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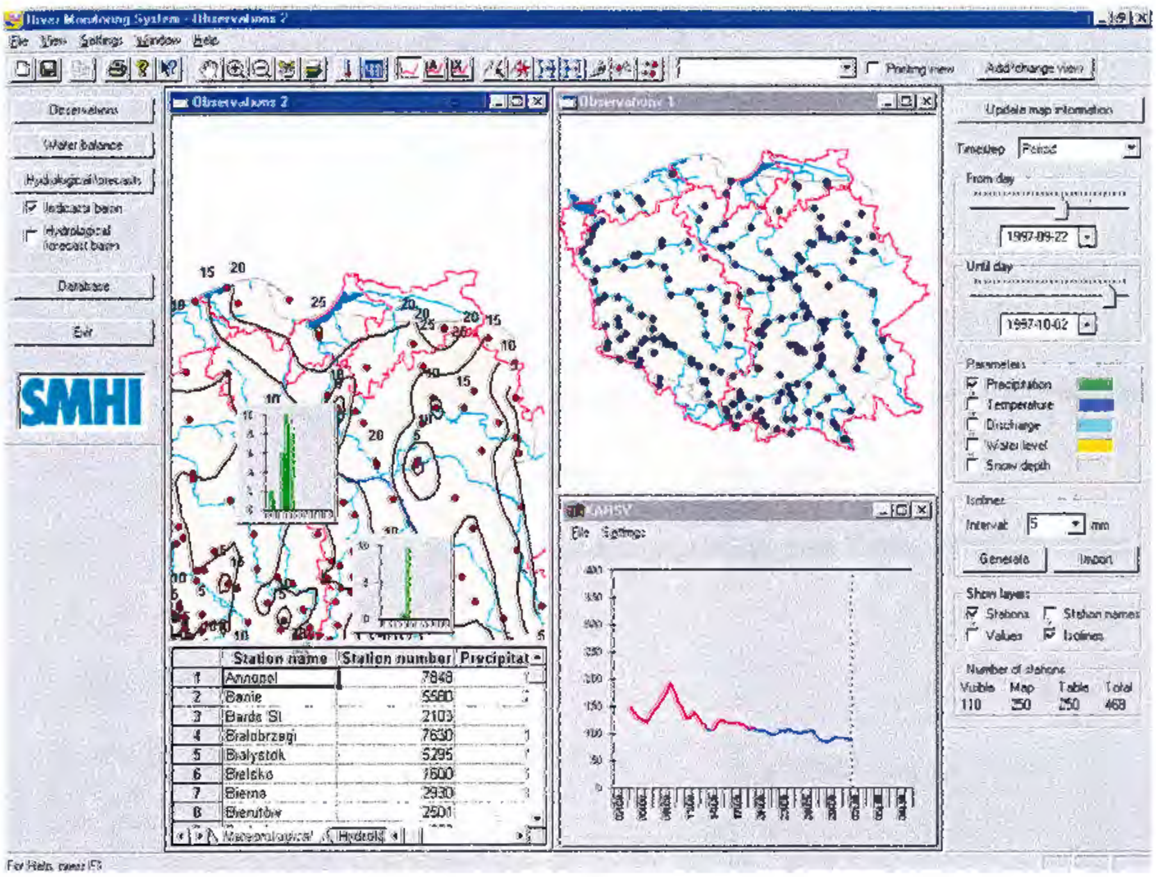

Intergrated Hydrological Monitoring and Forecasting System for the Vistula River Basin

Final report

Sten Lindell, Lars O Ericsson, Håkan Sanner and Karin Göransson, SMHI

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Integrated Hydrological Monitoring and Forecasting System for the Vistula River Basin

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Sten Lindell, Lars O Ericsson,
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Institute of Meteorology and Water Management of Poland

1 Introduction

1.1 General

This report is a technical description on the project Integrated Hydrological Monitoring and Forecasting System for the Vistula River Basin. The Swedish Meteorological and Hydrological Institute in Norrköping, Sweden, (hereinafter called SMHI) and Institute of Meteorology and Water Management in Warsaw, Poland, (hereinafter called IMWM) has fulfilled and co-operated in this project. SMHI have as consultants been responsible for design and development of the Vistula River Monitoring and Forecasting System, for on-the-job training and education in Windows programming and development as well as in set-up, calibration and applications of the HBV-model. IMWM responsibilities has been to provide the project with hydrometeorological data and information on land use for the calibration activities and to supply the project with the hydrodynamic model in use at the polish institute. IMWM has been deeply involved in the design and development of the Vistula River Monitoring and Forecasting System and had the main responsibility in the HBV-model calibration activities.

Funds from the Swedish International Development Authority (SIDA) financed the Swedish part of the project while IMWM financed the activities fulfilled in Poland and the participants from IMWM.

1.2 Project objectives

The development objective of the project was to support the water resources and environment strategy planning in Poland by strengthening the capacity of the IMWM to monitor water quantity and quality and to undertake hydrological forecasts and evaluations.

The specific objectives was to transfer knowledge about the basic design, applications, performance and data requirements of operational hydrological monitoring and modelling systems from SMHI to IMWM, and to build an integrated hydrological monitoring and modelling system for lower and middle Vistula river basin.

2 The IHMS-HBV hydrological modelling system

2.1 Model structure and data requirements

The rainfall-runoff model HBV was developed at SMHI and the first applications to hydropower developed rivers were made in the early seventies (Bergström, 1976). Originally the HBV model was developed for runoff simulations and hydrological forecasting, but new applications has introduced steadily (Bergström, 1995). It is characterised as a semi-distributed conceptual model with moderate demands on input data. A comprehensive re-evaluation of the model has recently been carried out (Lindström et al, 1997). Objectives in this re-evaluation were to improve the potential for more spatial distributed data, to make the model more physically reasonable and to improve model performance. This project could take full advantage of these new developments.

The model is normally run on daily values of rainfall and air temperature and monthly estimates of potential evapotranspiration, but shorter time-step up to one hour can easily be introduced in the calculations. The model contains routines for snow accumulation and melt, soil moisture accounting, runoff generation and a simple routing procedure (Figure 1). The catchment can be divided into subbasins. Each subbasin is then divided into zones according to altitude, lake area, glaciers and vegetation.

The Integrated Hydrological Modelling System, IHMS, is a modern menu-driven and well tested operational tool developed for installation on personal computer with Microsoft Windows. IHMS include modules for data control and quality test, options area-elevation distribution, and printing facilities of tables and figures from data base or from model result. The HBV model is included and integrated in IHMS and run totally within the IHMS interface.

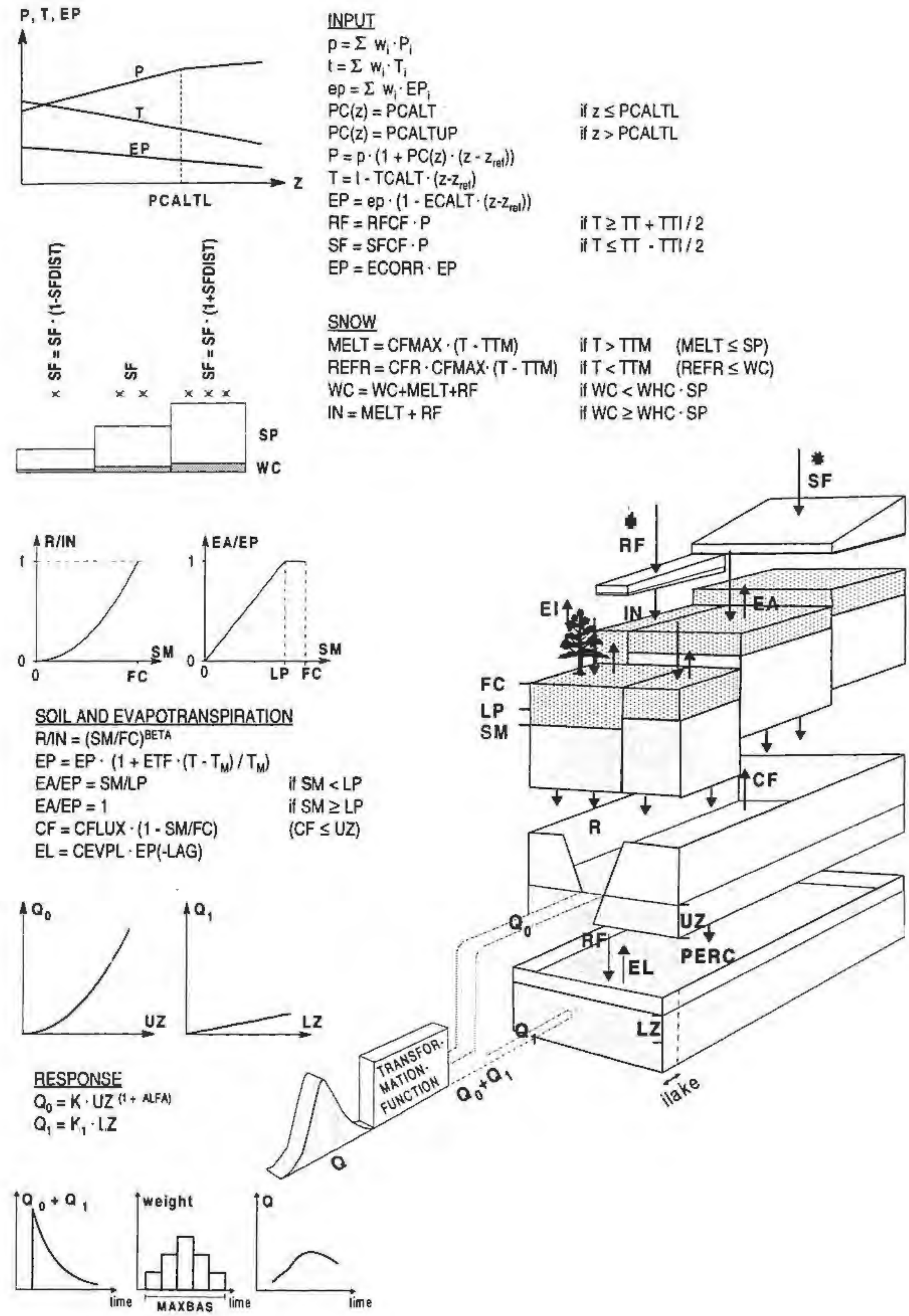


Figure 1. *Schematic structure of one subbasin in the HBV model, with routines for snow (top), soil (middle) and response (bottom). Bold letters in legend indicate that the parameter is normally calibrated.*

INPUT

Variables:

p	=	Weighted mean precipitation
t	=	Weighted mean temperature
ep	=	Weighted mean evaporation
P_i	=	Precipitation at station i
T_i	=	Temperature at station i
EP_i	=	Potential evaporation at station i (long-term mean values)
P	=	Zone precipitation
T	=	Zone temperature
EP	=	Zone potential evapotranspiration
RF	=	Zone rainfall
SF	=	Zone snowfall

Parameters and constants:

PC(z)	=	Elevation correction factor
TCALT	=	Elevation correction factor
ECALT	=	Elevation correction factor
z	=	Zone elevation
z_{ref}	=	Reference level
TT	=	Temperature limit for snow/rain
TTI	=	Temperature interval with a mixture of snow and rain
RFCF	=	Rainfall correction factor
SFCF	=	Snowfall correction factor
ECORR	=	Evaporation correction factor

SNOW

Variables:

SP	=	Frozen part of snowpack
WC	=	Liquid water in snow
MELT	=	Snowmelt
REFR	=	Refreezing of liquid water
IN	=	Infiltration to soil

Parameters and constants:

SFDIST	=	Distribution factor for snowfall
WHC	=	Water holding capacity
CFMAX	=	Degree day factor
TTM	=	Temperature limit for melting
CFR	=	Refreezing factor

SOIL AND EVAPOTRANSPIRATION

Variables:

SM	=	Soil moisture
R	=	Runoff from soil
EA	=	Actual evapotranspiration
EI	=	Interception evaporation
CF	=	Capillary flow
EL	=	Lake evaporation
T_M	=	Subbasin mean temperature (long-term daily means)

Parameters and constants:

FC	=	Maximum soil moisture content
LP	=	Limit for potential evapotranspiration
BETA	=	Parameter in soil routine
CFLUX	=	Maximum value of CF
CEVPL	=	Lake evaporation correction factor
LAG	=	Time lag for lake evaporation
ETF	=	Temperature correction factor

RESPONSE

Variables:

UZ	=	Storage in upper response box
Q_0	=	Outflow from upper response box
LZ	=	Storage in lower response box
Q_1	=	Outflow from lower response box
Q	=	Outflow from transformation function

Parameters and constants:

K	=	Recession coefficient
ALFA	=	Response box parameter
PERC	=	Percolation from upper to lower response box
K_1	=	Recession coefficient
MAXBAS	=	Transformation function parameter
ilake	=	Internal lake zone

Figure 1. Continuation

2.1.1 Snow

All precipitation values are multiplied by a general correction factor. Different factors can be used if the precipitation is rain or snow. A lapse rate for precipitation is applied to adjust to the actual altitude. Different lapse rates can be used for high or low altitudes.

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

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

where:
Q_m = snowmelt
CFMAX = degree-day factor
T = zone temperature
TT = temperature limit for snow/rain

The threshold temperature is normally used to decide whether precipitation is rainfall or snowfall. It is possible to have different threshold for accumulation and melting. The threshold can also be extended to an interval within precipitation is assumed to be a mix of rain and snow.

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

2.1.2 Soil moisture

The soil moisture routine is the main part controlling runoff formation. 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 precipitation and the relationship depends upon the computed soil moisture storage, the maximum soil moisture content (FC) and the empirical parameter BETA, as given in equation 2. Rain or snowmelt generates small contributions of excess water from the soil when the soil is dry and large contributions when conditions are wet (Figure 2).

$$Q_s(t) = \left(\frac{SM\ (t)}{FC}\right)^{BETA} \bullet P(t) \tag{2}$$

where:		
	Q_s	= excess water from soil
	SM	= soil moisture storage
	FC	= maximum soil moisture content
	P	= zone precipitation
	BETA	= empirical coefficient

The specified input potential evapotranspiration value can be corrected by a general evaporation correction factor and by altitude with an elevation correction factor. It can also be modified according to actual temperature related to normal temperature values. As an alternative to input of potential evapotranspiration it can be calculated by using a simplified version of the Thornthwaite´s formula.

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

$$EA(t) = \begin{cases} \dfrac{EP \bullet SM\ (t)}{LP} & if\ SM \le LP \\ EP & if\ SM > LP \end{cases} \tag{3}$$

where:		
	EA	= actual evapotranspiration
	EP	= zone potential evapotranspiration
	LP	= limit for potential evapotranspiration

SM = soil moisture content
ΔP = contribution from rainfall or snowmelt
ΔQ = contribution to the response function
FC = maximum soil moisture content
BETA = empirical coefficient
EP = potential evapotranspiration
EA = actual evapotranspiration
LP = limit for potential evapotranspiration

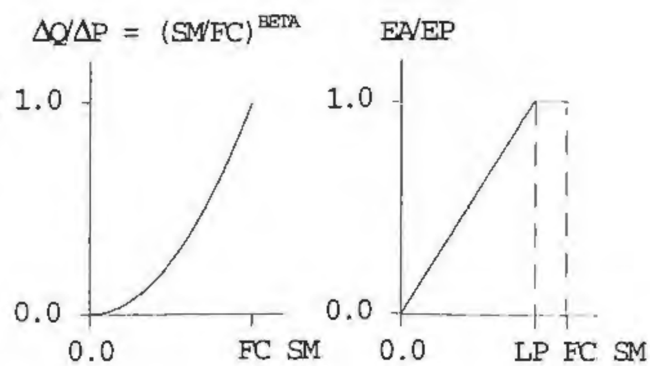


Figure 2. Schematic presentation of the soil moisture accounting subroutine.

2.1.3 Runoff response

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

$$Q_0(t) = K \bullet UZ^{(1+ALFA)} \tag{4}$$

$$Q_1(t) = K_1 \bullet LZ \tag{5}$$

where:

	Q_0	= runoff generation from upper response tank
	Q_1	= runoff generation from lower response tank
	K_0, K_1	= recession coefficients
	UZ	= storage in upper response tank
	LZ	= storage in lower response tank
	ALFA	= response box parameter

In order to account for the damping of the generated flood pulse ($Q = Q_0 + Q_1$) in the river, a simple routing transformation is made. This is a filter with a triangular distribution of weights. There is also an option of using the Muskingum routing routine to account for the river flow hydraulics.

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

2.2 Model applications

The HBV model was originally developed for inflow forecasting to hydropower reservoirs in Scandinavian catchments, but has now been applied in more than 30 countries all over the world (Figure 3). Despite its relatively simple structure, it performs equally well as the best known model in the world (see WMO, 1986, 1987 and 1992).

Some examples of model applications are: inflow and flood forecasting and computation of design floods in totally about 170 basins in Scandinavia (Häggström, 1989; Bergström et al., 1989; Harlin, 1992; Killingtveit and Aam, 1978; Vehviläinen, 1986), modelling the effects of clearcutting in Sweden (Brandt et al., 1988), snowmelt flood simulation in Alpine regions (Capovilla, 1990; Renner and Braun, 1990; Braun and Lang, 1986), hydrological modelling in Arctic permafrost environment (Hinzman and Kane, 1991), inflow forecasting to a dam in River Indus (Sanner et al., 1994) and flood forecasting in Central America (Häggström et al., 1990). Experiences from the integrated hydrological modelling system IHMS and the HBV-model in the Eastern Baltic region are from applications in Latvia (Lindell *et al.*, 1996a) and Estonia (Lindell *et al.* 1996b).

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

2.3 Model calibration

The HBV model, in its simplest form with only one subbasin and one type of vegetation, has altogether 12 free parameters, marked with bold letters in the legend to figure 1. Calibration of the model is usually made by a manual trial and error technique, during which relevant parameter values are changed until an acceptable agreement with observations is obtained. The judgement of the performance is also supported by statistical criteria, normally the R^2-value of model fit, ≈ explained variance, (Nash and Sutcliffe, 1970):

$$R^2 = \frac{\Sigma\,(\overline{Q}_o - Q_o)^2 - \Sigma\,(Q_c - Q_o)^2}{\Sigma\,(\overline{Q}_o - Q_o)^2} \qquad (6)$$

where: Q_o = observed runoff

$\overline{Q}_o$ = mean of observed runoff

Q_c = computed runoff

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

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

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

2.4 The forecasting procedure

The HBV model is often used for either short or long range forecasting. Before the day of forecast the model is run on observed input data until the time step (day) before the forecast. If there is a discrepancy between the computed and observed hydrographs during the last days of run, updating of the model should be considered. The HBV model is normally updated either manually or automatically by an iterative procedure during which the input data a few days prior to the day of forecast is adjusted. Updating should always be done with caution, since the updating procedure may introduce additional uncertainty over the forecast period. In the automatic updating routine introduction of updating limits help to avoid erroneos and unrealistic result. But still the outcoming result from the updating procedure must be carefully checked.

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

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

3 The HD hydrodynamic flow routing model

3.1 *Model description*

HD is a hydrodynamic model based on an implicit finite difference solution of the one-dimensional St. Venant equations of unsteady flow. This type of model has been used in IMWM for many research studies and in operational applications in Vistula, Bug, Narew, Dunajec, San, Odra, Kaczawa and other rivers (IMGW, 1987 and 1988; Kadlubowski and Szkutnicki 1992; Zelazinski 1995). In these applications a new model to a given river or river system were prepared depending on conditions. In this project a universal software which can be used to all typical river systems for operational and development works including model building and presentation of the results have been created.

The basis for HD are the equations of unsteady flow consisting of conservation of mass and momentum equations, i.e.,

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} - q = 0$$

$$\frac{\partial Q}{\partial t} + \frac{\partial \left(Q^2 / A \right)}{\partial x} + gA\left(\frac{\partial h}{\partial x} + S_f \right) - q v_x = 0 \qquad (7)$$

where:

	Q	= discharge
	A	= cross-sectional area
	q	= lateral inflow or outflow
	x	= distance along the river channel
	t	= time
	g	= gravity acceleration constant
	v_x	= velocity of lateral inflow in the x-direction
	S_f	= the friction slope described as:

$$S_f = \frac{n^2 |Q| Q}{A^2 R^{4/3}} \qquad (8)$$

where:

	n	= Manning roughness coefficient
	R	= hydraulic radius

The major assumptions made in deriving the St. Venant equations are :

- hydrostatic pressure distribution
- one-dimensional flow
- fixed channel geometry
- small channel slope
- uniform velocity distribution
- friction losses in unsteady flow can be approximated by losses in steady uniform flow

3.2 Solving method

Equations are solved by implicit finite difference techniques. This is more efficient in the use of computer time than an explicit solution. The „weighted four-point", first used by Preissmann (Preissman, 1961), give possibility to use unequal distance steps and good stability-convergence properties. Variables and their spatial and time derivatives are approximated by:

$$
\begin{aligned}
K &\cong \theta\left(K_i^{j+1} + K_{i+1}^{j+1}\right)/2 + (1-\theta)\left(K_i^{j} + K_{i+1}^{j}\right)/2 \\
\frac{\partial K}{\partial x} &\cong \theta\left(K_{i+1}^{j+1} - K_i^{j+1}\right)/\Delta x + (1-\theta)\left(K_{i+1}^{j} - K_i^{j}\right)/\Delta x \qquad (9)\\
\frac{\partial K}{\partial t} &\cong \left(K_i^{j+1} + K_{i+1}^{j+1} - K_i^{j} - K_{i+1}^{j}\right)/2\,\Delta t
\end{aligned}
$$

where subscript i designates the x position, superscript j time position, θ is a weighting factor.

Substitution of the finite difference quotients into model equations produces two algebraic equations which are non-linear with respect to the unknowns w and Q at the net points on the j+1 time line. All terms associated with the j-th time line are known from initial conditions or previous computations. The initial conditions are obtained from unsteady flow solution.

The two non-linear algebraic equations can not be solved in a direct manner since there are four unknowns, w and Q, at points i and i+1 on the j+1 time line and there are only two equations. However, if similar equations are formed for each of the N-1 reaches between upstream and downstream boundaries, a total of 2N-2 equations with 2N unknowns results. Then by adding two boundary equations, one upstream and one downstream, a system of 2N non-linear equations with 2N unknowns have been determined. The system is solved using Newton-Raphson method with modified Gaussian elimination algorithm (Amein and Fang 1970; Fread 1971).

Boundary conditions may be specified in form a known water stage hydrograph - w(t) or known discharge hydrograph Q(t). Irregular cross-sections are used to describe bed shape. The acceptable distance between cross-sections is dependent on the channel properties, waves shape and computational time step.

Manning roughness coefficients n are used to describe the resistance to flow due to channel roughness caused by bed forms, bank vegetation and obstructions, bend effects and eddy losses. The Manning n is defined for each cross-sections as a function of stage. Simulation results are often very sensitive to the Manning n. Coefficients are adjusted to reproduce historical observations of stage and discharge. Many hydrological handbooks containing tables of typical Manning coefficients sometimes with the photographs of typical channels (Chow, 1959).

3.3 Creation of a new application

A description of how to create, calibrate and run a new HD application can be made in a few steps.

