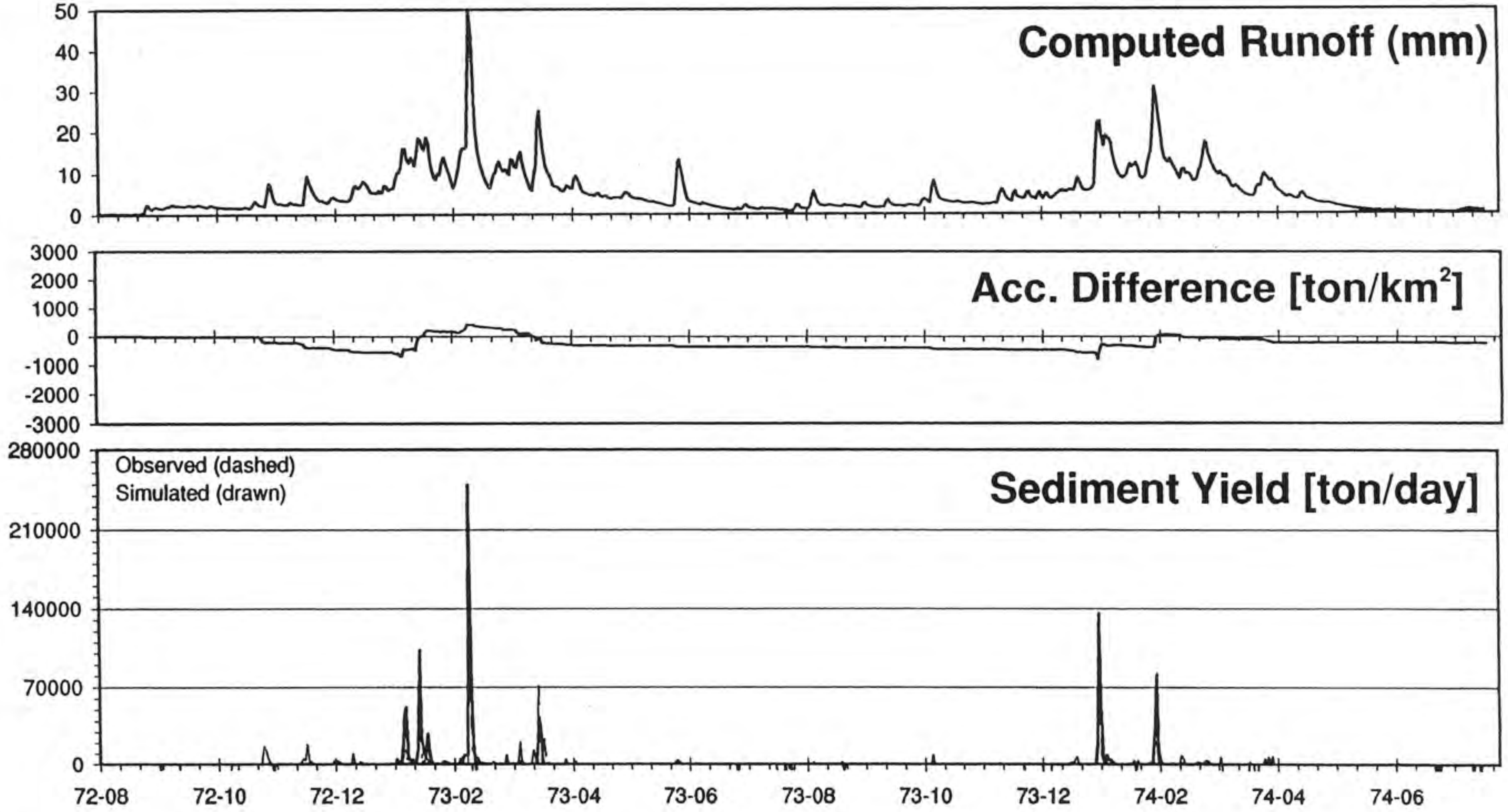

Figure 5.2. Sediment model performance.