1. Prepare data about the river system, i.e. location of stations along rivers, location of tributaries and select which should be used in the model.
2. Choose data sets for calibration of a model and collect discharge and water level data for the stations.
3. Create QW.KEY file and import data to QW.DAT file using *Data exchange* menu
4. Collect data about river bed shape and prepare them in HD/HBV format, check the shape of cross-sections, using *Generate cross section list* and *Edit cross sections shape* menu item, and perform corrections if necessary. It is also possible to remove cross-section from model making them NONACTIVE if they are not well done using *Edit cross section list.*
5. Prepare initial set of Manning coefficients using *Generate Manning coeff*
6. Calculate hydraulic parameters for river system using *Recalculation of parameters*
7. Prepare RUN.PAR file using *Describe model run*
8. Run the model using *Start HD model*
9. Compare model results with observations using *Station result graph*
10. If the results are unsatisfactory correct Manning coefficients using *Edit Manning coeff* and return to point 7

A critical task in the application of one-dimensional hydrodynamics models in natural rivers is the determination of the roughness parameter in the friction slope term of the momentum equation. The roughness parameter often varies with stage and with distance along the river. Each reach between gauging stations ought to be calibrated sequentially, starting from the most upstream reach and progressing reach by reach in the downstream direction.

4 The River Monitoring System

An efficient operative hydrological service demand a fast and reliable overview of the actual hydrological situation together with possibility for detailed local information in areas of interest. To fulfil these requests the River Monitoring System, RMS, was developed. RMS is a real time system that enables illustration of observed, forecasted and model calculated weather parameters. The presentation can be made on maps, such as values and isolines, in tables or in graphs. Observations, water balance information and hydrological and meteorological forecasts are presented in various menus.

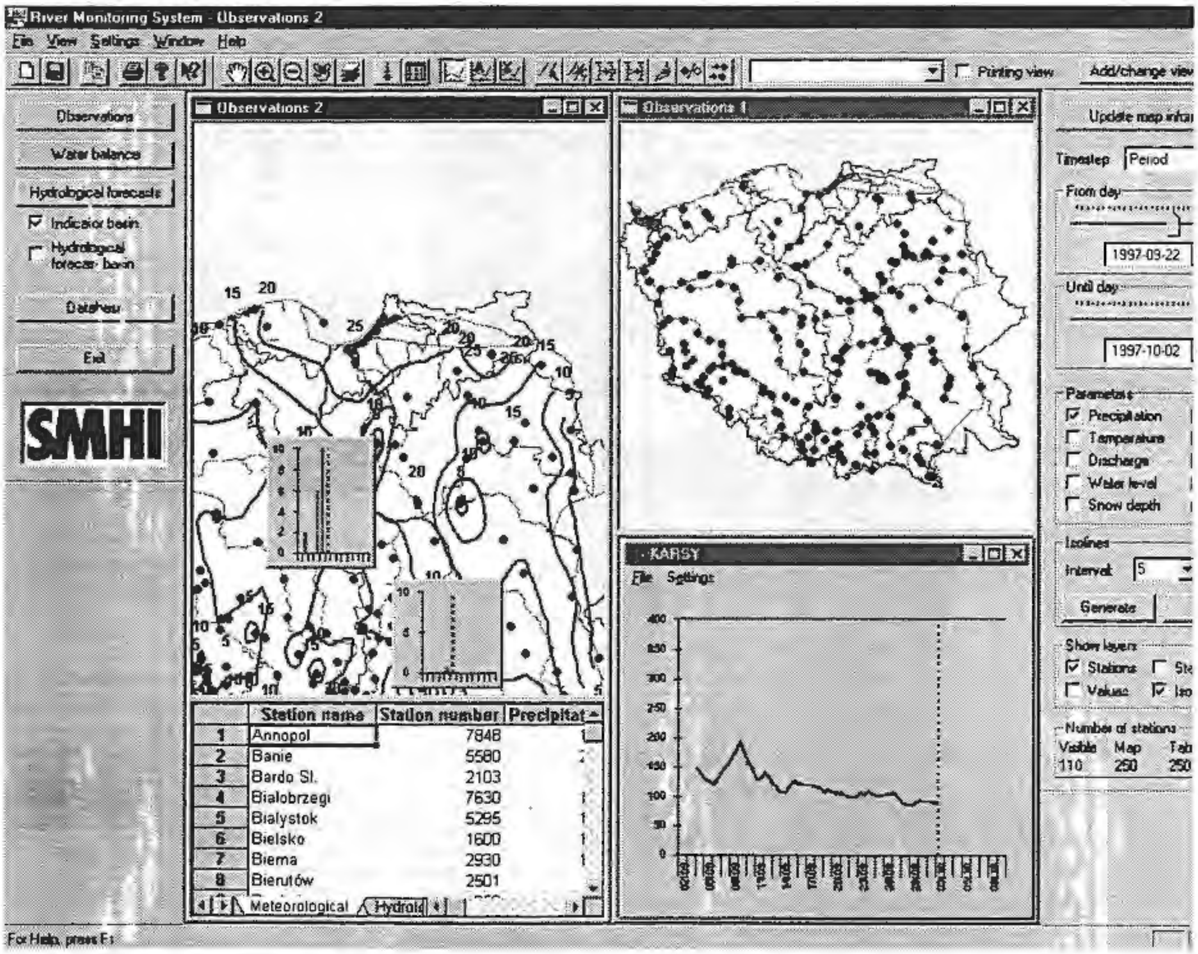


Figure 4. General view of the River Monitoring System

4.1 System outline

The River Monitoring System consist of three major parts :

- Menu system
- Geographical Information System
- Database

The menu system in the system use the database *Access* to store all kind of data. In the database real-time information from meteorological and hydrological stations are stored together with forecasted values. Background data, such as specific information on observation spots etc. can also be stored in the *Access* database. Data are processed in the system and presented as values, graphs, tables or isolines by use of the geographical information system *MapInfo*. All included parts are fully integrated in the system. The use of MapInfo makes it possible to use MapInfo standard functionality, such as zoom in and out in the map, "drag and drop" and adjust the different layers in the map, etc.

Real time data is transported to the system either by modem or, as in this project, directly from a central database. Data can also be imported or typed manually.

The River Monitoring System (RMS)

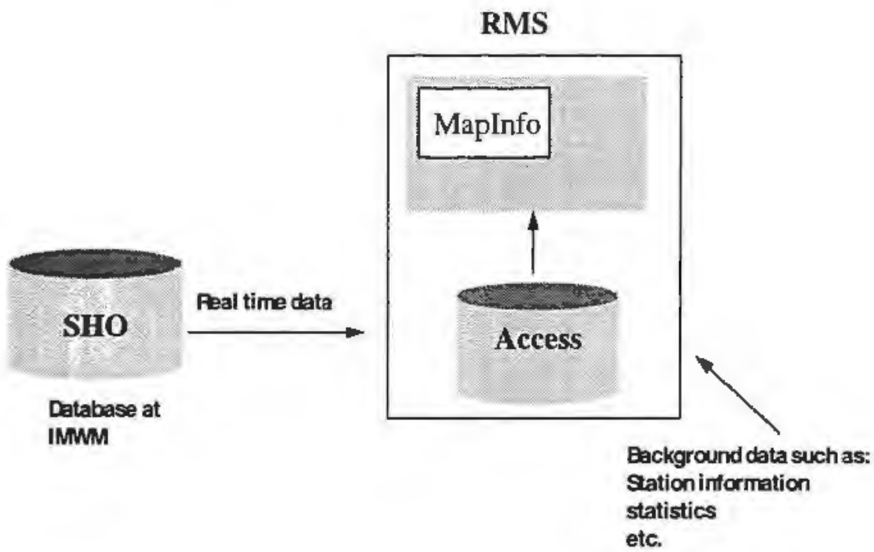


Figure 5. Schematic structure of the River Monitoring System

4.2 *System presentation forms*

4.2.1 Values, tables and isolines

The parameters and values stored in the *Access* database can be presented by use of a number of timesteps:

- Momentarily - every hour
- 6 hour - every six hours, starting at 00.00 every night
- 12 hour - 06.00 and 18.00 every day
- Day - once a day
- Month - once a month
- Period- a selected time interval with presentation of the average, as for temperature, or the sum, as for precipitation

The values for chosen timestep is presented on maps. Isolines can be created and visualised.

Below the map a table with identical information can be displayed. This table can be sorted according to any column by clicking on the header of the column, figure 6.

A table giving all values from one selected station is also available.

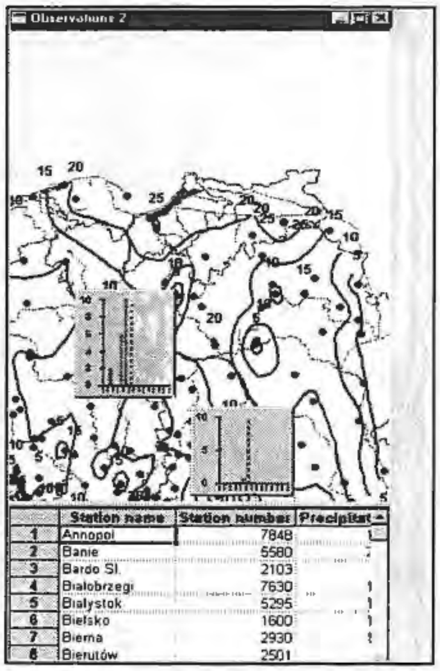


Figure 6. Isolines and tables in the River Monitoring System

4.2.2 Graphs

Visualisation of graphs can be effected by selecting the graph tool and clicking on the preferred station. There are different graphs depending on parameters. The user has a wide range of possibilities to change the design of the graphs. As an example one type of graphs is designed for hydrological forecasts, figure 7.

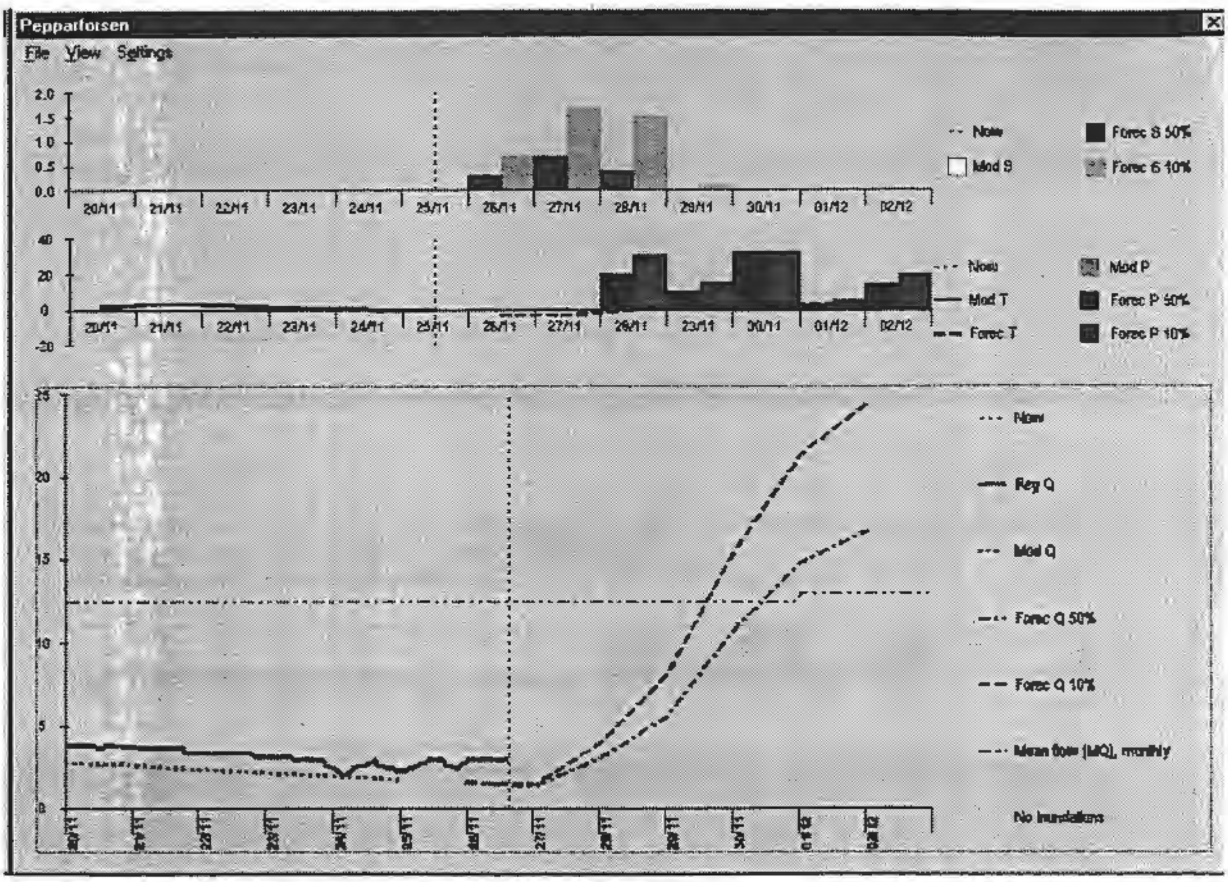


Figure 7. *Presentation of hydrological forecasts in the River Monitoring System.*
Top graph - water content in snow
Middle graph - temperature and precipitation
Bottom graph - runoff
Vertical line separate observations and model update from model forecast

4.2.3 Station information

A presentation system for information on the meteorological and hydrological stations is also available in the River Monitoring System. This information is reached by choosing the information tool and clicking on selected station, figure 8.

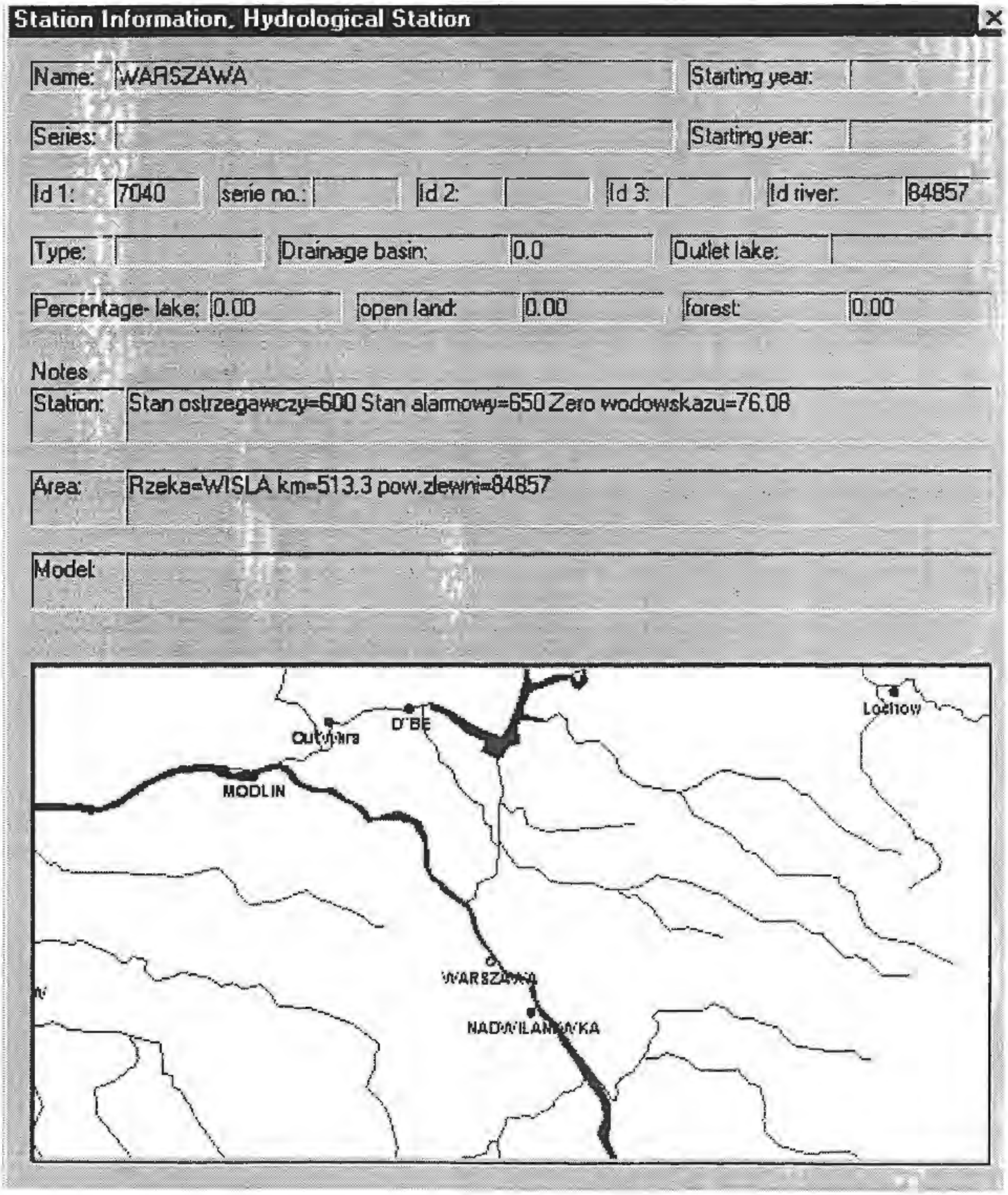


Figure 8. Basin and station information in the River Monitoring System.

4.3 Parameters

The system has separate menus for observations, water balance information and hydrological forecasts. All parameters that can be presented in the system are listed in table 1.

Table 1. Parameters in the River Monitoring System

Parameter	Observed	Calculated	Forecasted
Precipitation	X		X
Temperature	X		X
Snow depth	X		
Snow storage		X	X
Soil moisture		X	X
Runoff generation		X	X
Discharge	X	X	X
Water level	X	X	X

5 System development and integration

This chapter describes the system structure of the Integrated Hydrological Monitoring and Forecasting System for the Vistula River Basin. The system consists mainly of two subsystems: a) IHMS which integrates the HBV and HD models and b) RMS. An existing database (SHO) at IMWM is used for data storage.

The project work has been focused on integration of HD model and IHMS menu system and implementation of new functions.

System data flow, added functionality and usage of software and tools are also described in this chapter.

5.1 System Outline

The system consists of major parts as follows:

- **Model** - IHMS - Integration of hydrological model HBV and hydrodynamic model HD
- **Monitoring** - RMS - River Monitoring System
- **Database** - SHO - Hydrological operational systems database (existing at IMWM)

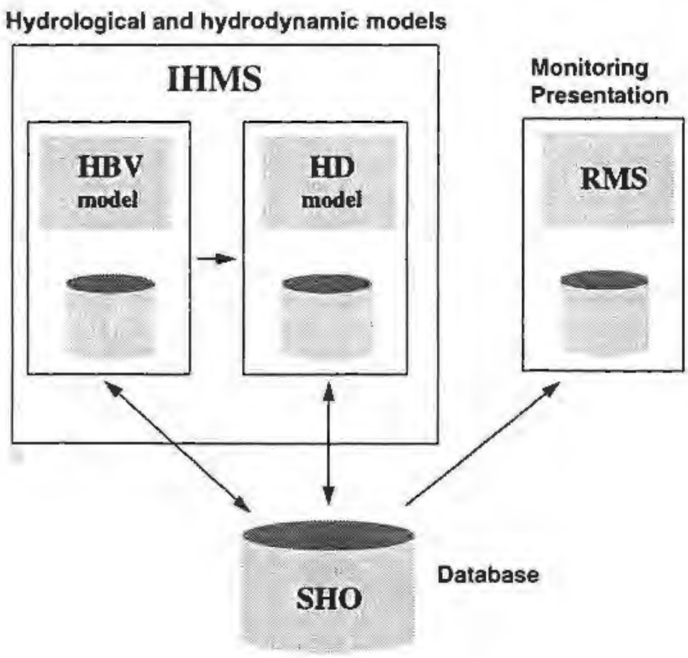
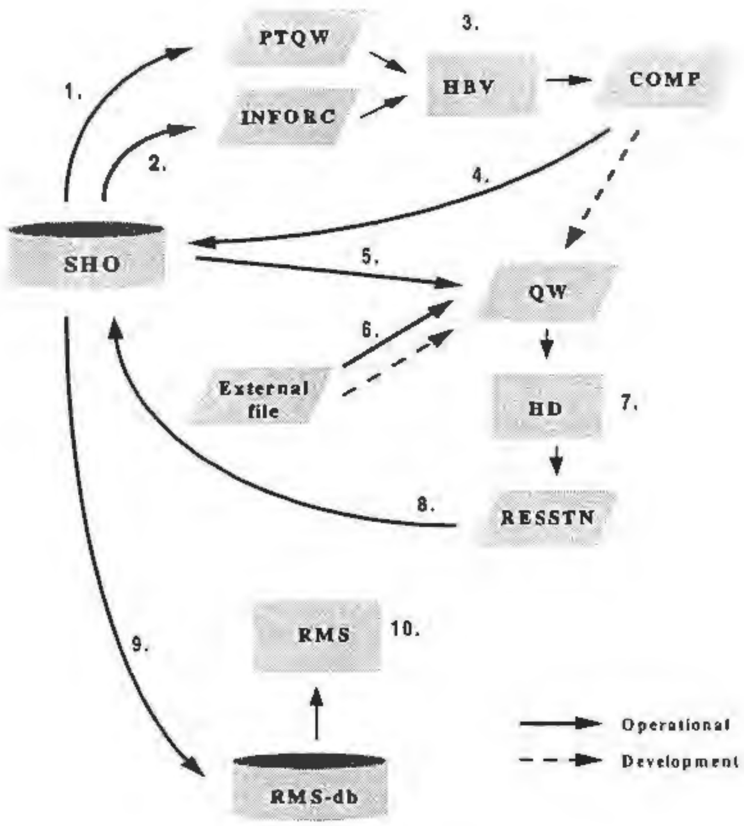


Figure 9. Schematic structure of system outline.

The IHMS menu system fully integrates the HBV and the HD models and the system retrieves and stores operational hydrological data in the existing SHO database. The RMS system is a stand alone application used for monitoring and presentation of any kind of computed or recorded data, including model results, from the SHO database.

5.2 *System Data flow*



SHO	- Database with recorded and computed data
PTQW	- Recorded P, T, Q and W
INFORC	- Forecasted P and T
HBV	- HBV model program
COMP	- Computed Q and W (result from HBV model)
QW	- Recorded and computed Q and W
External file	- Q and W from external source
HD	- HD model program
RESSTN	- Computed Q and W for stations (result from HD model)
RMS	- River Monitoring System
RMS-db	- Database with recorded and computed data for presentation in RMS

Operational data flow:

1. Recorded P,T,Q,W as input to HBV model from SHO database
2. Forecasted P,T as input to HBV model from SHO database
3. HBV model execution
4. Computed Q,W from HBV model run loaded into SHO database
5. Recorded and computed Q,W as input to HD model from SHO database
6. Recorded and computed Q,W as input to HD model from external source
7. HD model execution
8. Computed Q,W from HD model run loaded into SHO database
9. Computed and recorded data loaded into RMS database from SHQ database
10. Monitoring and presentation of data in RMS

Figure 10. Schematic structure of system data flow.

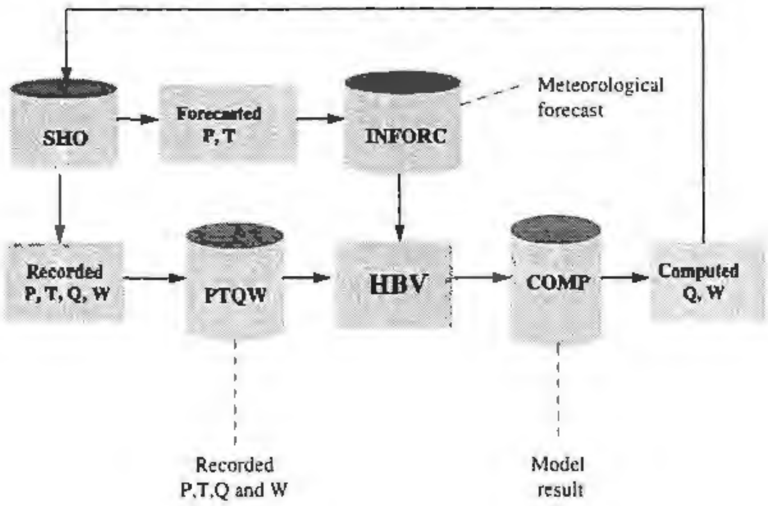


Figure 11. Schematic structure of HBV model data flow

Figure 12. Schematic structure of HD model data flow.