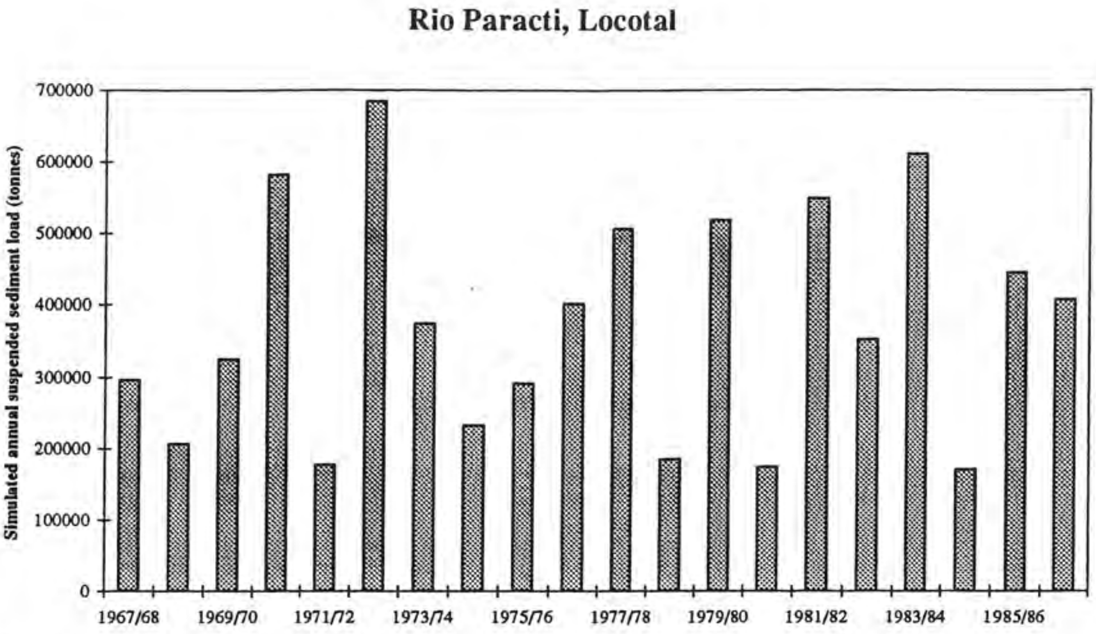

Figure 5.3. Simulated annual sediment load.

6. Extreme storm flood events

During the period from 1968 to 1987 the runoff peak in February 1973 is the highest simulated peak. Unfortunately, the simulated peak, which is based on observed rainfall, can not be confirmed by observed runoff. The simulated and observed runoff as well as the observed suspended sediment concentration are shown in Fig. 6.1.