5.3 IHMS - New functionality

This section gives a summary of the new functionality that has been implemented by the project.

5.3.1 Program execution modes

The IHMS system can basically be used in two different modes:

- **Operational mode**, which means running the system with real-time production data.
- **Development mode**, which enables the user to run calibrations etc. with different sets of test data for development purposes.

Operational mode and Development mode are clearly distinguished by having separate data catalogues. To access these two data parts the IHMS user interface is used.

When the IHMS program is started the following choices are available:

- **Development** - the user grants access to the entire IHMS menu system, but only Development data can be accessed.

- **Operational - Run** - the models are executed in sequence being configured according to the system manager's settings (Automatic model run).

- **Operational - Presentation** - the IHMS menu system is shown, but only the menu alternatives for Presentation and Help are selectable.

- **Operational - Configuration** - the user grants access to the entire IHMS menu system, but only Operational data can be accessed. To enable this choice the user must specify correct username/password. This is to protect the data used for the daily operational work from being changed by mistake. Only if the user can identify himself/herself as having the rights of the system manager the complete IHMS system is accessible.

5.3.2 Automatic model run

The program AUTORUN implements user controlled and configurable automatic model run. The automatic model run can be configured to execute the HBV and the HD model in sequence for any number of districts and data sets.

The execution sequence typically selects district and data set, changes date and hour in parameter files, invokes DLL-functions and executes model programs in an user configurable order. The automatic model run execution sequence is specified by the user (system manager) in a separate script file.

When starting the automatic model run the user must enter a reference time; that is date and hour that specifies the "logical start time" for the automatic model run. Usually the reference date is "today" and the reference hour is a predefined starting hour depending on timestep etc. This enables the user to run the models for an arbitrary day.

The outcome of each command in the execution is displayed to the user and also logged in a log file

If an error occurs during the automatic model run the user is notified and he can choose to abort or continue the execution.

5.3.3 Data exchange

A general concept for data exchange is implemented to enable integration of different parts of the IHMS system. The data exchange consists of import and export program modules that transport various types of information.

All import and export program modules are implemented as DLL modules and they can be invoked from the menu system or executed as console applications from a stand alone executable program. That means that all import and export program modules can be used by the automatic model run function.

An objective in the system design is to use the same data file format for all kinds of import and export. The IHMS standard file format is used but with some restrictions and extensions.

When used interactively from the menu system all data exchange programs can be controlled from a data exchange control program.

With the control program the user can do following tasks:

- View and edit the parameters in the control files that specifies the data exchange
- Start import and export programs
- View and edit data files
- View log files

The following data exchanges can be controlled from this program:

- Load PTQW (HBV) data from SHO database.
- Load INFORC (HBV) data from SHO database.
- Load COMP (HBV) data into SHO database.
- Load QW data from COMP file (HBV).
- Load QW data from SHO database.
- Load QW data from external file.
- Load result data (RESSTN) into SHO database
- Load data in SHO database to the River Monitoring System (RMS)

5.3.4 HBV - Modifications

The existing program functions supporting the IHMS/HBV model is modified to facilitate new functionality as follows:

- Shorter time step (bottom limit now one hour instead of 24 hours)
- Automatic model run (see above)
- Import PTQW and INFORC data from external source e.g. SHO database (see above)
- Export COMP data to external system e.g. SHO database, HD model (see above)

5.3.5 HD - Menu commands

New functionality has been implemented in IHMS to enable integration of HD model as follows:

- **Data set** - Select active data set
- **HBV model** - Switch to HBV model mode
- **Edit QW.KEY** - Update key file for QW-data
- **Data exchange** - General program for data exchange, i.e. various import and export functions
- **Edit QW-data** - View and edit single data items in QW-data file
- **Compile table (QW-data)** - Generates a table of QW-data for viewing or printing
- **Display table (QW-data)** - View or print table file with QW-data.
- **Change last date (QW-data)** - Extend QW-data file.
- **Stations** - View and edit station parameters.
- **River System description** - View and edit river system parameters.
- **Generate cross section list** - Utility program that generates a cross section list.
- **Edit cross section list** - View and edit cross section parameters.
- **Edit cross section shape** - View and edit cross sections graph (river bottom shape).
- **Generate Manning coefficients** - Utility program that generates Manning parameters.
- **Edit Manning coefficients** - View and edit Manning parameters for a cross section.
- **Recalculation of parameters** - Utility program that recalculates hydrological parameters needed for the HD model.
- **Select output stations** - Specify stations to be included in the result files.
- **Describe model run** - View and edit model run parameters.
- **Start HD model** - Executes the HD model program.
- **Show log file** - View the log file from HD model run.
- **Compile result table** - Generates a table of result data for viewing or printing.
- **Display result table** - View or print table file with result data.
- **Cross section result graph** - Display the result from a model run as a time series graph showing water levels and discharge.
- **Station result graph** - Display the result from a model run as a time series graph showing station result data.
- **Help function** - Help texts describing HD menu commands

5.4 Software and tools

The Vistula System is designed for Windows NT or Windows 95 environment. The IHMS part is also possible to use on Windows 3.11.

5.4.1 Runtime

The following software is necessary in runtime:
- Windows NT v4.0 or later or Windows 95
- MS Access v7.0 or later (part of MS Office Professional)
- MapInfo runtime v4.1 or later
- Graphics Server

MS Access and MapInfo are only used in RMS.

5.4.2 Development

Software development of IHMS system is based on tools as follows:
- Visual Basic Professional v3.0
- Graphics Server v4.52
- Visual C++ v4.2
- Fortran Power Station Standard Edition v4.0 (HBV model)

Software development of RMS is based on tools as follows:
- Visual C++ v4.2
- Formula One
- First Impression
- ForeHelp v2.96
- MapInfo v4.1

Visual SourceSafe is used for version control and to make parallel development at SMHI and IMWM possible.

5.4.3 Language independence

The IHMS system is designed for language independence. All text strings in the application are stored in separate files that are dynamically invoked from the executable program. With this solution it is easy to generate user interface in additional languages and to switch between different languages.

5.5 Hardware requirements

Recommended minimum hardware configuration:
- Pentium 166 MHz
- 32 MB RAM
- 20 inch monitor
- 1024*768 pixels resolution
- 65536 colours

6. The IHMS-HBV model application to subbasins in middle and lower Vistula river catchment

6.1 Climate and hydrology of middle and lower Vistula river catchment

The subject of this work is middle and lower Vistula river basin with an area of 143 693 km^2.

Vistula river basin area is 194 424 km^2 with a total river length of 1 047 km. 87.5 % of the area is within the country of Poland. Vistula river basin is situated in the geometrical centre of Europe between latitude 49 ° - 54 ° and longitude 18 ° - 24 °. The basin is a Baltic Sea asymmetric catchment with a predomination of right tributaries.

The Vistula river basin is divided into three parts with different hydrological and geomorphological characteristics (IMGW 1986):

- upper Vistula basin - main river length 394 km, drainage area 50 732 km^2 - this part contains all Carpathians tributaries, the mean annual flow 436 m^3/s, 100-year flood estimate 7 740 m^3/s, 100 -year low flow estimate 67 m^3/s;
- middle Vistula basin - main river length 218 km, drainage area 109 530 km^2 - this part contains the biggest lowland tributaries - Narew, Bug and Pilica, the mean annual flow 869 m^3/s, 100-year flood estimate 8 680 m^3/s, 100-year low flow estimate 140 m^3/s;
- lower Vistula basin -main river length 436 km, drainage area 34 163 km^2 - this part contains the depression region very close to Baltic Sea, the mean annual flow 1 000 m^3/s, 100-year flood estimate 9 190 m^3/s, 100-year low flow estimate 225 m^3/s.

The main part of middle and lower Vistula river basin is situated in lowland with mean altitude about 170 m above sea level. The basin has band character with the upland range in the South, the lowland range in the middle part, the lake district heights and seaside lowlands. In the middle part Vistula river valley is very wide and irregular (600 - 1 000 m). In Warsaw city the valley is artificially reduced to 350 m of width. Close to Warsaw city several tributaries fall into the Vistula river: Radomka, Pilica, Bzura and Narew with Bug and Wkra. In kilometre 675 the Wloclawek Reservoir is situated with the biggest hydropower station in Poland (160 MW). Reservoir area is 7 040 ha, the length is 59 km, the width is 2.5 km, the maximum depth is 8 m and the water storage is 408 mln m^3. About kilometre 886 the Vistula river falls into a delta, a very lowly situated region with depression to -1.8 m below sea level. This area is threatened by storm floods, when winds dam up the water in the Gdansk Bay.

In the lowland part of the basin mean slope of the river bed is between 0.18 ‰ - 0.22 ‰ but in the river mouth about 0.02 ‰. Mean water temperature in winter is 2.3 °C - 3.5 °C, in summer, 16.6 °C - 16.8 °C. The ice phenomenon begins in the third decade of November. It disappears in February or March. The average duration of ice phenomenon is from 80 to 100 days. The average ice cover depth is 30 - 40 cm. (Kondracki, J. 1981; Mileska, M.I. 1983).

Mean annual outflow of Vistula river to the Baltic Sea is 30.7 km^3. Mean discharge in characteristic cross sections of the Vistula river are as follows (IMGW 1986):

- Zawichost (inflow to the middle Vistula river) 443 m^3/s;
- Warsaw 573 m^3/s;
- Torun 992 m^3/s;
- Tczew (outflow to the Baltic Sea) 1 080 m^3/s.

The hydrological regime in all river in the basin is typical to most of the east-European rivers with a maximum flood during spring (in March and April). The second period of floods is in the end of June after heavy rainfall in the mountainous south part of Poland. During summer and autumn the water level and the discharge is rather low with periodical increases due to rainfall. Water level amplitude is from 6.5 m in middle part to about 10 m in lower part of the Vistula river.

All territory of Poland is within one climate region - moderately mild and moist with attributes of western oceanic and eastern continental climates. Winds are predominant West. Big variability of the weather, from the sub-tropical to the arctic conditions, is characteristic for Poland. The sub-tropical air in summer is the reason of very heavy rainfall. In winter the air from south causes fogs and heavy snowmelt. The arctic air is coming for few days in the year. In winter there are very frosty days with snow-storm and in spring and autumn ground frost.

Annual mean air temperature is between 6 °C and 8 °C. The coldest regions are situated in North-eastern part of Poland. The air temperature decreases in eastern direction with meridian character of isotherms. The coldest areas are in upper parts of the following subbasins: Kamienna, Wieprz and Biebrza (the tributary of upper Narew). The average temperature in winter is here about -5 °C.

July is the warmest month in Poland. In the north part of Vistula river basin the air temperate is 17 °C - 18 °C. The July temperature in the remaining part of the catchment is 18 °C - 19 °C. The amplitude of mean monthly air temperature in July is changing from 19 °C to over 23 °C. In the very eastern regions over 60 days are with frost and over 130 days with ground frost. In lowland the first ground frost begins in the first decade of October and last until the second decade of May (Kondracki, J. 1981; Mileska, M.I. 1983).

The mean precipitation in middle and lower Vistula river basin is about 600 mm/year. The lowest amount of precipitation (lower than 500 mm/year) falls in the North. The largest precipitation (600 - 700 mm) is in Mazuria Lake district. Most part of the lowland has a precipitation between 500 and 600 mm/year. The numbers of days with precipitation is about 130 in the middle part and about 180 days in the lake district. The highest yield of rainfall is in the summer months (about 70 % of total precipitation), and the lowest, in January and February. Between April and September (and very often in July) there are storm rainfalls. The snow falls in winter, from November to April. The mean number of days with snow is 30 in the middle part and 60 days in the North-eastern part of the basin. The snow is 15 % to 25 % of the average annual sum of precipitation. Snow cover has an average duration of 90 to 110 days. The average depth is a few to twenty centimetres. (IMGW 1986).

Potential evaporation is about 750 mm/year and 75 % of this value is in summer months. The area evapotranspiration is 400 - 500 mm/year with the main portion (80 - 90 %) during the vegetation period. (IMGW 1986).

The water balance of the Vistula river basin is in average as follows - precipitation is about 600 mm, the river outflow is about 170 mm and the evaporation is about 430 mm. The outflow coefficient of the Vistula river is equal to 29 %.

Table 2 gives a summary of hydrological and climate characteristics of the tributaries of middle and lower Vistula.

Table 2. Climate and hydrological characteristics of the middle and lower Vistula river tributaries.

NAME OF TRIBUTARY	River length [km]	Area [km^2]	Mean annual rainfall [mm]	Numbers of days with snow cover	Mean air temp. [°C]	High flow [m^3/s]	Low flow [m^3/s]	Amplitude of water stage [m]	Period of ice phenomena	Altitude of the river mouth [m]	Mean river bed slope [‰]
KAMIENNA	138.3	2007.9	550-650	80-120	7.0-7.5	77.0	1.98	2.0-5.0	XI-III	127.0	10.0-0.6
WIEPRZ	303.2	10415.2	550-750	80-90	7.0-7.5	591	9.20	2.5-4.2	XII-III	111.0	2.0-0.1
RADOMKA	107.0	2109.5	550-750	60-80	7.5	200	2.00	2.5-3.2	XI-III	101.0	4.0-0.7
PILICA	319.0	9273.0	550-700	60-80	7.5	471	14.2	2.5	X-IV	93.0	4.4-0.5
Upper NAREW	238.1	14307.7	600-650	80-120	5.5-7.0	992	11.2	2.2-4.5	X-IV	100	0.5-0.05
NAREW	484.0	75175.2	550-650	80-100	5.5-7.0	1460	33.7	2.3-4.5	X-IV	68.0	0.5-0.05
BUG	755.0	39420.2	500-600	80-100	7.0-8.0	2400	19.8	5.0	XI-IV	79.0	0.19-0.1
WKRA	249.1	5322.1	550-600	70-90	7.0-7.5	466	2.00	2.0-4.6	XII-III	69.0	0.4
BZURA	166.2	7787.5	520-600	50-70	7.8-8.2	480	2.80	2.0-4.5	XI-III	64.0	2.0-0.3
DRWECA	207.2	5343.5	500-600	60-90	6.6-7.5	150	8.15	2.5	XII-III	39.0	0.6

6.2 Model application

6.2.1 Basin subdivision

The total catchment of middle and lower Vistula river basin is 143693 km^2. For the HBV model set-up eight districts are chosen within the river basin (Figure 10 and Table 3). Each district is divided into subbasins (Figure 1-8 and Table 1 -8, in Appendix 1). Seven of the districts are connected into the Vistula river at the most downstream subbasin including the tributary river mouth. One district, Upper Narew, is connected into the Vistula river passing through the hydraulic HD-model. In the model application the eight districts are connected into Vistula river basin with altogether 42 subbasins.

The subbasin division is mainly based on the location of discharge stations. Runoff data from these stations are used for calibration of the model parameters.

Table 3. The Vistula River Basin. Division into districts

District	Number of subbasins	Total area (km^2)	Forest (%)	Open field (%)
Kamienna	8	2007.9	40.3	59.7
Wieprz	7	10415.2	22.2	77.8
Radomka	2	2109.5	28.2	71.8
Pilica	9	9273.0	40.0	60.0
Upper Narew	7	14307.7	35.7	64.3
Wkra	3	5322.1	19.2	80.8
Bzura	3	7787.5	18.6	81.4
Drweca	3	5343.5	27.0	73.0
	Sum = 42	Sum = 56566.4	Average = 28.9	Average = 71.1

Remark: "Number of subbasins" includes the river mouth subbasins

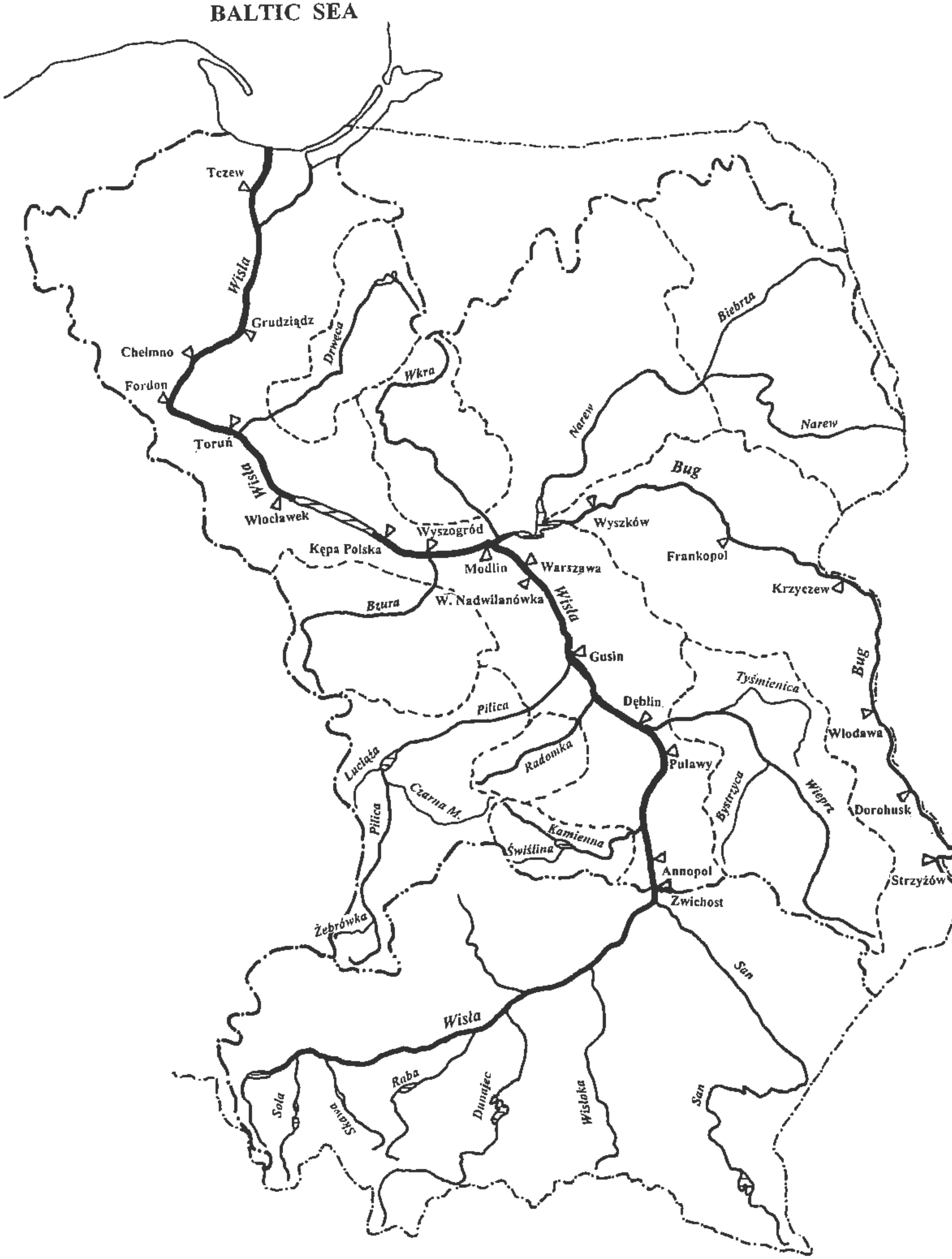


Figure 10. The Vistula River Basin. Division into districts.

6.2.2 Analysis of input data

Precipitation is the source of streamflow generation and consequently the most important input data to the HBV model. Furthermore temperature data and long term estimates of potential evapotranspiration are needed as input.

A control of the homogeneity of the precipitation and discharge stations has been accomplished with the double mass technique. This technique takes advantage of the fact that the mean accumulated precipitation for the number of gauges is not very sensitive to changes at individual stations because many of the errors compensate each other. However the cumulative curve for a single gauge is immediately affected by a change at the station. The mean accumulated precipitation for all other stations is plotted on the X-axis against the precipitation for the gauge being studied, which is plotted on the Y-axis. If the double mass curve has a change in slope at some point in time it indicates a break in homogeneity. A jag in the double mass curve can be caused by missing values at the observed station or by seasonal differences in the precipitation pattern. The slope of the curve is proportional to the intensity, i.e. if the observed station records exactly as much as mean of the rest, the curve follows the diagonal. If the station records more the slope will be steeper and if it records less the double mass curve will lie below the diagonal.

Most stations in Vistula river basin show homogeneity in the double mass plots. For a few precipitation stations though there are found severe inhomogeneities. These stations were excluded from use. For the remaining stations new double mass plots were created (Appendix 2). Some of these stations have short periods with missing data and a few show a slight inhomogeneity.

For example in Pilica district a replacement precipitation station had to be changed because of deviating angle of double mass plot for Sulejow. For the period 1970 to 1973 three stations were used as replacement stations, for remaining period only Sulejow station was used. In Wieprz district precipitation station Wysokie was eliminated. This station is not too bad, only a little unstable. The mean annual sum of precipitation is similar to other stations but in the 70-ties the single daily sums in Wysokie were very high in comparison to surrounding stations. Due to small inhomogeneities for some precipitation stations minor changes on station weights had to be done.

A couple of discharge stations with severe inhomogeneities were also detected, Szczekociny and Bonowice. For these two stations no results are presented.

For the discharge station Kunow in Kamienna district the recorded outflow is lower than the sum of discharges for upstream stations Brody and Nietulisko. In Table 3 the influence of human activities for discharge stations in Vistula river district is marked. Due to increase in population, growing economy, changes in land use and industrial development the runoff regime has been changed.

Natural processes also affect the quality of discharge registrations. In winter, when there are ice phenomenon, and in summer, when the immense amount of vegetation in rivers is observed, the special coefficients for discharge have to be used. The values are though not constant and consequently estimated subjective.

Table 3. Water regime for discharge stations in Vistula river basin.

DISTRICT	DISCHARGE STATION	WATER REGIME
KAMIENNA	Bzin	C
	Wachock	C
	Michalow	C
	Brody	TC
	Nietulisko	QN
	Kunow	C
	Czekarzewice	QN
WIEPRZ	Nielisz	QN
	Krasnystaw	QN
	Sobianowice	C
	Lubartow	C
	Tchorzew	QN
	Kosmin	QN
RADOMKA	Rogozek	QN
PILICA	Szczekociny	C
	Bonowice	QN
	Przedborz	QN
	Dabrowa	QN
	Sulejow	QN
	Kludzice	QN
	Spala	TC
	Bialobrzegi	QN
UPPER NAREW	Narew	QN
	Suraz	N
	Fasty	C
	Strekowa Gora	C
	Osowiec	N
	Burzyn	N
	Wizna	N
WKRA	Trzciniec	QN
	Cieksyn	N
BZURA	Kwiatkowek	C
	Sochaczew	QN
DRWECA	Nowe Miasto	N
	Elgiszewo	N

Legend: N - natural water regime,
QN - quasi-natural regime,
C - changed regime,
TC - total changed regime.

The remaining stations are assumed to be reliable.

Information about precipitation, temperature and potential evapotranspiration are presented in Appendix 3, "Meteorological and hydrological tables", in table 1 and 2. Hydrological information is presented in the same Appendix, table 3.

6.2.3 Calibration

Calibration was carried out against runoff data for the period 1970-11-01 - 1995-10-31, with various periods for the different districts, depending on the availability of data. An example of model results for the most downstream subbasin with a discharge station of each district is presented in Appendix 4. The plot period 1992-10-01 - 1994-05-31 is selected for all subbasins.

In 1982 the long hydrological drought began in Poland. It lasted until 1995. During this period for many meteorological stations, especially in central Poland, the precipitation deficit was higher than mean annual sum of precipitation. This effect was reflected in the observed hydrographs. In the 90-ties for many gauge stations outflow was very low and water stages were lower than ever in history of observation. For a few discharge stations systematic deviation was noticed in HBV model simulation. It was characteristic that since 1986 the accumulated difference has increased. In order to eliminate this deviation a precipitation correction factor below 1.0 has been used from this year.

Inhomogeneities in data

Due to inhomogeneities in data for some stations it was not possible to obtain any good calibration results with the first onset of station weights in the concerned subbasins. A few changes of station weights were done, which resulted in better calibration results. Some examples:

Kamienna district

Elimination of a little unstable precipitation station Suchedniow, with weight 0.25, improved results for the Wachock subbasin in Kamienna district. In the end in this subbasin area precipitation was estimated based on only one station, Wielka Wies.

Wkra district

In order to make better calibration for subbasin Trzciniec in Wkra district the precipitation weights were changed in comparison with original values.

Pilica district

Detected inhomogeneities, among other for Szczekociny and Bonowice in Pilica district, made it impossible to obtain acceptable calibration results within these subbasins.

Regulations

The existing hydrotechnical infrastructure also caused some inconvenience during the calibration process. For example in Bzura district and Bystrzyca (the Wieprz river tributary) there are some small dams, weirs and sluice gates which affect natural outflow, but for which regulation rules are unknown.

Pilica and Kamienna districts

For two subbasins in Pilica and Kamienna districts, the function "Regulation schedule" in the IHMS system has been used for reservoir description. The existing descriptions of the regulation rules could not be transferred directly into the IHMS regulation schedule. Instead only general ideas of reservoir water management was described, taking into account main tasks of the reservoir (first of all water supply).

Wieprz district

For upper subbasins in Wieprz district, where there are carst phenomenon, water vegetation problems and hard human pressure on the environment, a lot of problems occurred during the calibration. In 1969 a transfer channel was built to take out water from Wieprz river to another subbasin in Bug district. The water is used for irrigation and water supply. The momentary abstraction is very unstable and changes from 2 m^3/s to 15 m^3/s. During the floods in 1979 and 1980 the abstractions were over 30 m^3/s. Normally, water is taken in summer but also in March, May and December. In the second part of the 80-ties and in the 90-ties the autumn abstractions dominated. Abstractions for historical period were described in the model during calibration but it is impossible to use them in forecasts because of lack of any information about planned abstraction.

6.2.4 Model result

In Table 4 the calibration results for all subbasins in the Vistula river district are presented. Calibration is carried out for the period 1978-11-01 to 1995-10-31, when the big spring flood (1979) and the very long hydrological drought (1982 - 1995) occurred. Verification was made for the period 1970-11-01 to 1978-10-31.

During calibration the R^2 -value of the model together with accumulated difference between the simulated and observed runoff were used to check model performance. These two hydrographs were also visually inspected, taking into account shape and time accordance. The R^2 -values fluctuated from 0.25 to 0.89 for the calibration period and from 0.22 to 0.89 for all period. It should be noticed that extreme values (< 0.5 and > 0.8) are usually concerned with new stations, with a short time of observations, or stations with a changed river regime or, finally, with stations situated close to a reservoir outflow, where the observed runoff from a gauging station is used as inflow to the subbasin instead of computed runoff from an upstream subbasin.

For many subbasins calibration results are more or less acceptable with an R^2-value equal or higher than 0.6 and accumulated differences with acceptable values.

Table 4. *R2 values and accumulated differences (Accdiff) for the modelled outflow of the subbasins in the Vistula river basin.*

		CALIBRATION PERIOD			TOTAL PERIOD		
District	**Subbasin**	**Period**	**R2**	**Accdiff**	**Period**	**R2**	**Accdiff**
KAMIENNA	Bzin	791101-951031	0.55	37.0	791101-951031	0.55	37.0
	Wachock	781101-951031	0.54	129.0	701101-951031	0.59	84.0
	Michalow	931101-951031	0.38	39.0	931101-951031	0.38	39.0
	Brody	781101-951031		inqrec	731101-951031		inqrec
	Nietulisko	781101-951031	0.66	-100.0	701101-951031	0.67	80.0
	Kunów	781101-951031	0.88	151.0	701101-951031	0.89	290.0
	Czekarzewice	781101-951031	0.79	-53.0	701101-951031	0.74	85.0
WIEPRZ	Nielisz	921101-951031	0.31	-1.0	921101-951031	0.31	-1.0
	Krasnystaw	781101-951031	0.43	30.0	701101-951031	0.22	127.0
	Sobianowice	781101-951031	0.25	-103.0	701101-951031	0.29	82.0
	Lubartow	781101-951031	0.63	-55.0	701101-951031	0.49	17.0
	Tchorzew	781101-951031	0.50	-66.0	711101-951031	0.50	47.0
	Kosmin	781101-951031	0.69	-55.0	701101-951031	0.61	39.0
RADOMKA	Rogozek	781101-951031	0.67	33.0	701101-951031	0.63	95.0
PILICA	Szczekociny	781101-951031	bad	station	751101-951031	bad	station
	Bonowice	781101-951031	bad	station	721101-951031	bad	station
	Przedborz	781101-951031	0.55	126.0	701101-951031	0.56	-22.0
	Dabrowa	781101-951031	0.68	42.0	701101-951031	0.67	-41.0
	Sulejow	781101-951031	0.60	27.0	711101-951031	0.63	-115.0
	Kludzice	781101-951031	0.54	77.0	701101-951031	0.54	174.0
	Zapora	820901-951031		inqrec	820901-951031		inqrec
	Spała	820901-951031	0.89	-36.0	820901-951031	0.89	-36.0
	Bialobrzegi	820901-951031	0.74	-25.0	820101-951031	0.74	-25.0
UPPER NAREW	Narew	781101-951031	0.53	43.0	701101-951031	0.56	66.0
	Suraz	781101-951031	0.62	134.0	701101-951031	0.64	115.0
	Fasty	781101-951031	0.46	30.0	701101-951031	0.35	144.0
	Strekowa G.	781101-951031	0.53	45.0	701101-951031	0.54	-54.0
	Osowiec	781101-951031	0.69	10.0	701101-951031	0.68	-35.0
	Burzyn	781101-951031	0.74	3.0	701101-951031	0.75	34.0
	Wizna	781101-951031	0.72	52.0	701101-951031	0.71	-12.0
WKRA	Trzciniec	781101-951031	0.64	-50.0	701101-951031	0.59	51.0
	Cieksyn	781101-951031	0.64	30.0	701101-951031	0.60	53.0
BZURA	Kwiatkowek	901101-951031	0.53	21.0	901101-951031	0.53	21.0
	Sochaczew	781101-951031	0.59	-4.0	701101-951031	0.61	-23.0
DRWECA	Nowe Miasto	781101-951031	0.38	86.0	701101-951031	0.43	68.0
	Elgiszewo	781101-951031	0.54	135.0	701101-951031	0.50	146.0

Legend: „inqrec" - the inflow to the subbasin is the observed runoff from a gauging station
Observed outflow from reservoir Brody is the inflow to the Kunow subbasin and observed outflow from reservoir Zapora is inflow to the Spala subbasin.

„bad station" - jam caused by vegetation affects discharge and it is impossible to achieve good model results. In the future these two stations will be replaced by only one, situated more downstream.

Table 5. Span of the most important model parameter values for the calibrated subbasins in Vistula river basin.

Parameter	**Value**	**Function**
Snow routine		
SFCF	1.0 - 1.7	Snowfall correction factor
TT	-1.0 - 0.5	Threshold temperature for snowmelt
CFmax	3.0 - 7.0	Degree-day factor
Soil routine		
FC	150.0 - 450.0	Field capacity
LP	0.35 - 0.90	Limit for potential evapotransporation
Beta	0.85 - 2.50	Empirical coefficient
Response routine, upper zone		
Cflux	0.0 - 1.2	Capillary flux
Alfa	0.2 - 1.5	Recession parameter
HQ	0.60 - 2.32	Peak flow level
KHQ	0.008 - 0.500	Recession at HQ
Response routine, lower zone		
Perc	0.08 - 5.00	Ground water percolation
K4	0.001 - 0.300	Base flow recession parameter

6.2.5 Discussion

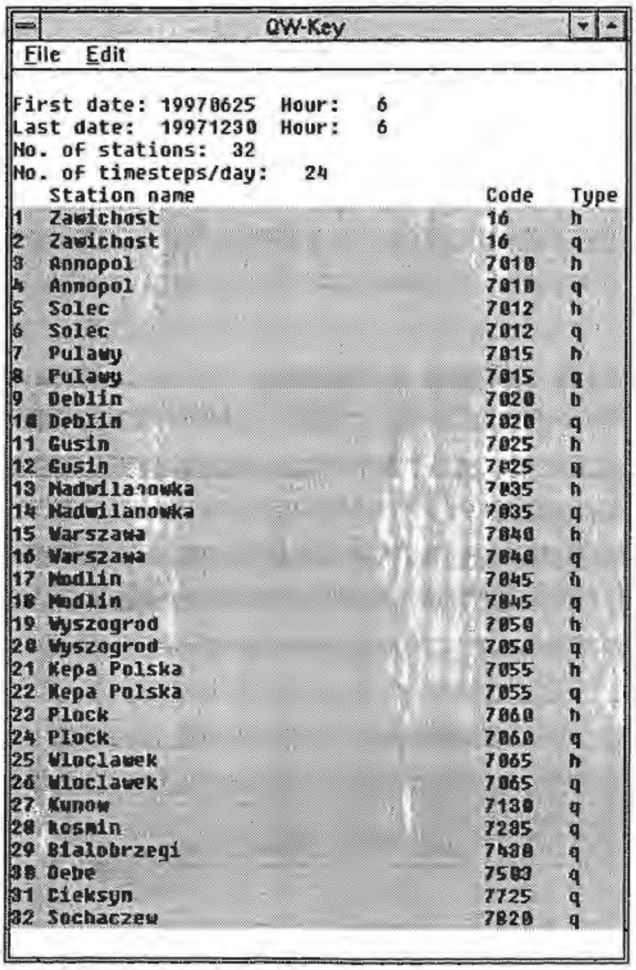
The main reason to apply the HBV model in Vistula river basin is to perform short-range runoff forecasts for the eight tributaries in the IHMS system. These forecasts shall be used as inflow to the HD model prepared for Vistula and Narew rivers and in a flood warning system to warn people and local authorities. The HBV model will also be a good help in the check of quality of discharge measurements and runoff data and a useful tool for simulation of discharge where observations by any reason are missing, temporarily or permanent.

7 The HD-model application to middle Vistula river

In this project the HD-model were prepared for the middle and lower Vistula river and for the two tributaries Bug and Narew. As an example application to middle Vistula river is described.

The model for middle Vistula river is an interesting and important example of application of the hydraulic HD-model. The model include the reach of Vistula river between Zawichost (km 288, area 50 732 km^2) and Wloclawek (km 702, area 174 119 km^2) with main tributaries. Information on water stage and discharge in this part of Vistula river is very important during extreme floods as well as during low flows.

The operational version of the model use outflow forecasts from Kamienna, Wieprz, Radomka, Pilica and Bzura river calculated by the HBV model, figure 10. During development observed data from these tributaries were used. The QW-key file describe the data used to run the model. For this part of Vistula river 13 stations with water level and discharge are use and 6 stations are used to describe discharge form tributaries, figure 11.


QW-Key
File Edit

First date: 19970625 Hour: 6
Last date: 19971230 Hour: 6
No. of stations: 32
No. of timesteps/day: 24

	Station name	Code	Type
1	Zawichost	16	h
2	Zawichost	16	q
3	Annopol	7010	h
4	Annopol	7010	q
5	Solec	7012	h
6	Solec	7012	q
7	Pulawy	7015	h
8	Pulawy	7015	q
9	Deblin	7020	h
10	Deblin	7020	q
11	Gusin	7025	h
12	Gusin	7025	q
13	Nadwilanowka	7035	h
14	Nadwilanowka	7035	q
15	Warszawa	7040	h
16	Warszawa	7040	q
17	Modlin	7045	h
18	Modlin	7045	q
19	Wyszogrod	7050	h
20	Wyszogrod	7050	q
21	Kepa Polska	7055	h
22	Kepa Polska	7055	q
23	Plock	7060	h
24	Plock	7060	q
25	Wloclawek	7065	h
26	Wloclawek	7065	q
27	Kunow	7130	q
28	Kosmin	7285	q
29	Bialobrzegi	7480	q
30	Debe	7583	q
31	Cieksyn	7725	q
32	Sochaczew	7820	q

Figure 11. Example of QW.KEY file for middle Vistula model system.

The HD-model normally uses hourly time-step for the calculations. Normally measured data and HBV-model calculation are on a longer time scale. When the model need data every hour a linear interpolation is used between observations and HBV-model calculations, figure 12.

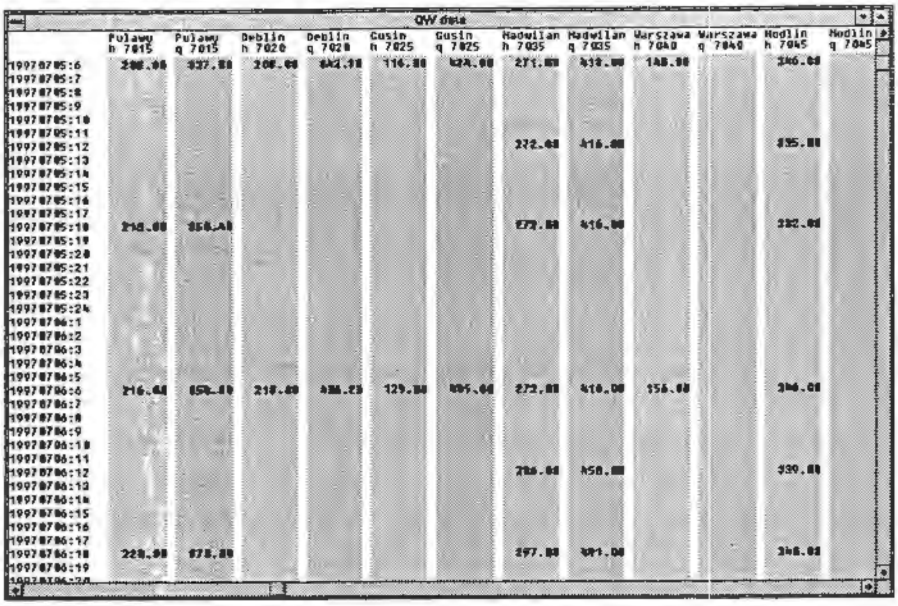


Figure 12. Example of the input file QW.DAT for middle Vistula model.

A description of river bed shape were made with use of 155 cross sections describing the topography of Vistula river bed and floodplain, figure 13. Corrections and modifications on the cross-sections shape are easily made by using software included in the model system. Model quality is extremely dependent on the shape of each cross section.

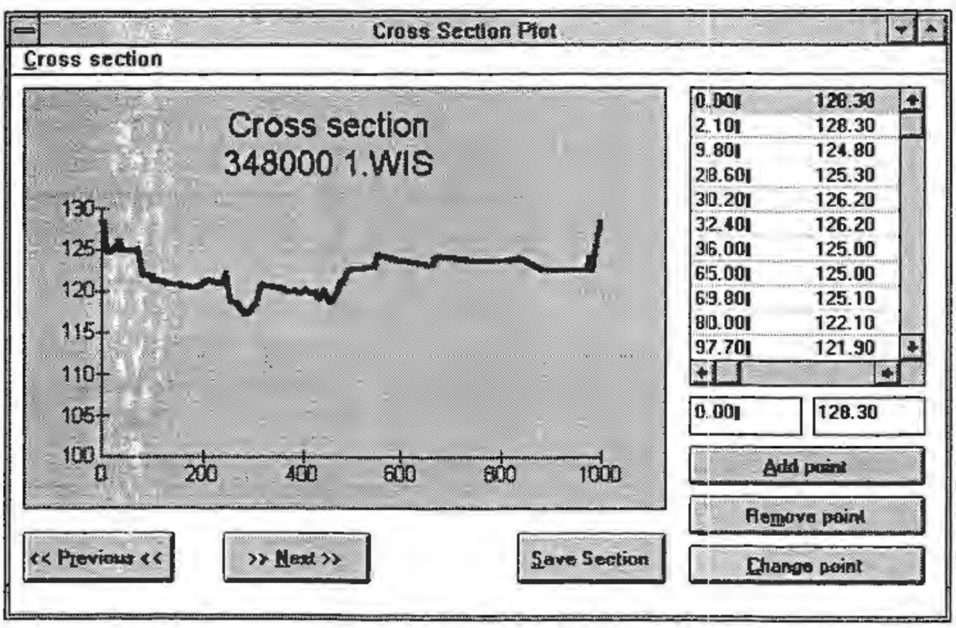


Figure 13. Shape and dimension of cross section at km 348 in Vistula river.

For each cross section a set of Manning coefficients is selected during model calibration. At least two coefficients, at low and high river-bed level, must be adjusted for each cross section. An additional coefficient for bank water level can be necessary to accomplish a more accurate model calibration, figure 14.

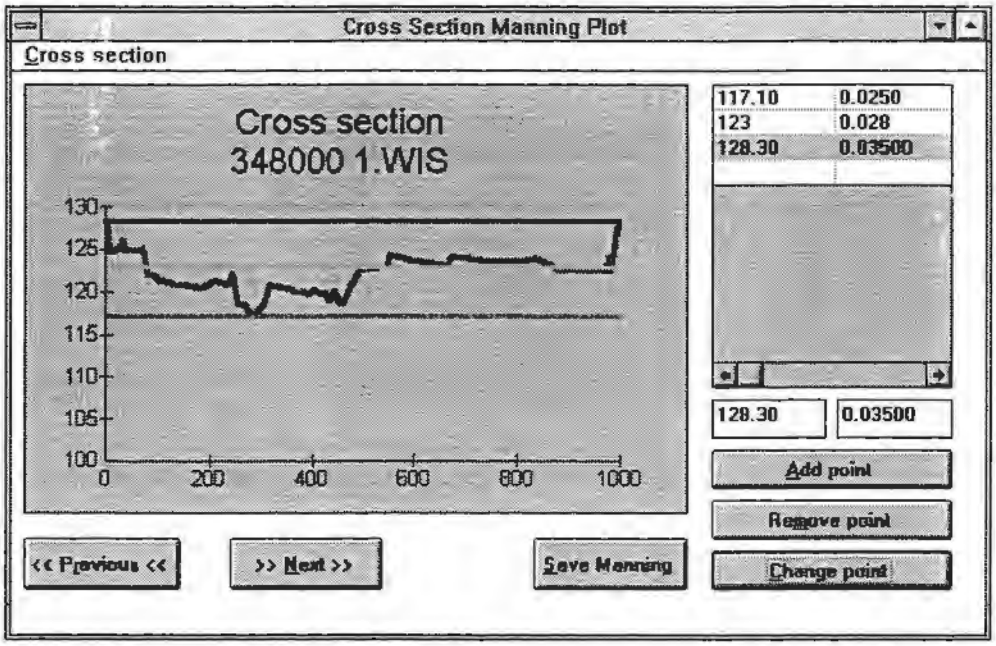


Figure 14. Manning coefficients for cross section at km 348 in Vistula river.

During calibration of the model calculated values on water level and discharge are compared with observations. By changing the values of Manning coefficients on each cross-section the model calculated values are fit with the observations. Calculated discharge and water level can be presented graphically for each cross section used in the model, figures 15 and 16.

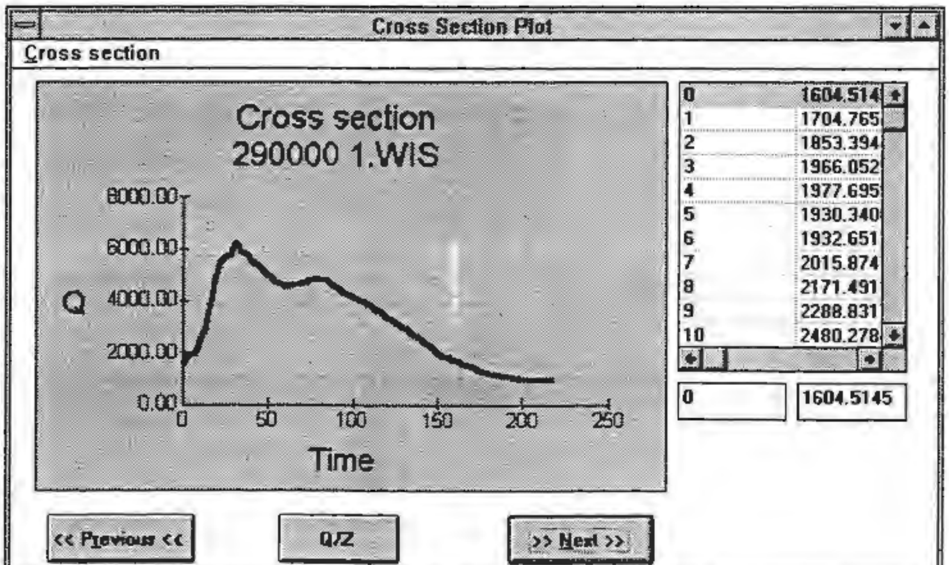


Figure 15. Calculated discharge hydrograph for the cross section at km 290 in Vistula river

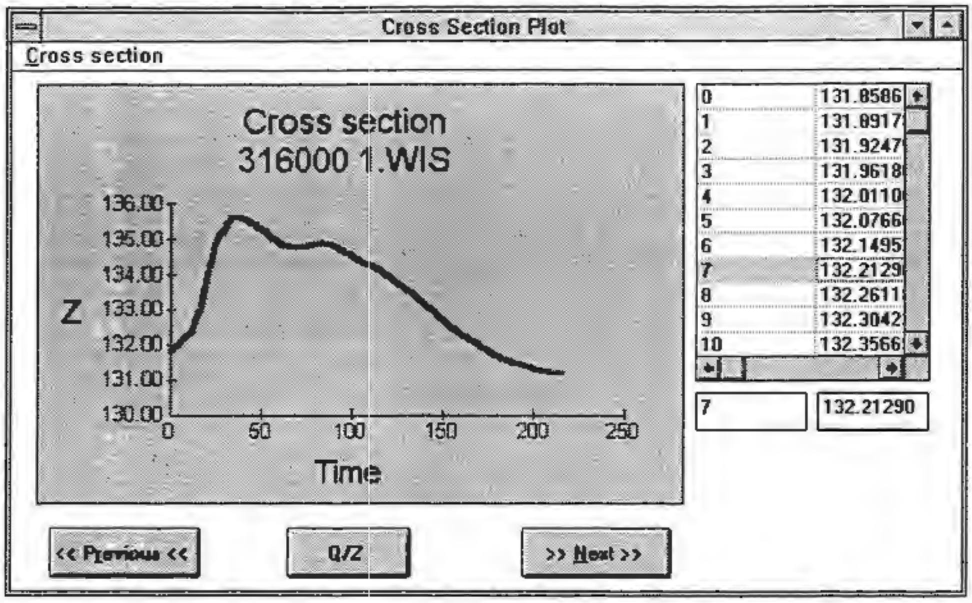


Figure 16. Calculated water level hydrograph for the cross section at km 316 in Vistula river.