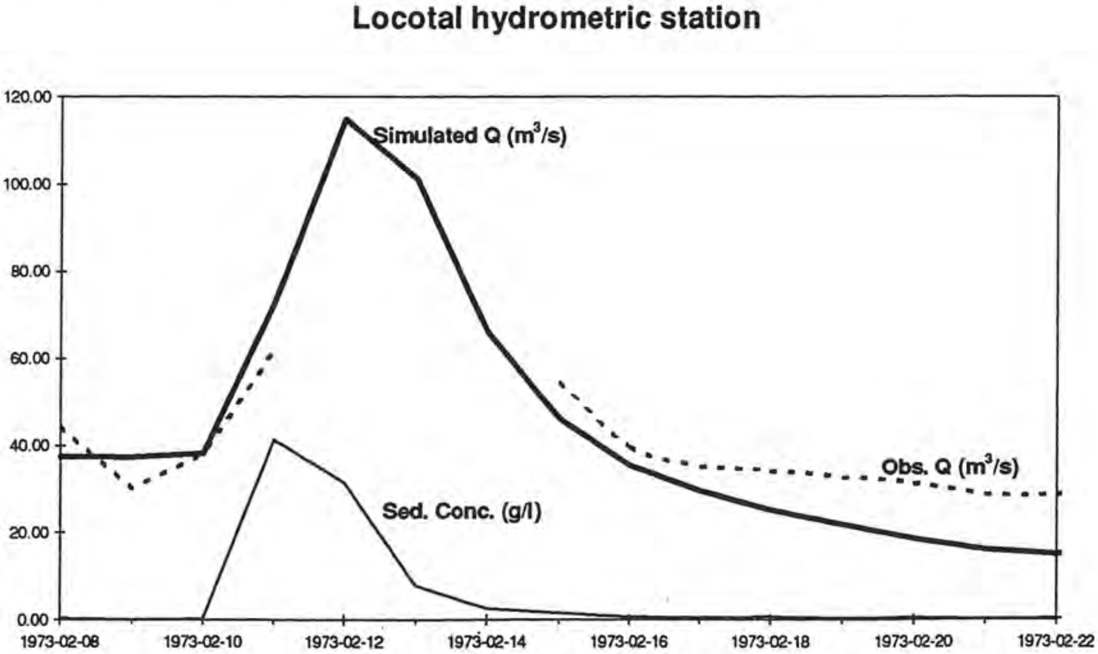

Figure 6.1. Observed and simulated runoff and observed suspended sediment during the storm flood in February, 1973.

If the simulated values are assumed as a good estimate of the runoff during the three days 12-14/2 the suspended sediment yield is caused by the storm flood, 10-18/2, was 630 000 tonnes.

The sediment model simulation of the suspended sediment yield during the same storm flood, which gives 305 000 tonnes, shows that, if the above assumption is correct, the model fails to simulate the sediment yield at this extreme storm flood event. During the storm floods 1973/74, however, the sediment model shows acceptable agreement with observed yield. This may indicate that the calibrated sediment model in general underestimates extreme flood events. However, the storm flood in February 1973 must be considered as very extreme based on the period of 20 years that was studied. The highest simulated runoff peaks at Locotal during the period are presented in Tab. 6.1.

Year	*Peak runoff (m^3/s)*
1972/73	114.9
1977/78	81.0
1981/82	72.5
1969/70	72.4
1973/74	71.0

Table 6.1. The highest simulated daily mean runoff peak,1968 - 1987.

To make a rough quantification of the dimension of the model error that may exist at these extreme storm flood events the following assumptions can be made;

- a storm flood and corresponding sediment yield peak of the 1972/73 magnitude have a return period of approximately 10 years
- the sediment model underestimates the sediment yield by approximately 50% during these extreme events, i.e. 315 000 tonnes.

The effect of extreme storm flood events on the long term simulated annual suspended sediment load at Locotal should then be, in average, 31 500 tonnes/year.

7. Sediment yield into the Corani dam

In March 1973 and in September-November 1988 levelling of the Corani dam was done. The levelling gave a dam volume 1973 and 1988 of 150.0 million m^3 respectively 141.8 million m^3. The difference is 8 200 000 m^3.

If the decrease in dam volume is assumed to be caused trough sedimentation from the rivers that yield into the reservoir and a sediment density of 1.8 tonnes/m^3 is assumed, the mean annual sediment yield, including bed load, is approximately 940 000 tonnes/year or 3275 tonnes/year and km^2.

The Corani Embalse basin is located in the south of the Icona basin and has a catchment area of 287 km^2. The bedrock is mostly mudstones and vegetation is scarce. The area is agricultural.

It should, however, be noted that during the period between the times of levelling the new Cochabamba-Santa Cruz road was constructed just beside the Corani reservoir. This construction may have significantly increased the sediment yield into the dam.

8. Discussion and conclusion

8.1 Locotal

Combining the result from the sediment yield model and the estimated correction for extreme storm flood events, the mean annual suspended sediment yield at Locotal is approximately 400 000 tonnes/year.