8 Real time system application

8.1 Semi-automatic system run

To run the integrated hydrological monitoring and forecasting system at IMWM a new computer Pentium 166 MHz was installed and connected with existing computer network at the institution. Every day the integrated system is run semi-automatically according to a specified program.

1. Data from hydrological and meteorological network are collected and stored in the SHO database
2. The meteorologist prepare forecast of temperature and precipitation
3. The hydrologist prepare forecast for reservoir, sea water stages and water stages for selected river stations
4. An automatic model run is started on the "HBV-HD-computer"
   - The observations are imported from SHO database to PTQW-file
   - Data control made by the hydrologist
   - For each district
     - Forecast imported from SHO database to INFORC file
     - HBV-model run
     - HBV-model result exported from COMP-file to SHO database
   - For each river dataset
     - Observations and HBV-model forecast imported from SHO database to QW file
     - HD model run
     - HD model results exported from RESSTN file to SHO database
5. Observations and forecasts exported from SHO to RMS database
6. RMS is run analyse the hydrological situation.
7. Results from HBV and HD models are used for production of bulletins and maps.

8.2 Experience from 1997

For a few months the constructed model system with HBV and HD model together with the real-time presentation system has been running at IMWM office in Warsaw. The system and model fit is thoroughly tested during these months. In July 1997, during the catastrophic flood in southern and western Poland, also middle Vistula river basin had extreme floods and high water level in the main river and westsided tributaries.

This extreme situation was a very hard test of the model system. Unfortunately a good experience on system use had not yet been fully established at IMWM before the flood. Despite this lack of experience some system options could be in use during the flood. In Kamienna, Radomka and Pilica rivers the discharge was high and the water stage increased alarm levels for a few gauge stations. Time agreement between observed and simulated peaks was quite good but the volume errors of simulation were significant mainly for the most downstream subbasins. Problems with back-water from the high water level in main Vistula river up in the tributaries is probably the main reason for this disagreement.

Figures 17 and 18 show model results as discharge and water level calculated by the system models for the extreme flood in July 1997.

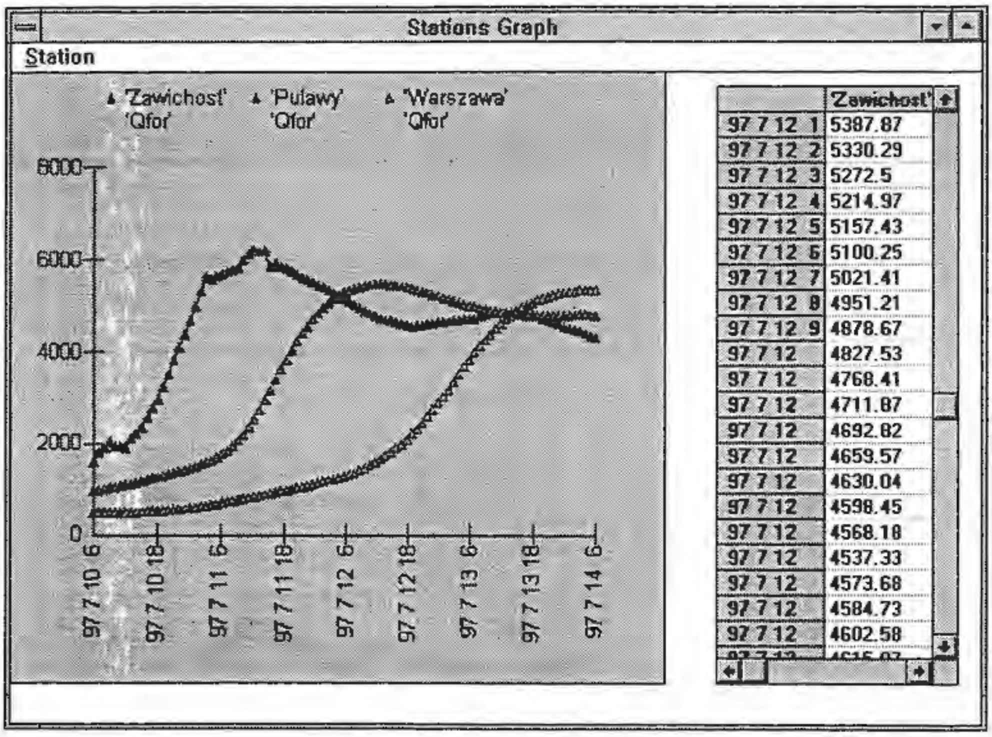


Figure 17. Comparison of discharge hydrographs for three stations in middle Vistula.

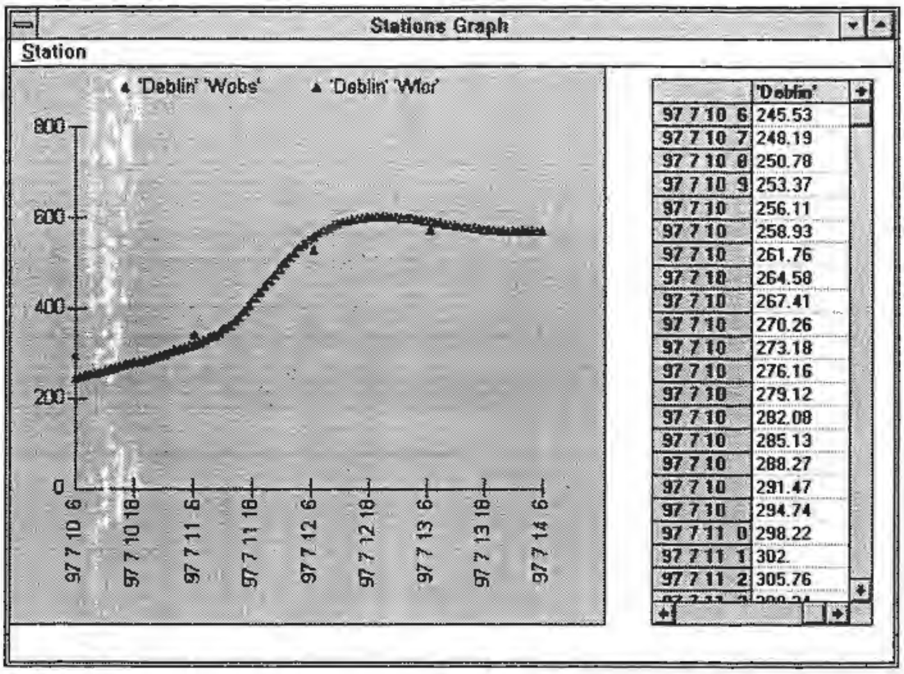


Figure 18. Observed and calculated water level for station Deblin.

The calculated water stages are in good agreement with observations, both in time and shape. For the discharges model result is higher than discharge calculated with use of stage-discharge curves during the high flows. This is mainly the situation for stations in the upper part of analysed reach. Analysis made at IMWM after the flood indicate that the calculated results are more reliable than the old stage-discharge relations. Water level were at many water level stations above highest level of observations made before. New relations is to be prepared and analysed at IMWM in the future.

9 Conclusions

This co-operation project between IMWM and SMHI has render a fully integrated hydrodynamic and hydrological model system possible. The well known hydrological model HBV, developed and extensively used at SMHI during the last 20 years, and the hydrodynamic model HD, developed at IMWM, has successfully been introduced in the integrated hydrological modelling system, IHMS. This system is now a fully implemented hydrological and hydrodynamic model system running on a daily basis covering middle and lower Vistula river basin. A modern and comprehensive geographical information system is used for presentation of observations from meteorological and hydrological observation spots and forecasts from included models. The system can be implemented also in the upper part of Vistula river basin as well as other river systems in Poland, on condition that calibration of the models are fulfilled for the included basins.

Original project plans was to introduce a presentation system in use at SMHI since beginning of 1990. Development of GIS software in the last years made it possible to introduce a more comprehensive and modern presentation system. The new developed river monitoring system improved the Vistula river real time monitoring and modelling system considerably.

The hydrological model calibration has during project activities been concentrated on a one day time step. Daily time step is sufficient for a majority of the tributaries in middle and lower Vistula. Some of the river in middle Vistula though have a rather quick response especially to rainfall but also in a lesser extent to snowmelt. Calibration of discharge in these rivers would be improved if shorter time step were used. In the project plans this activity was included, but due to lack of time the introduction of shorter time step had to be postponed.

Southern part of Poland, including the upper part of Vistula and Odra rivers, were during summer 1997 subjected to extremely heavy rainfall resulting in the heaviest flood during the last decade in these two important Polish rivers. The flooding occurred just after installation of the system at IMWM in Warsaw. A fully test and implementation in real time of the new system could therefore not be made. Experience from the flooding period can though be used in the future to improve the River Monitoring and Forecasting System of Vistula river basin.

10 Recommendations

During on-the-job training education and practice in set-up and calibration of the HBV-model as well as education in Windows programming has been made. It is very important that the so educated staff members from IMWM will have opportunity to spread there knowledge to other hydrologists and programmers at the institute and if possible also to universities and high-schools. If IMWM allow students to use the model system in there examination work persons educated in hydraulic and hydrological modelling will become more frequent. If this spreading of the know-how is neglected IMWM will be extremely dependent on the persons who attended the on-the-job training courses at SMHI within this project.

The calibration process and the obtained results showed that the most important factor for a good model result is the quality of input data such as discharge, precipitation and air temperature during wintertime. It will probably be necessary to make some re-calibration and update the HBV model parameters using a few new stations with a short time scale of observations for some subbasins and for planning of some new discharge stations to replace the old ones in upper Pilica subbasin.

Calibration on shorter time step than one day was not possible to fulfil during the project. IMWM personnel has though been educated in this calibration process and it is recommended that an introduction to 12-hour time step is made in some of the tributaries in middle Vistula river basin. This would probably improve the result as concerned both the hydrological and the hydraulic model giving higher accuracy to the output forecast on discharge and water level in Vistula river.

When choosing time step one must regard not only the hopefully improved model result. Also the fact that shorter time step demand more input data during calibration as well as during real time run must be considered. Shorter time step also require higher computer performance and more space and memory in the database. If these buts are considered and found acceptable introduction of shorter time step can improve model performance and give higher accuracy of the forecasted discharge and water level presented to end users.

Upper Vistula river basin is mainly in the Carpatian mountain area and of great importance concerning flooding problems in the lower and middle parts of the total basin. A calibration of the tributaries in this area is therefore a necessity for the achievement of an effective and reliable hydrological and hydraulic forecasting and presentation system. IMWM has started this calibration process and it is highly recommended that this activity will be fulfilled. Introduction of shorter time step is necessary in the mountain area because of the normally short lead times between rainfall and runoff in the small and steep mountain rivers.

The catchment of Bug tributary is partly located in the neighbouring countries Belorussia and Ukraine. An introduction of this part in the modelling system demand a co-operation with corresponding institutes in these two countries. A first start of model application in Bug, before this co-operation and exchange of data can be established, is to use weather data from the synoptic network and use as input to HBV-model calibration. This will result in a draft calibration that can be used to forecast discharge input to main Vistula river from Bug tributary.

The integrated system produce important information concerning the hydrological and hydraulic situation with very high accuracy. This information must be delivered to decision makers, to radio, television and newspaper and distributed to the Polish public. An effective distribution system would highly improve the effectiveness of the system. Fast and reliable information from the system give possibility to take appropriate actions depending on the forecasted hydrological situation. A way to improve the effectiveness of the distribution system is to introduce Internet and Web-side distribution as a way of communication. IMWM have experience from Internet for institutional information and ongoing activities. This information would be remarkably enriched if presentation of real-time data and forecasts on a daily basis concerning water level and discharge in Vistula river basin were included.

Vistula river is the most important water resource in Poland. This resource is used for water supply, for cooling water to thermal power plants, for industries located along the rivers, etc. Unfortunately, the water resources in Vistula river vary essential in time and they are heavily polluted by industrial, agricultural and municipal wastes. Build up of the integrated system for the Vistula river basin could be an essential start in a process to improve the water quality of the main river in Poland. Utilisation of the developed system and continuation of the integration process by including models aimed for calculation of nitrogen and phosphorous leakage will enhance the capability for decision-makers to plan, design and operate the water resources in the whole Vistula river basin.

11 Acknowledgement

The project could not have been carried out without significant work from a large number of persons. First of all Dr Januz Zielazinski who came up with creative ideas and help in starting-up phase of the project. Without his enthusiasm in project start-up and useful advises during project we would not have been were we are today with a fully implemented hydraulic and hydrologic model system for Vistula river. Secondly we want to thank Dr Joakim Harlin and Mr Peter Dahlén, who both participated in the start-up process and worked intensively together with Dr Zielazinski to fulfil the scope of services for the project.

An enormous amount of hydrological and meteorological data has been collected and typed into databases by IMWM personnel in Warsaw branch and at observation spots located in Vistula basin. They are all to thank for this important and fundamental work in hydrological modelling. Special thanks to Ms Halina Budzynska who have been working hard with the data process and also with calibration of the HBV-model from the IMWM office in Warsaw.

The efficiency of communication between IMWM and SMHI improved significantly when IMWM, mainly thanks to Dir Vladislav Zyla, introduced E-mail at IMWM. This communication link has been very valuable both in the system development activities and in calibration and report writing.

System development and computer programming activities has been one of the most important tasks in the project. Appreciation is expressed to Ms Helena Larsson, to Mr Yngve Einarsson and to Mr Johan Wester who all has been deeply involved in this work during different project phases.

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Appendix 1

Maps and tables of the subbasin division of the districts in the HBV model of Vistula river basin

Legend:
O Precipitation station
←O Precipitation station situated out of subbasin
▽ Discharge station

Figure 1 Subbasin division of Kamienna district and Radomka district in Vistula river basin.

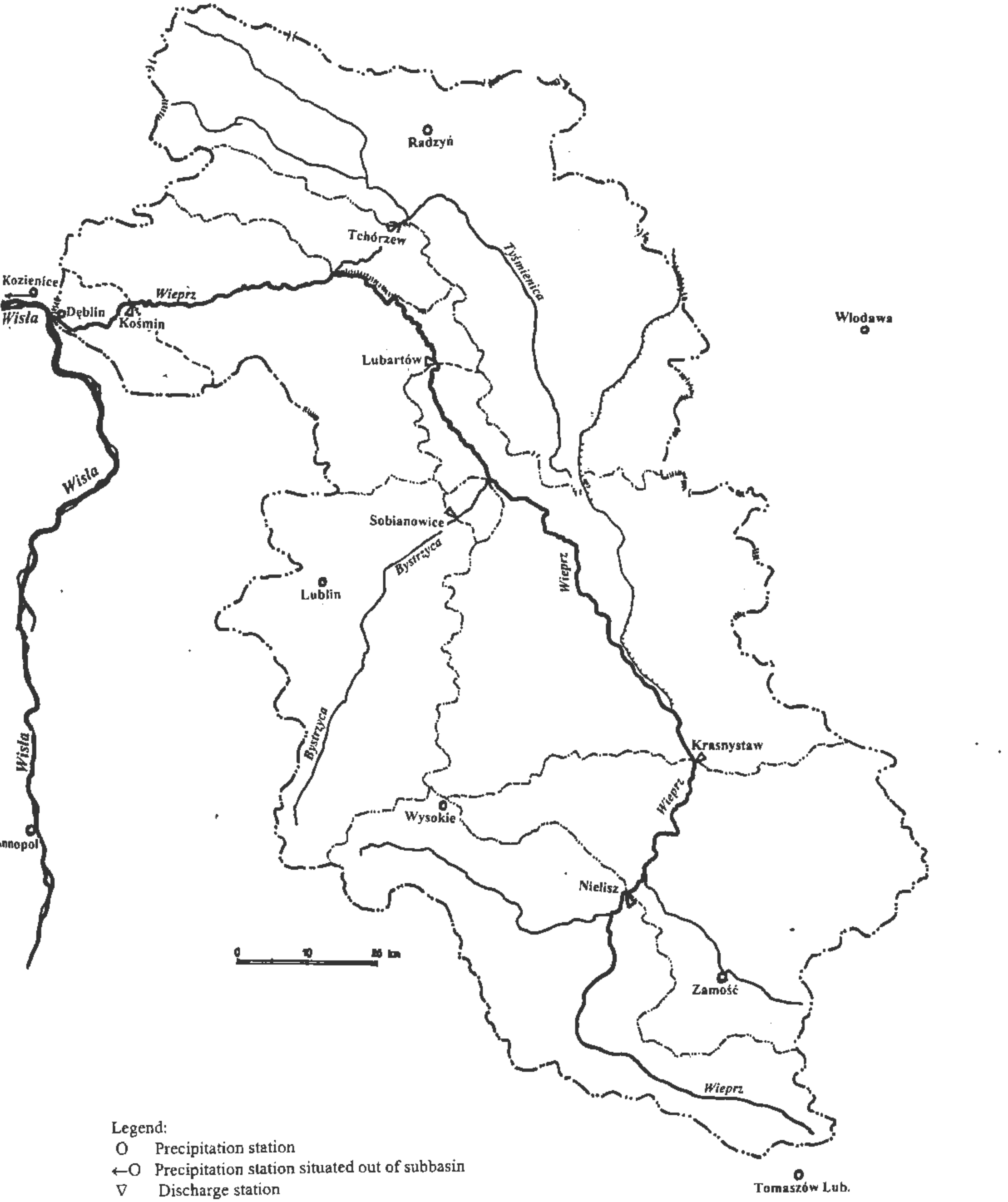


Figure 2 Subbasin division of Wieprz district in Vistula river basin.

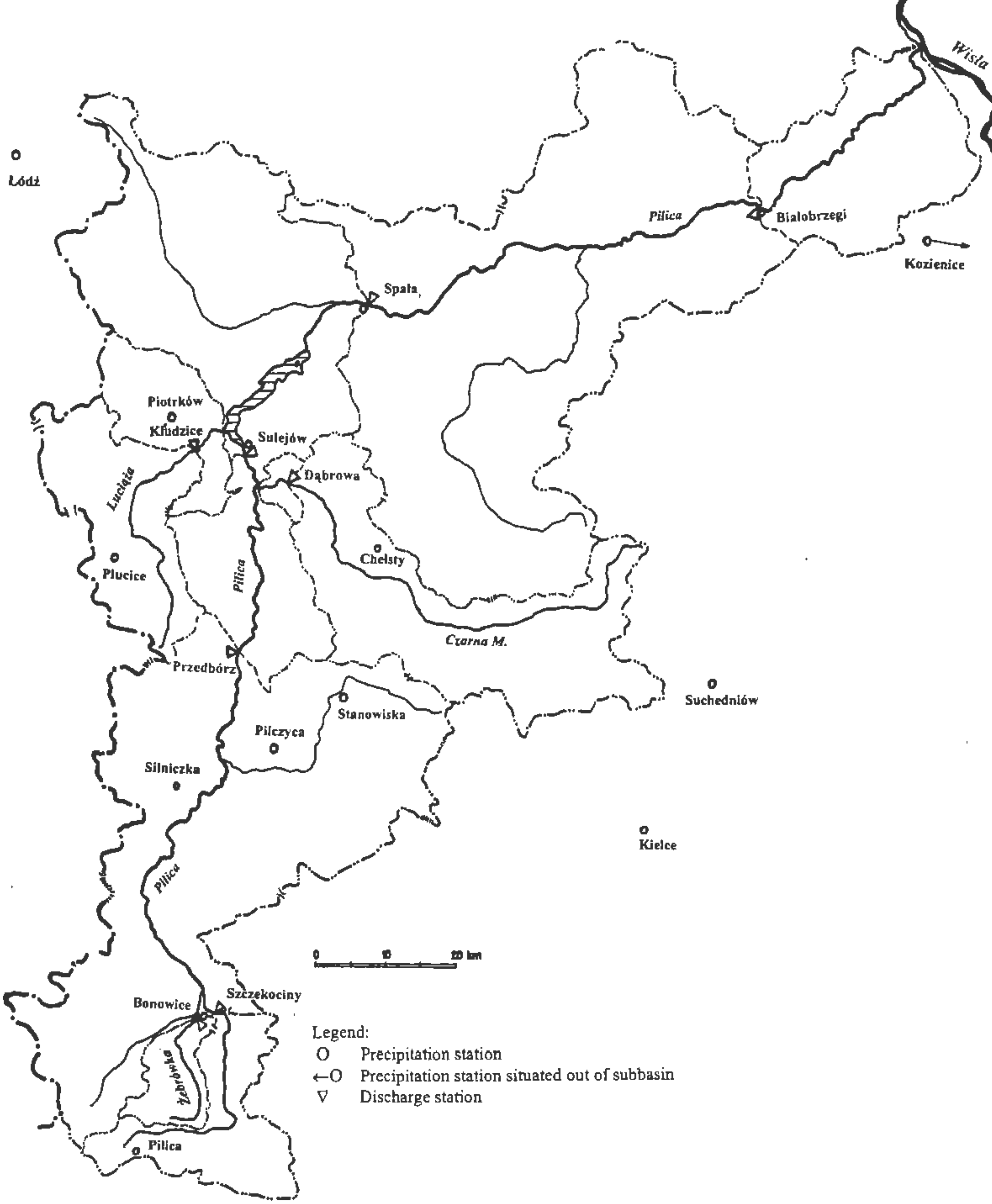


Figure 3 Subbasin division of Pilica district in Vistula river basin.

Legend:
O Precipitation station
←O Precipitation station situated out of subbasin
▽ Discharge station

Figure 4 Subbasin division of Upper Narew district in Vistula river basin.

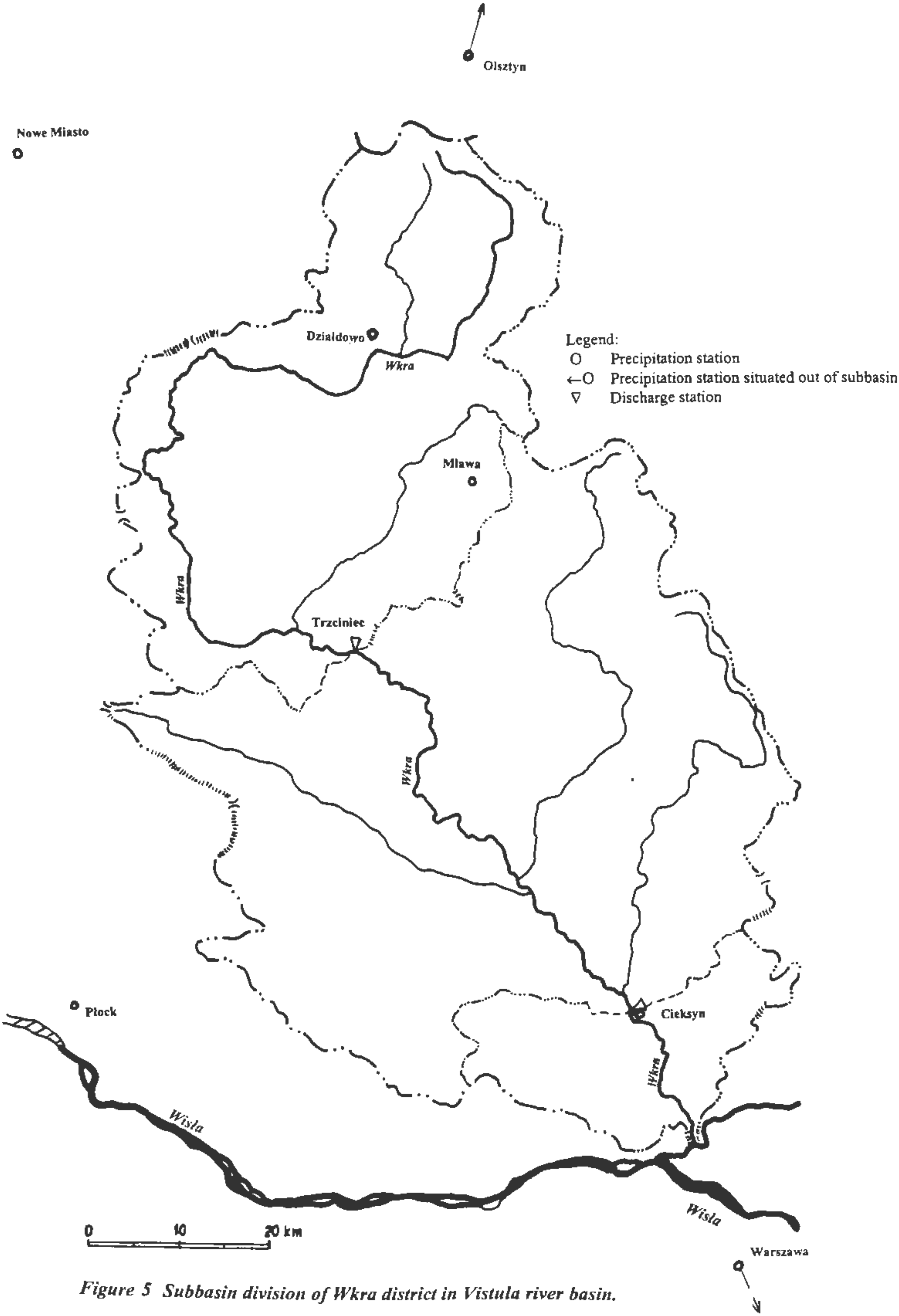


Figure 5 Subbasin division of Wkra district in Vistula river basin.

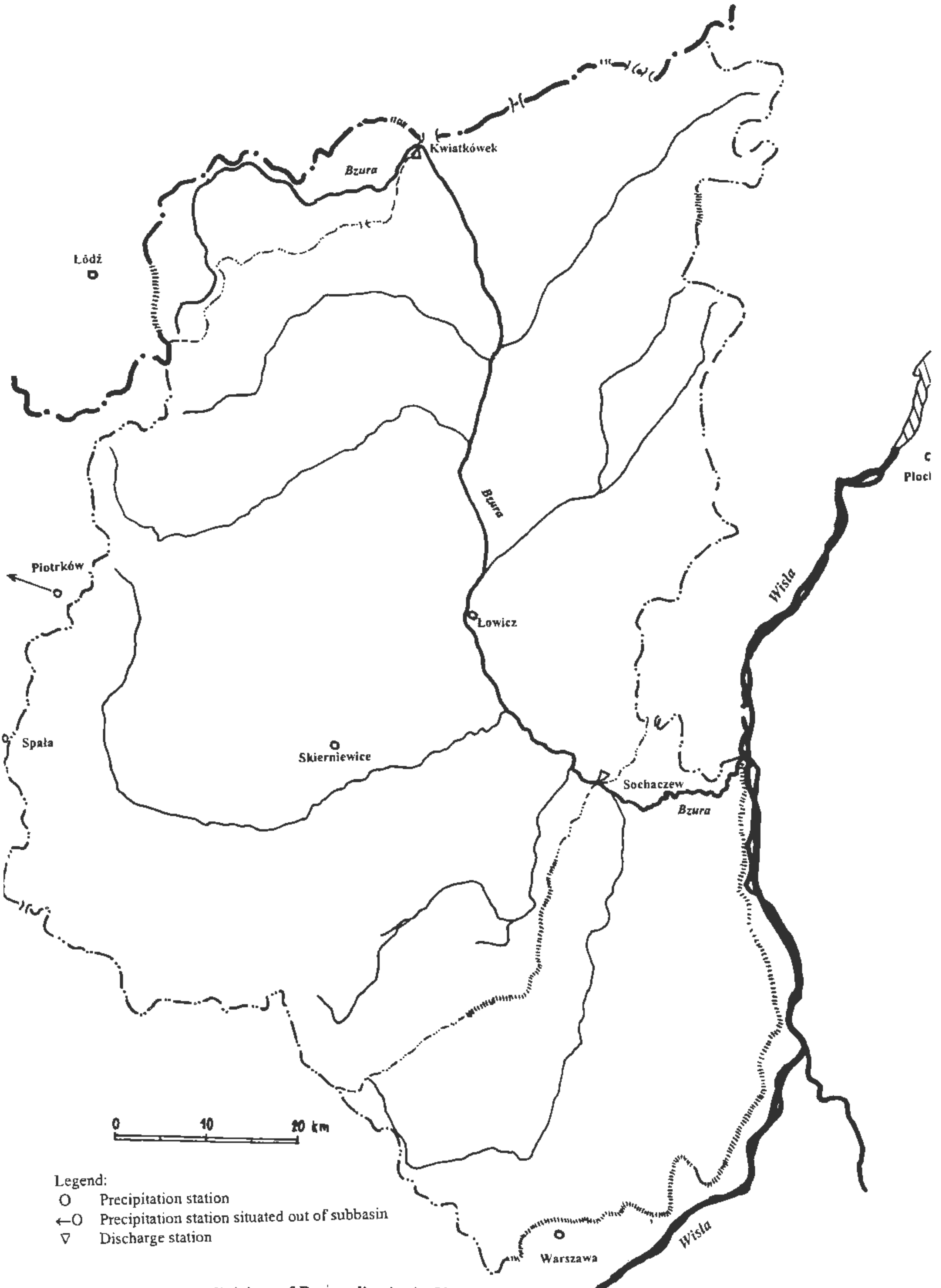


Figure 6 Subbasin division of Bzura district in Vistula river basin.

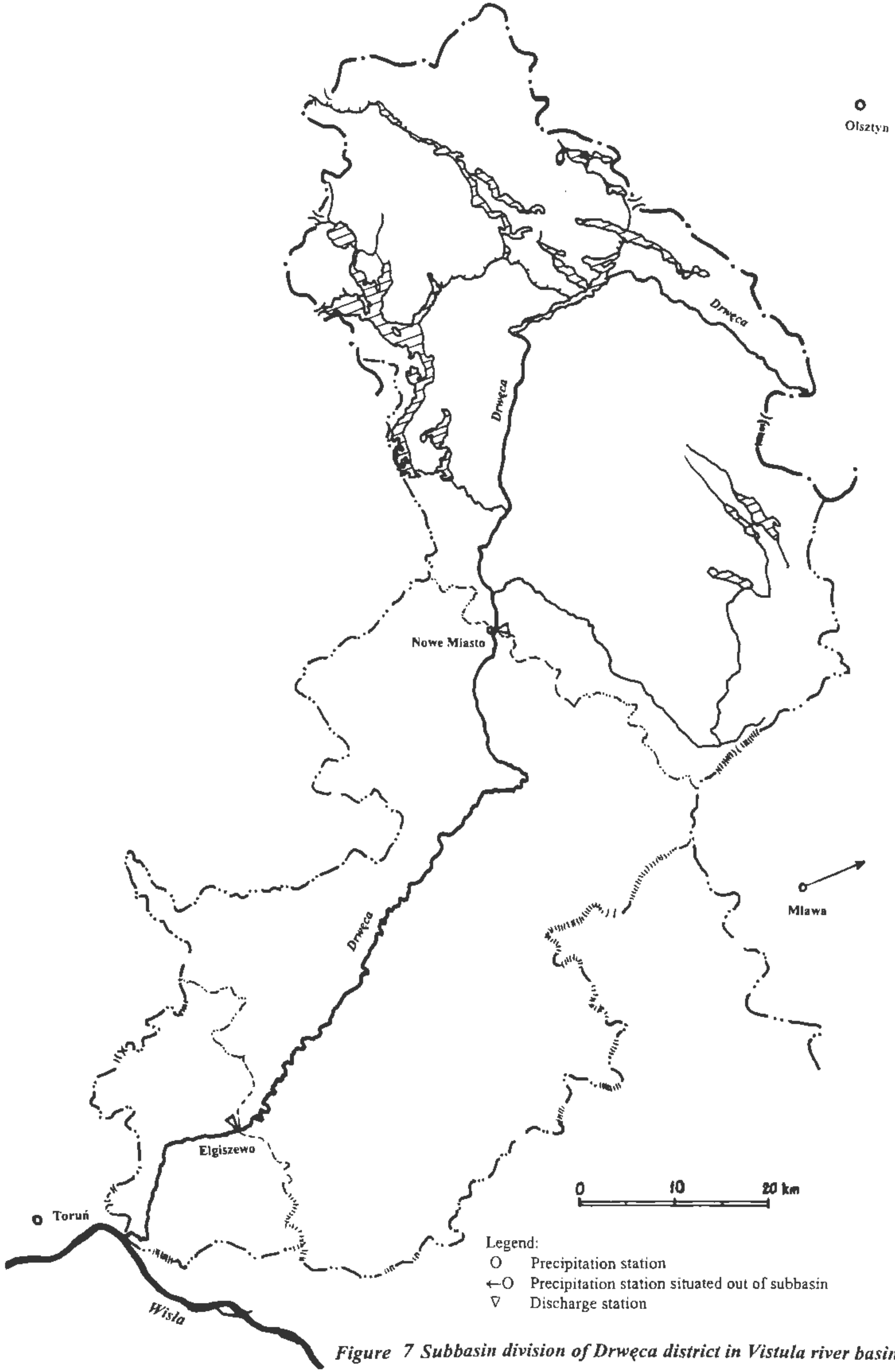


Figure 7 Subbasin division of Drwęca district in Vistula river basin.

Table 1. Subbasin division of Kamienna district in Vistula river basin.

Subbasin (Name)	Total area (km^2)	Forest (%)	Open field (%)
Bzin	276.8	65.3	34.7
Wachock	199.2	61.0	39.0
Michalow	109.6	75.7	24.3
Brody	43.7	53.8	46.2
Nietulisko	405.1	24.0	76.0
Kunow	70.8	53.7	46.3
Czekarzewice	772.8	28.8	71.2
Outkamienna	129.9	31.5	68.5

Table 2. Subbasin division of Wieprz district in Vistula river basin.

Subbasin (Name)	Total area (km^2)	Forest (%)	Open field (%)
Nielisz	1349.0	34.0	66.0
Krasnystaw	1652.0	18.9	81.1
Sobianowice	1264.9	11.8	88.2
Lubartow	2099.6	16.9	83.1
Tchorzew	2339.0	22.5	77.5
Kosmin	1526.1	27.5	72.5
Outwieprz	184.6	47.9	52.1

Table 3 Subbasin division of Radomka district in Vistula river basin.

Subbasin (Name)	Total area (km^2)	Forest (%)	Open field (%)
Rogozek	2060.4	27.5	72.5
Outradomka	49.1	59.5	40.5

Table 4. Subbasin division of Pilica district in Vistula river basin.

Subbasin (Name)	Total area (km^2)	Forest (%)	Open field (%)
Bonowice	129.2	27.6	72.4
Szczekociny	352.8	16.7	83.3
Przedborz	2053.9	41.5	58.5
Dabrowa	941.3	51.8	48.2
Sulejow	441.6	48.6	51.4
Kludzice	505.7	23.5	76.5
Zapora	501.3	40.1	59.9
Spala	1029.4	26.8	73.2
Bialobrzegi	2709.0	43.8	56.2
Outpilica	608.8	46.8	53.2

Table 5. Subbasin division of Upper Narev district in Vistula river basin.

Subbasin (Name)	Total area (km^2)	Forest (%)	Open field (%)
Narew	1978.0	62.2	37.8
Suraz	1398.5	23.9	76.1
Fasty	1816.6	54.1	45.9
Strekowa Gora	1987.1	28.2	71.8
Osowiec	4365.1	27.3	72.7
Burzyn	2535.3	28.4	71.6
Wizna	226.3	41.7	58.3

Table 6. Subbasin division of Wkra district in Vistula river basin.

Subbasin (Name)	Total area (km^2)	Forest (%)	Open field (%)
Trzciniec	1928.0	20.9	79.1
Cieksyn	2951.0	18.6	81.4
Outwkra	443.1	16.5	83.5

Table 7. Subbasin division of Bzura district in Vistula river basin.

Subbasin (Name)	Total area (km^2)	Forest (%)	Open field (%)
Kwiatkowek	350.2	32.5	67.5
Sochaczew	5931.2	15.5	84.5
Outbzura	1506.1	27.4	72.6

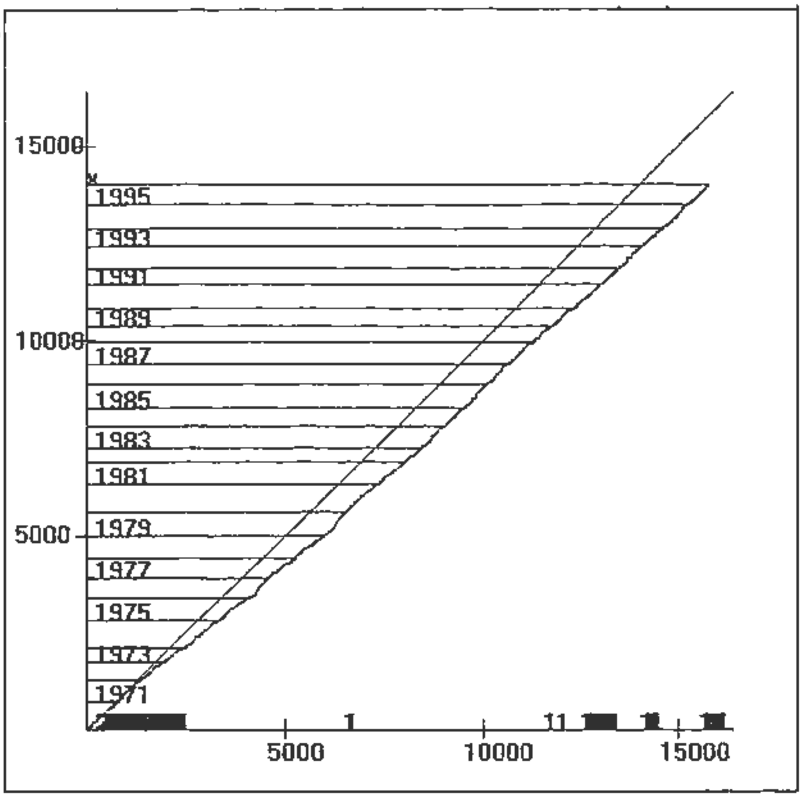
Table 8. Subbasin division of Drweca district in Vistula river basin.

Subbasin (Name)	Total area (km^2)	Forest (%)	Open field (%)
Nowe Miasto	2725.0	31.1	68.9
Elgiszewo	2234.4	22.8	77.2
Outdrweca	384.1	23.2	76.8

Appendix 2

Double mass plots
for precipitation stations

SANDOMIERZ



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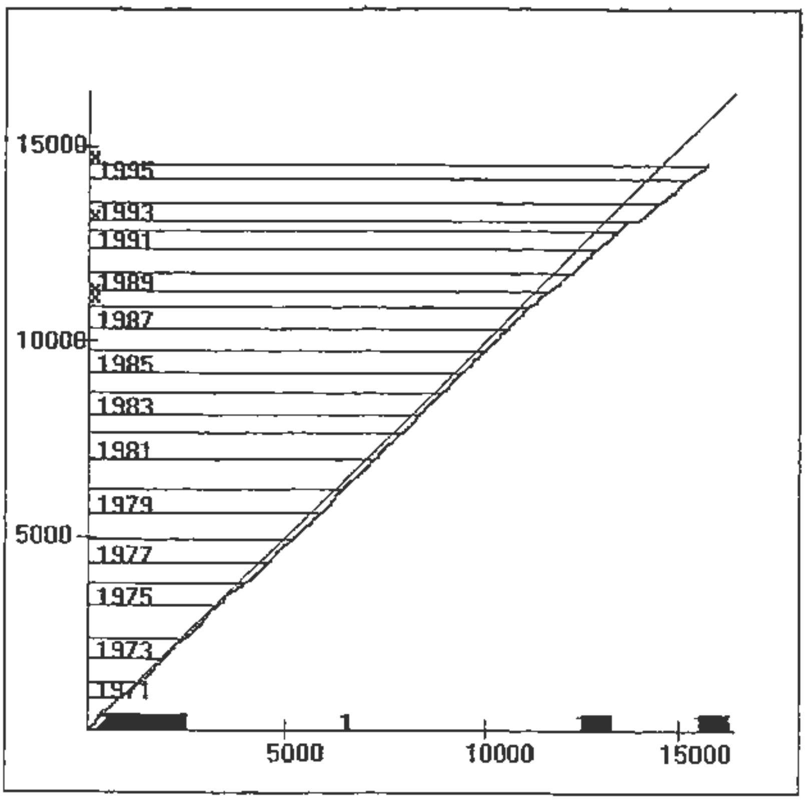

Kamienna district 1970-01-01—1996-05-20

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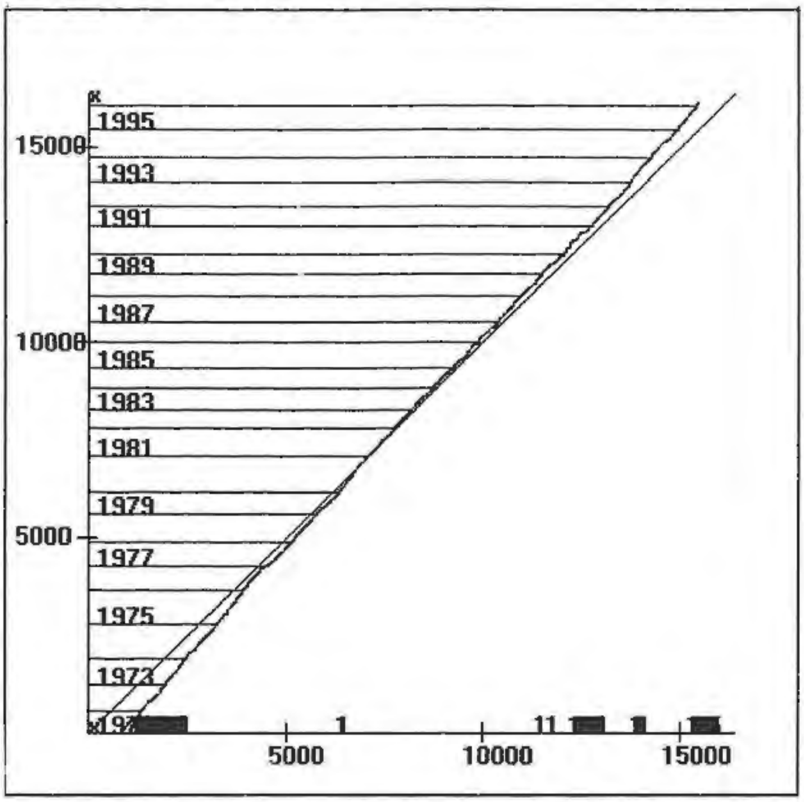

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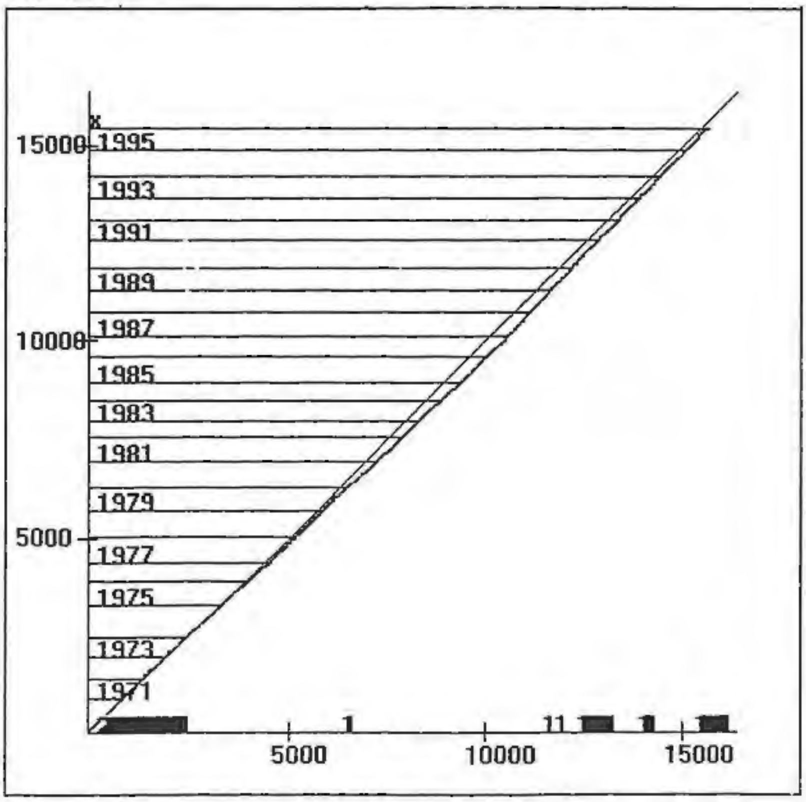
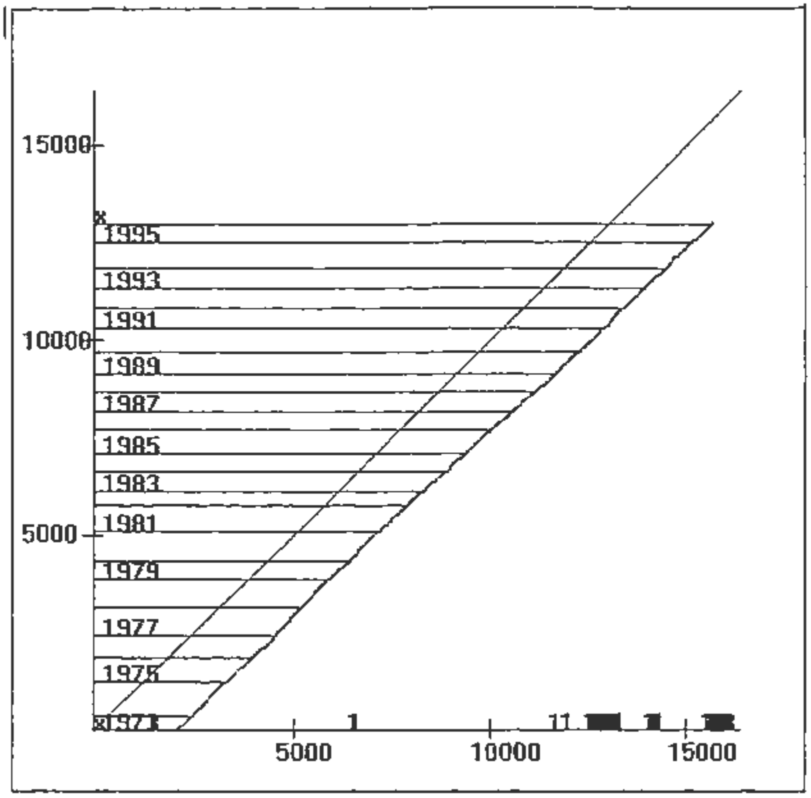