In previous studies, the San José Feasibility Report, the estimated mean annual suspended sediment yield was approximately 600 000 tonnes/year. This figure was retrieved by choosing a rather conservative runoff-sediment relationship, which may be correct due to the general uncertainty in estimation of sediment load.

None of the above mean annual suspended sediment loads can be neglected. The figure 400 000 tonnes/year seems to be a fair estimate, while 600 000 tonnes/year possibly is on the conservative side.

The calculation of mean annual bed load is very complex and in this study, the available data were judged to be to meagre to make an evaluation. The value presented in the San José Feasibility Report, 66 000 tonnes/year, however, seems to be realistic and this figure may be added to the above estimated suspended sediment yields to get an estimate of the total sediment yield at Locotal.

8.2 Icona

No suspended sediment samples have been collected in the Rio Juntas Corani near the planned Icona hydroelectric plant. An evaluation of the annual sediment yield at Icona is, thus, extremely difficult to do and will include large uncertainties.

The sediment yield model has not been used for the Icona basin because the uncertainties are judged to be to large as no sediment yield data are available for calibration. Also, temporal deposition is likely in the Rio Juntas Corani, which the model can not manage.

Generally the geology, soil, vegetation and slopes in the Icona basin show that the erosivity is probably less for the Icona basin as a whole than the erosivity for the Locotal basin. This is mainly, because areas with soft bed rock and thick deposits have little areal covering. Also, the slopes are less steep in the Icona basin as a whole.

The estimated annual sediment yield into the Corani reservoir, 940 000 tonnes/year indicates that the agricultural areas in the south may give relatively large sediment yields. However, the estimate may be overestimated due to the road construction. Furthermore, the Corani dam catches all sediment from the Corani basin and the runoff in Corani Bajo is almost completely cut by the reservoir. That leaves only Palca, Jatun Mayo Alto and Lacayes as areas with possible large erosivity.

Thus, the conclusion is that the areal erosion and sediment yield in the Icona basin is considerably less than the areal erosion and sediment yield in the Locotal basin. However, as no sediment samples are available, the only figure that is possible to present is an estimate based on the results in Locotal.

Assuming 400 000 tonnes/year in Locotal the areal load is 2000 tonnes/year and km^2. If the Icona catchment area is reduced with the Corani basin area the resulting mean annual suspended sediment yield at Icona is approximately 3 700 000 tonnes/year. This load is, however, probably a conservative estimate.

No evaluation of the bed load at Icona has been made as the prerequisites are to poor. The bed load is probably small, relative to the suspended sediment load.

8.3 General conclusions

The performed study has given valuable new information regarding sedimentation in the Locotal and Icona basins. The retrieved estimates of sediment yield are essential information for future hydroelectric development in the area.

The performed sediment modelling has verified the dimension of the previous retrieved estimates and has given modified values of the mean annual sediment yield at the studied sites.

The observed sediment samples at Locotal hydrometric station are concluded to be representative for the Locotal basin. The observed data seem to be of good quality and the period covered, includes the extreme year, 1972/73, regarding rain and runoff. Also, the Locotal basin is little affected by human impact. The annual sediment yield is mainly caused by rain and runoff.

However, evaluation of sediment yield is rather complex. The sediment samples plotted in Fig. 4.1. show little evidence of an unambiguous relationship between runoff and sediment yield. There are clearly other factors affecting the dynamics of the sediment yield. Thus, a more thorough evaluation of the basin characteristics and their effect on the sediment yield is needed.

The sediment yield model simulates both the source of sediment material and the transport of sediment. This means that the model takes account for what happened in previous years as well as the present situation. Furthermore, there are possibilities to describe the differences in for example soil, slope, precipitation and runoff in the different parts of the basin.

This study has shown that for homogenous basins with a representative sampling record, the sediment yield model has potential to simulate long term sediment accumulation and discharge.

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