Kamienna district 1970-01-01 – 1996-05-20

WLK.WIES



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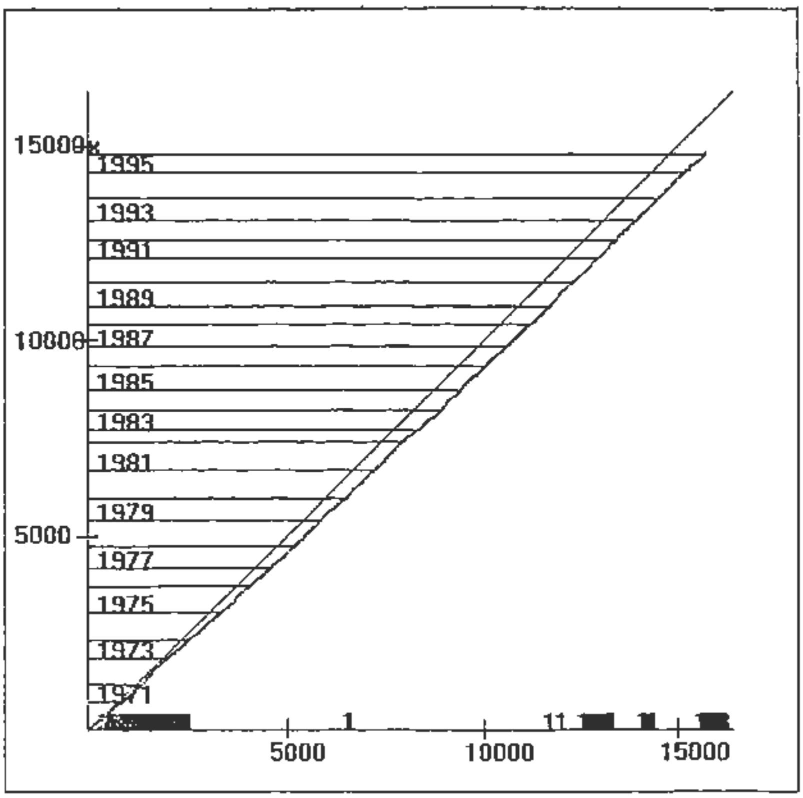

Kamiena district 1970-01-01—1996-05-20

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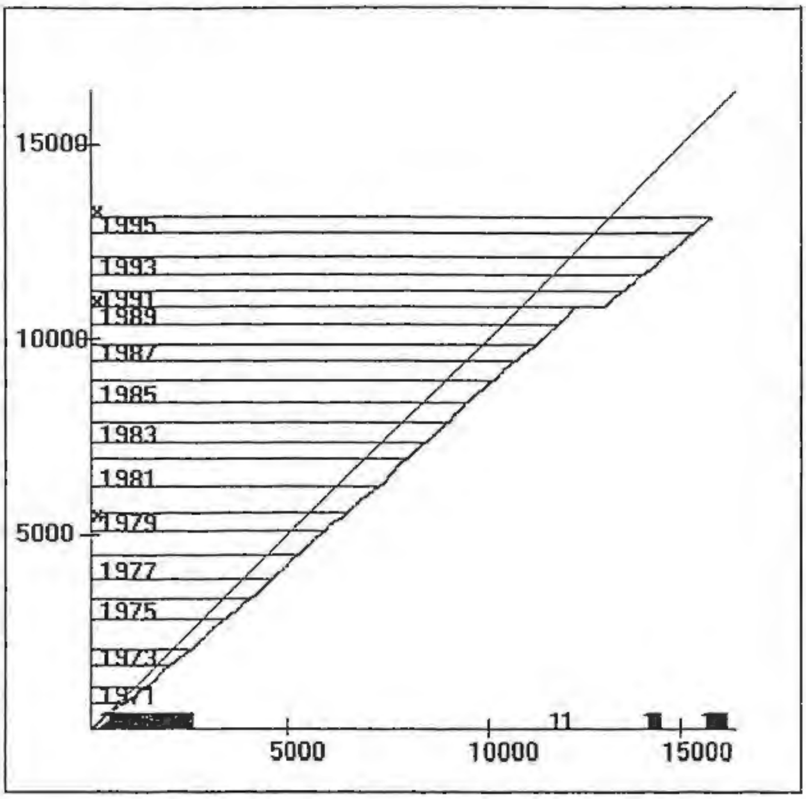

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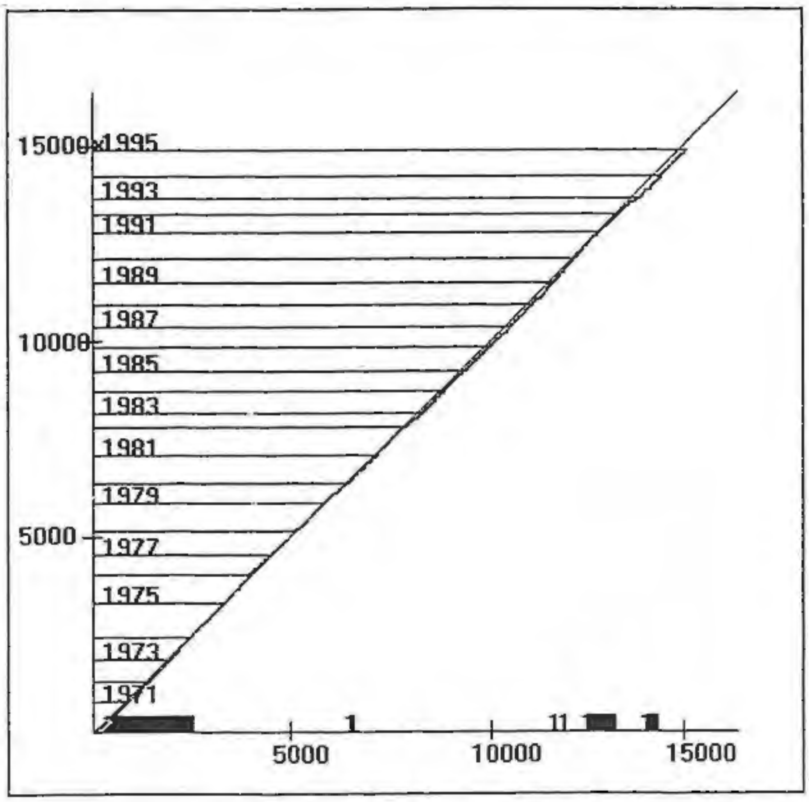

Kamienna district 1970-01-01—1996-05-20

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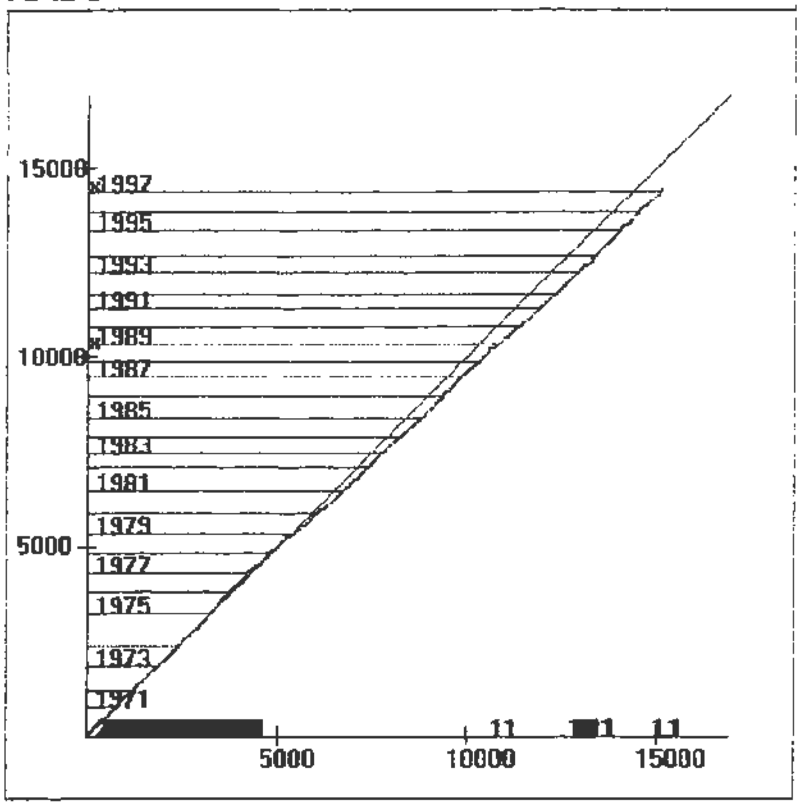

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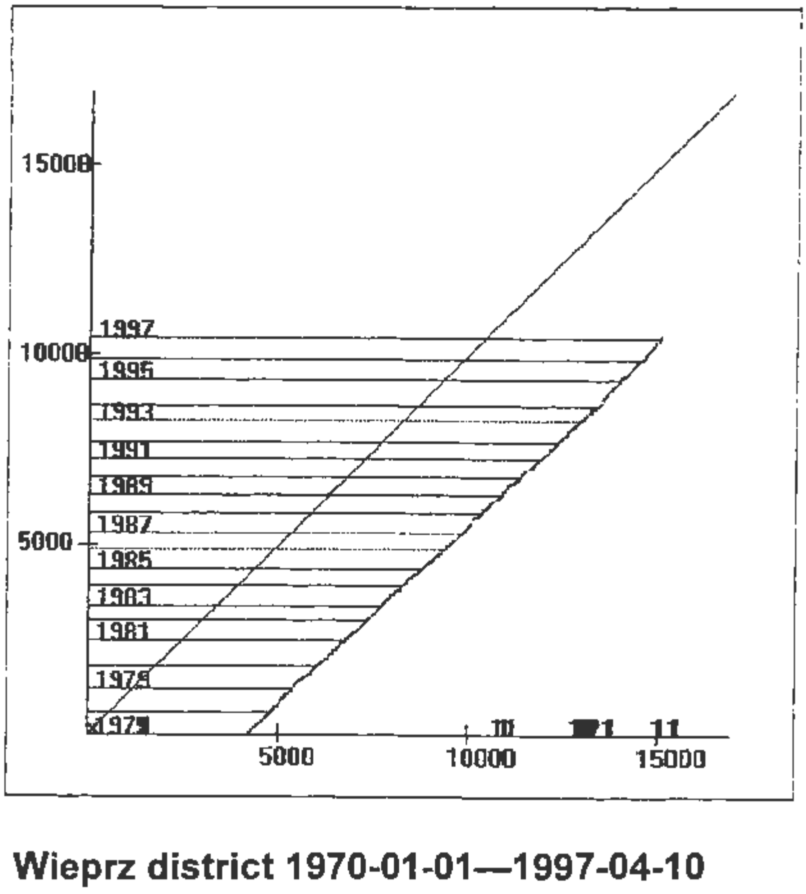

Wieprz district 1970-01-01—1997-04-10

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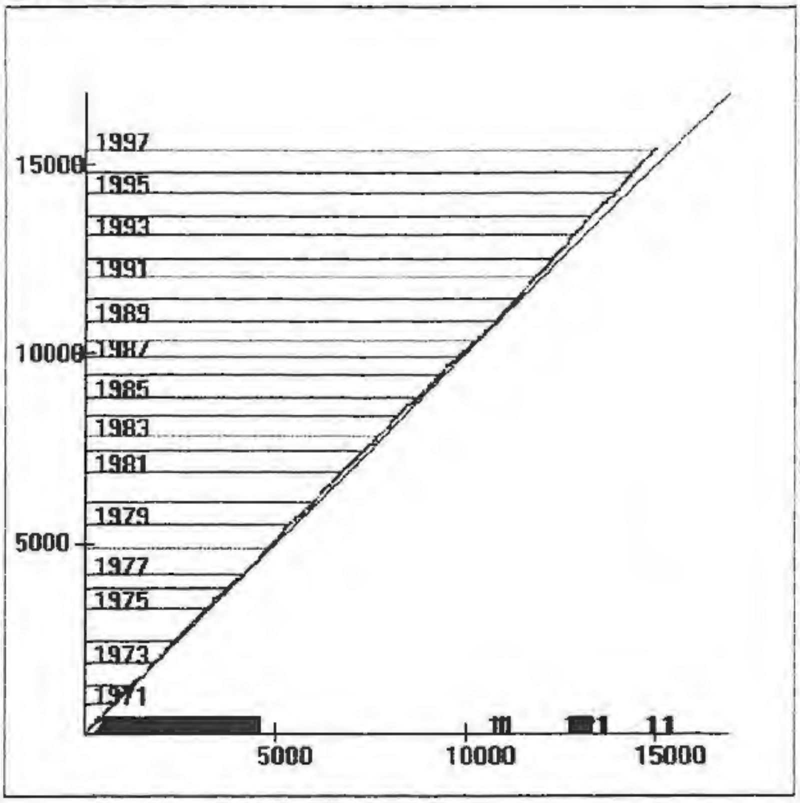

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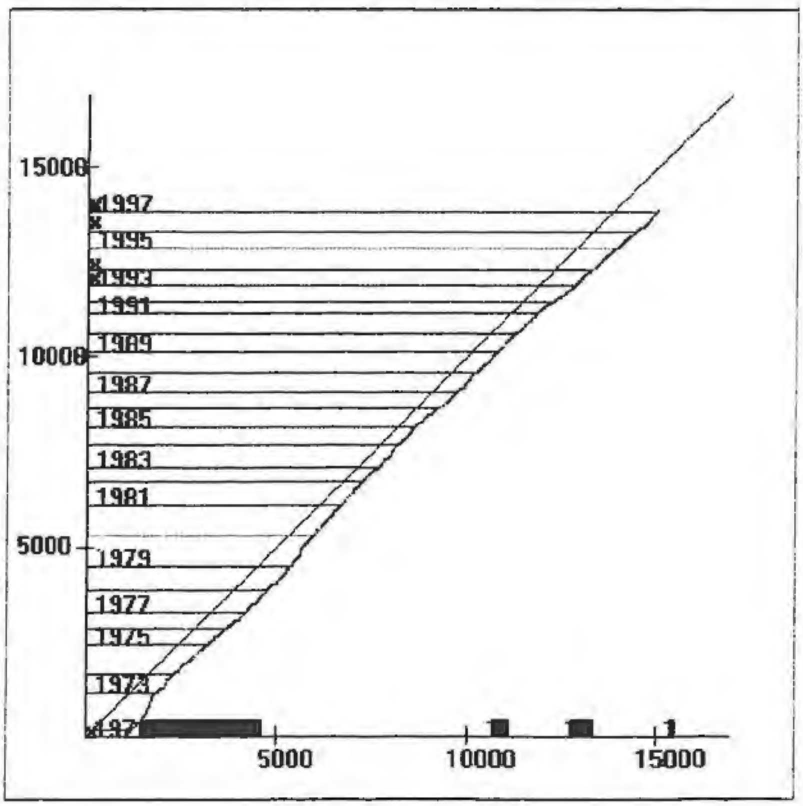

Wieprz district 1970-01-01—1997-04-10

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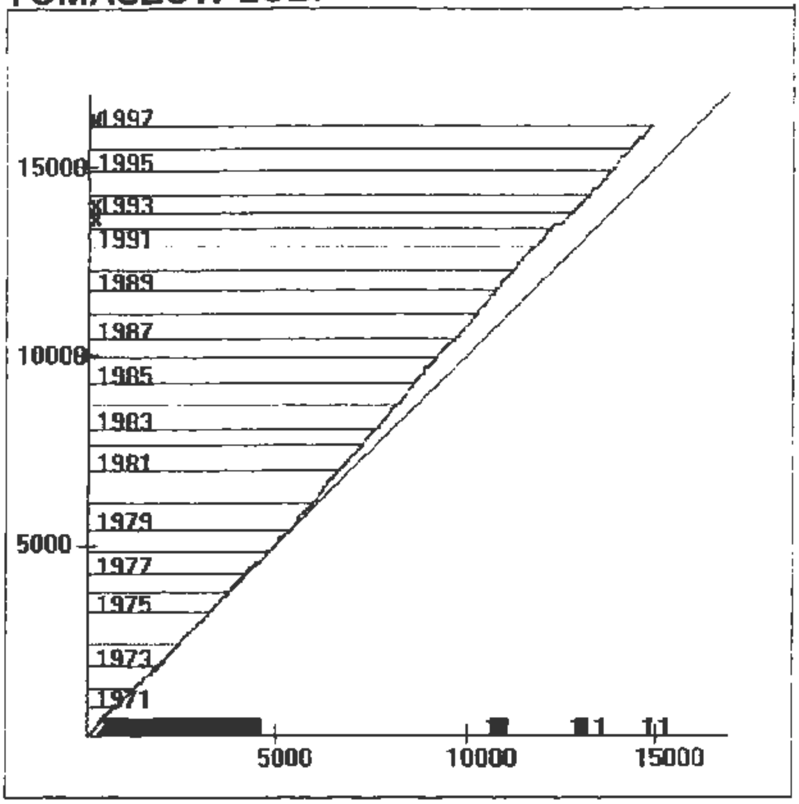

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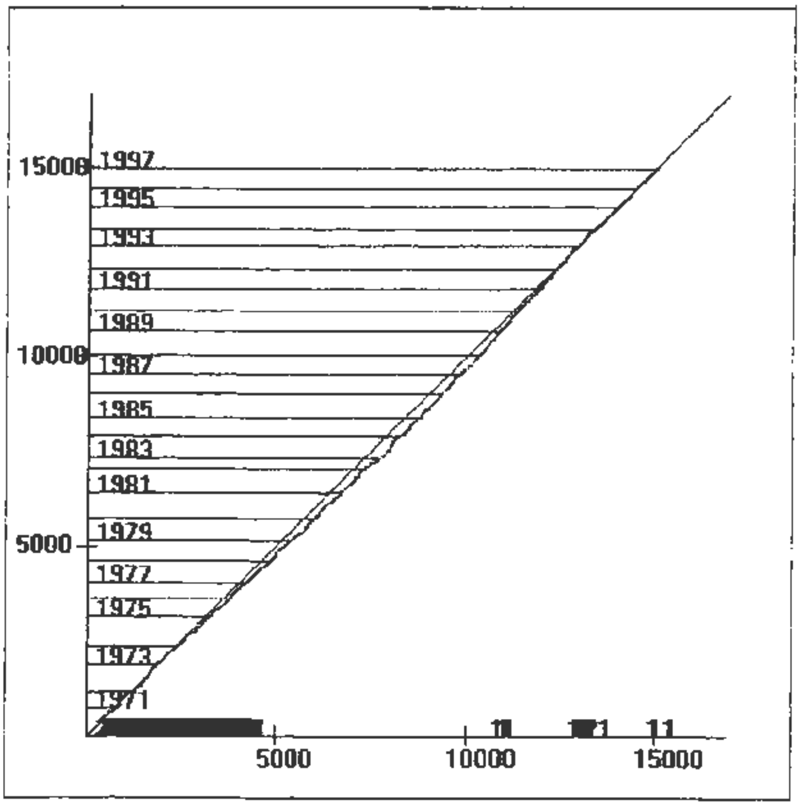

Wieprz district 1970-01-01—1997-04-10

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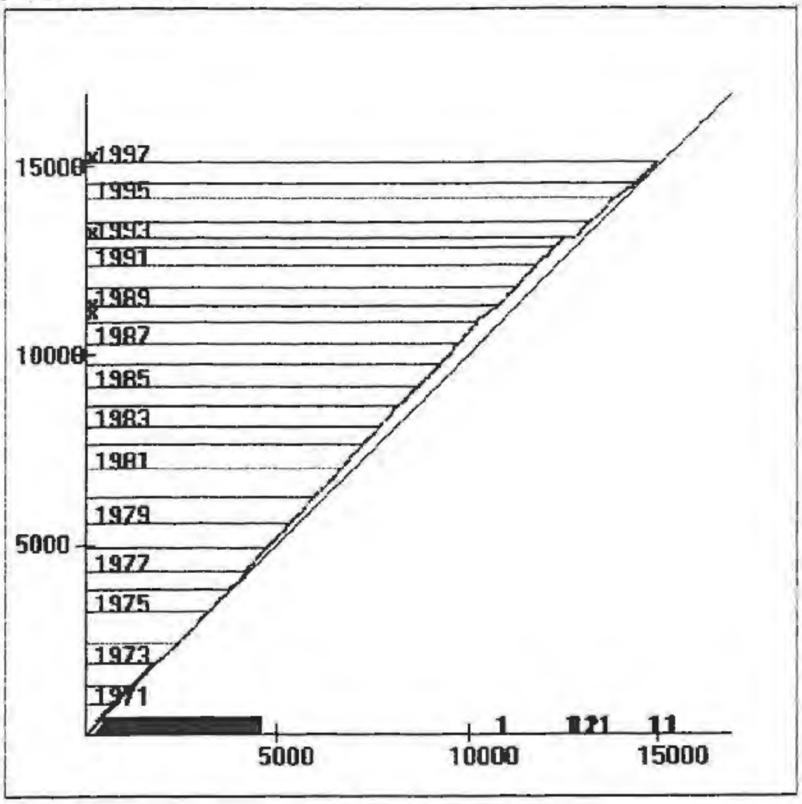

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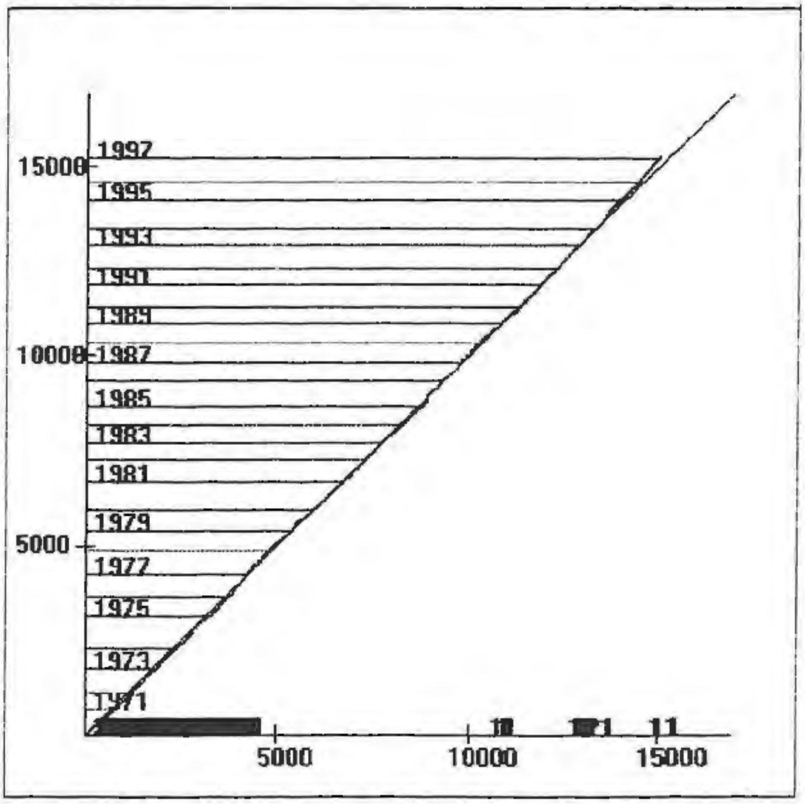

Wieprz district 1970-01-01—1997-04-10

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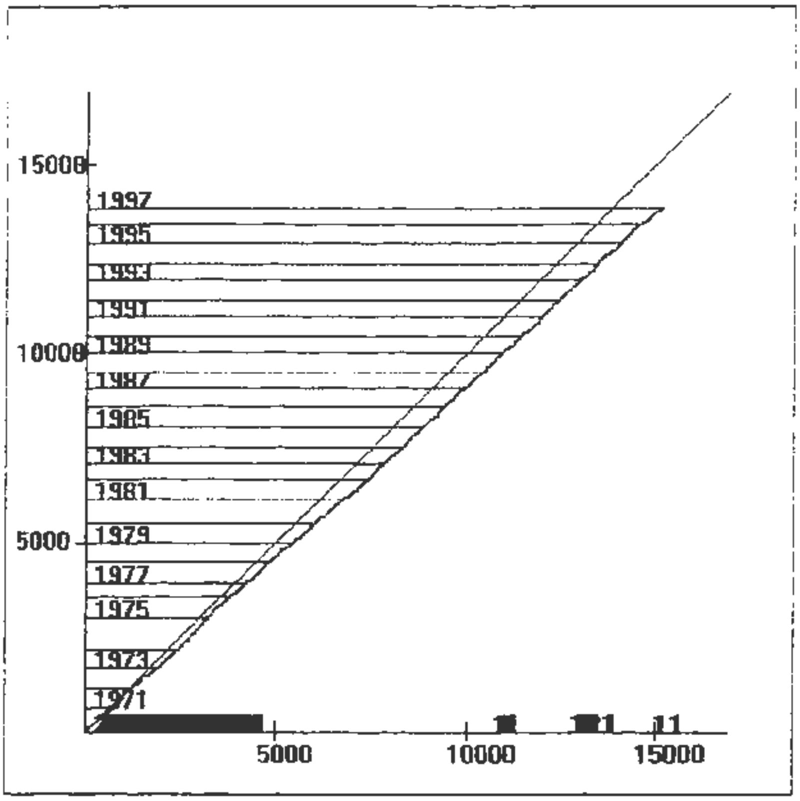

Wieprz district 1970-01-01—1997-04-10

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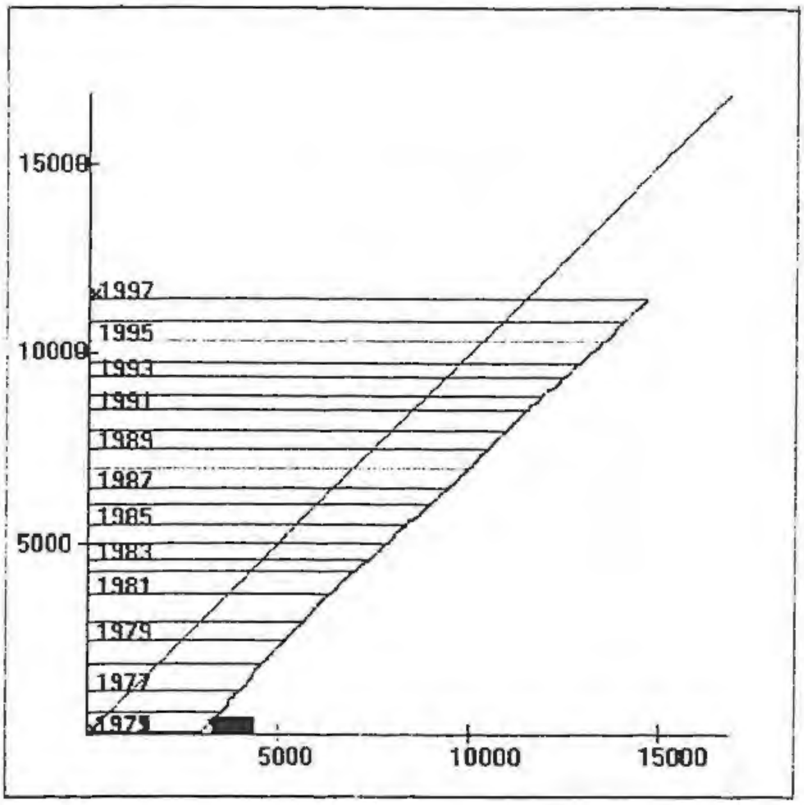

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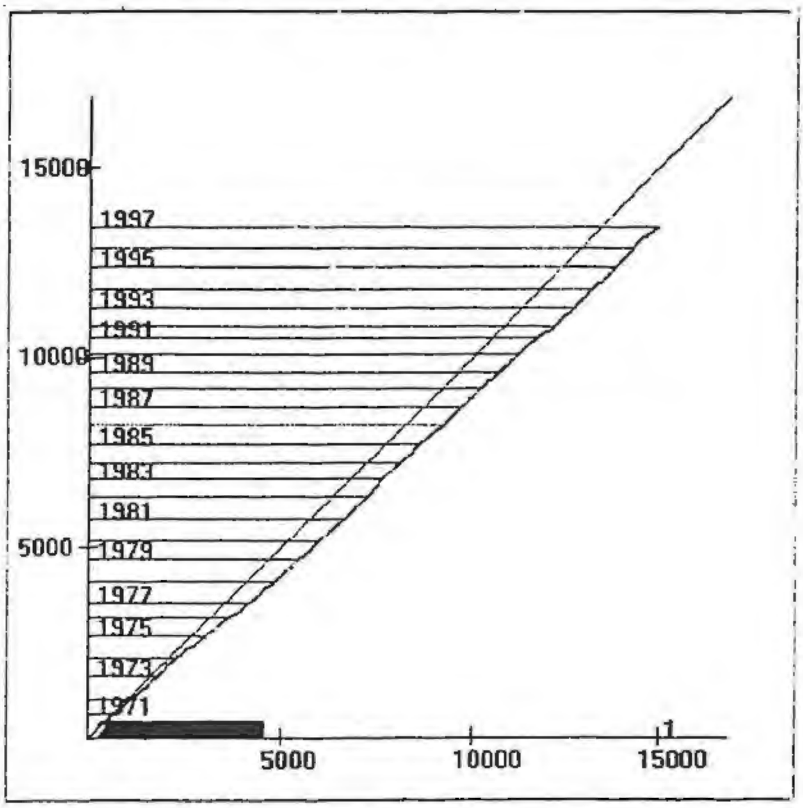

Radomka district 1970-01-01—1997-03-05

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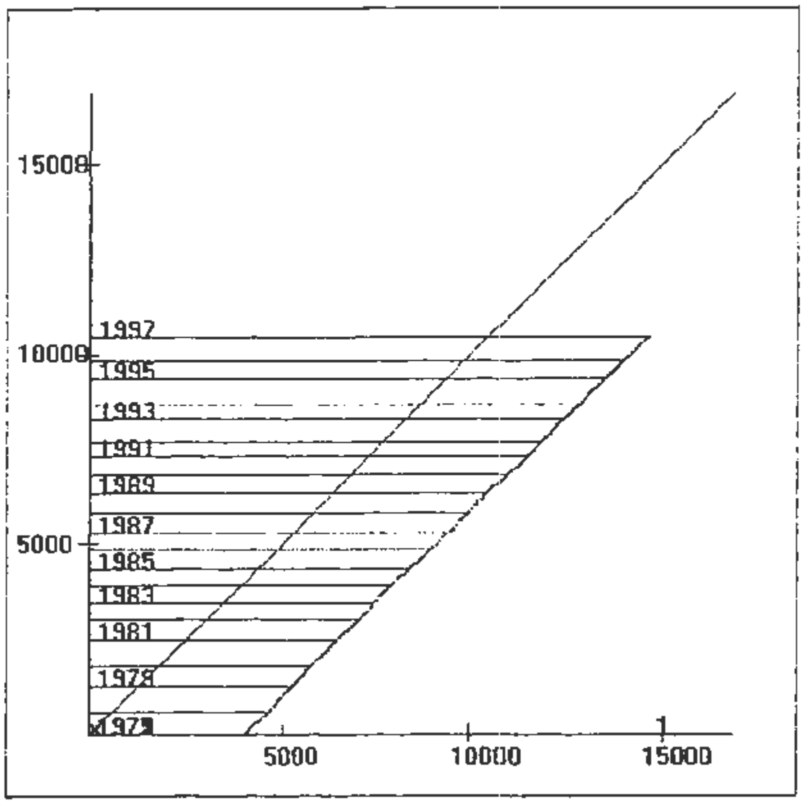

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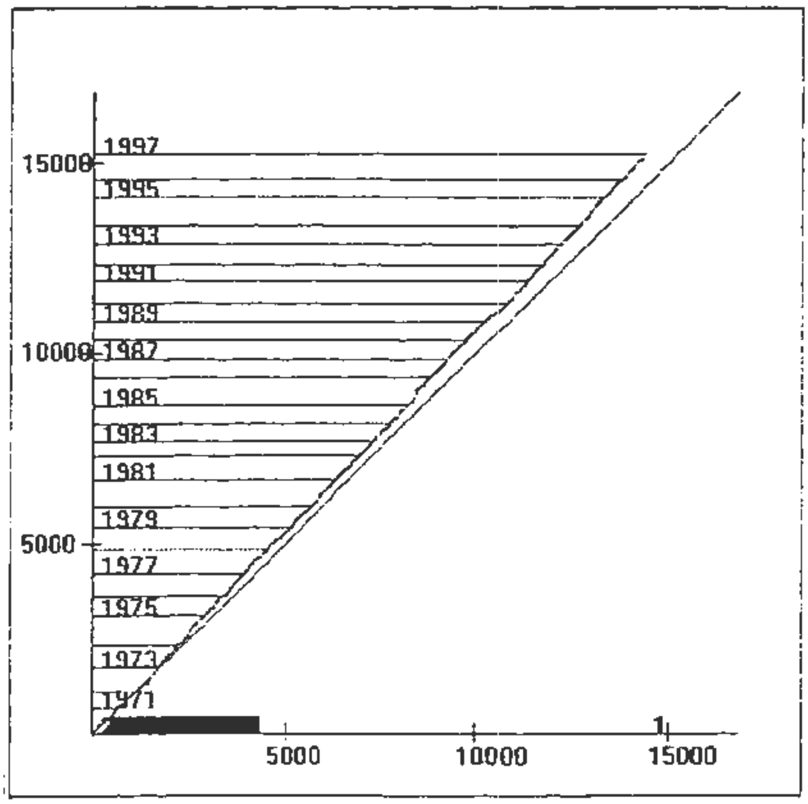

Radomka district 1970-01-01—1997-03-05

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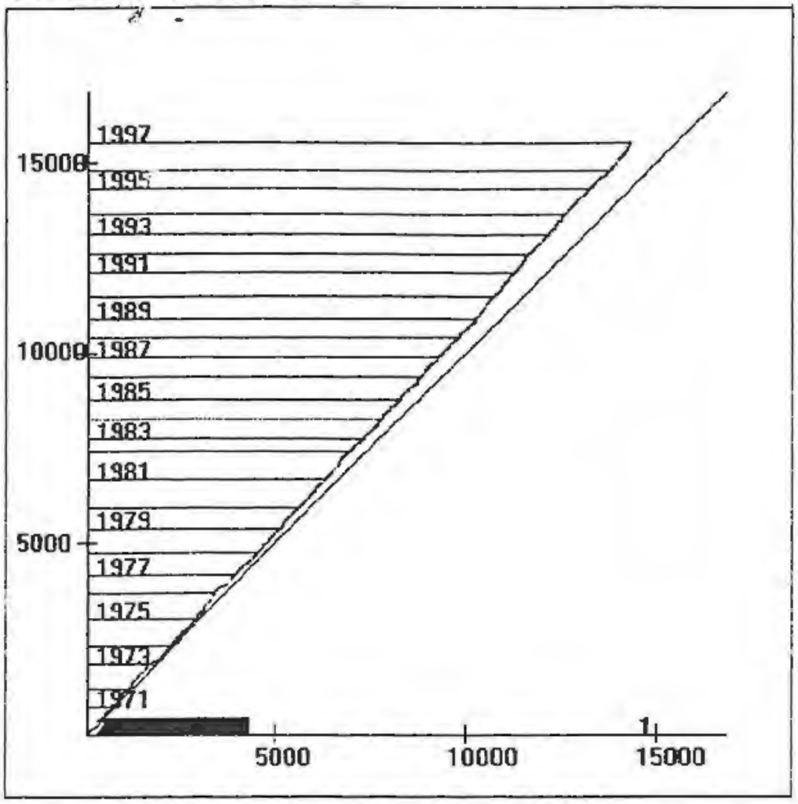

Radomka district 1970-01-01—1997-03-05

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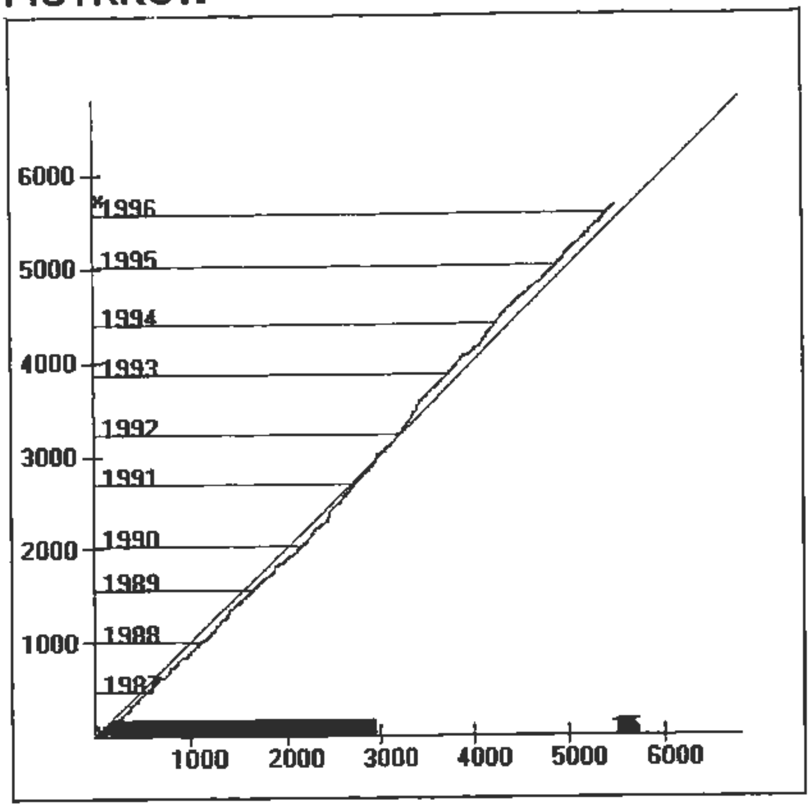

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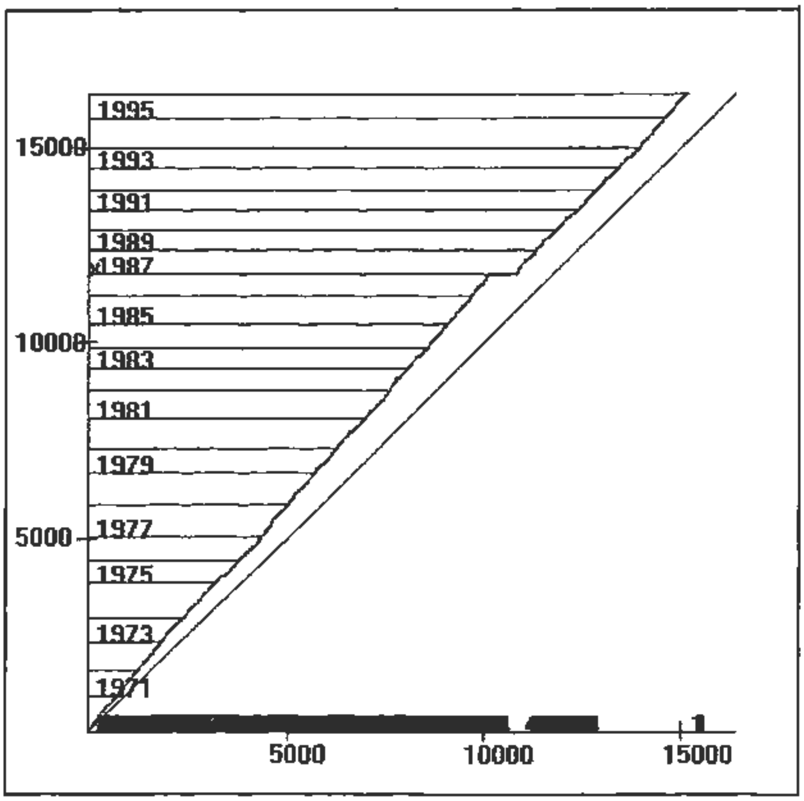

Pilica district 1970-01-01—1996-05-20

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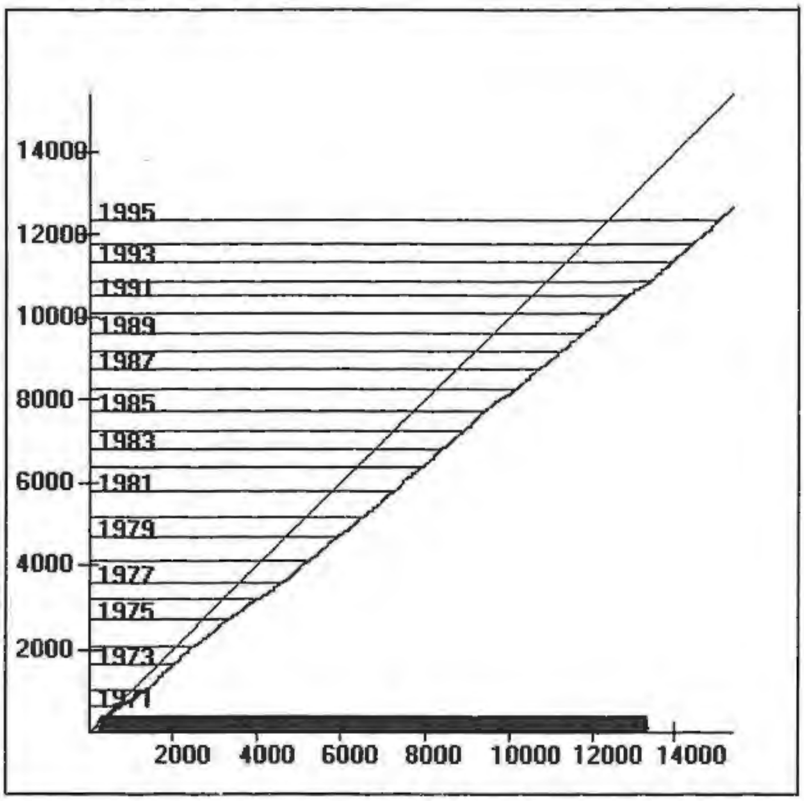

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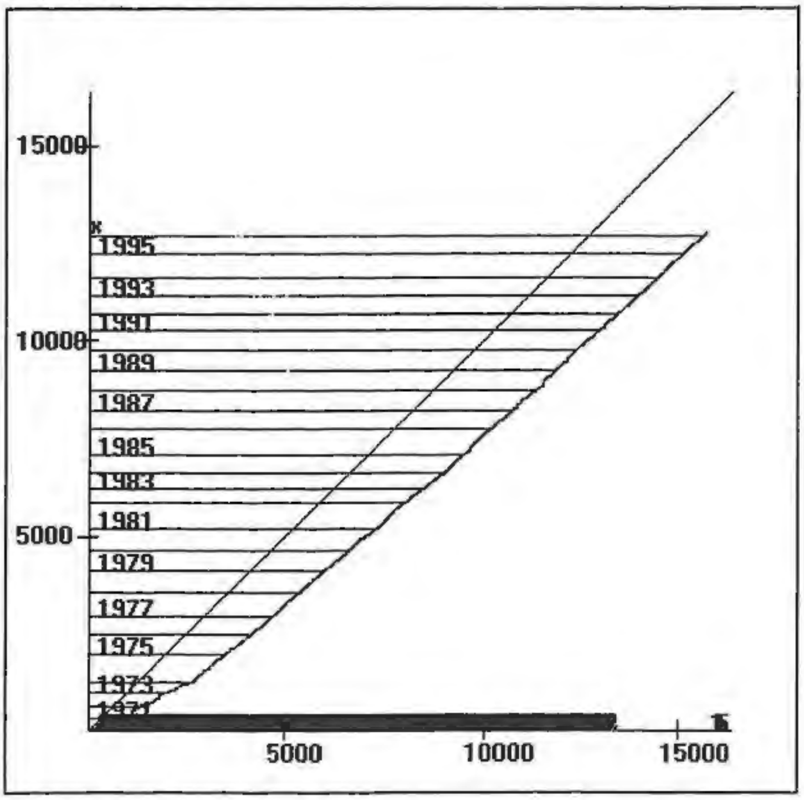

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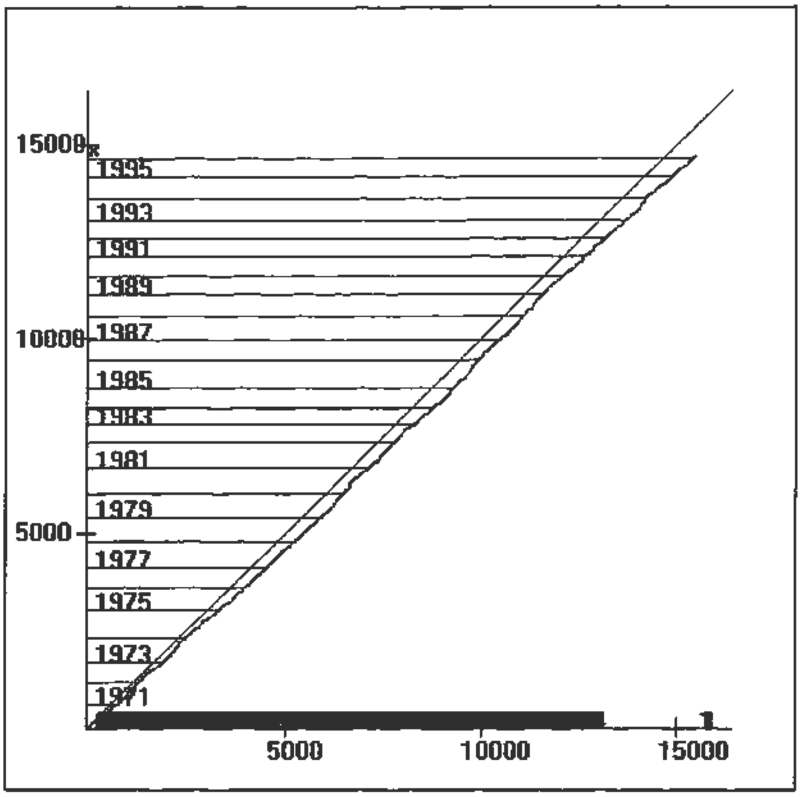

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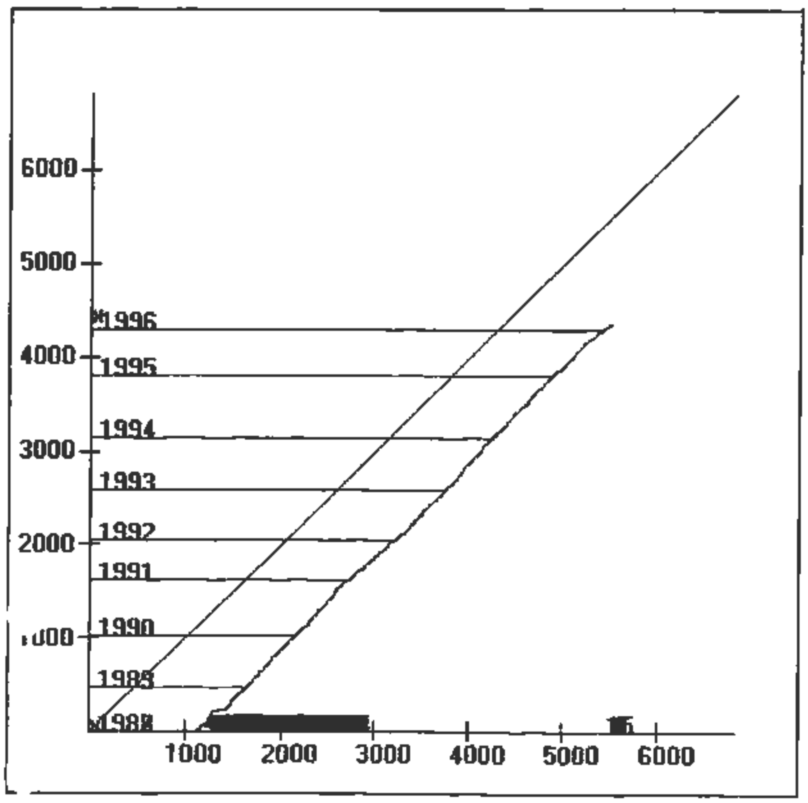

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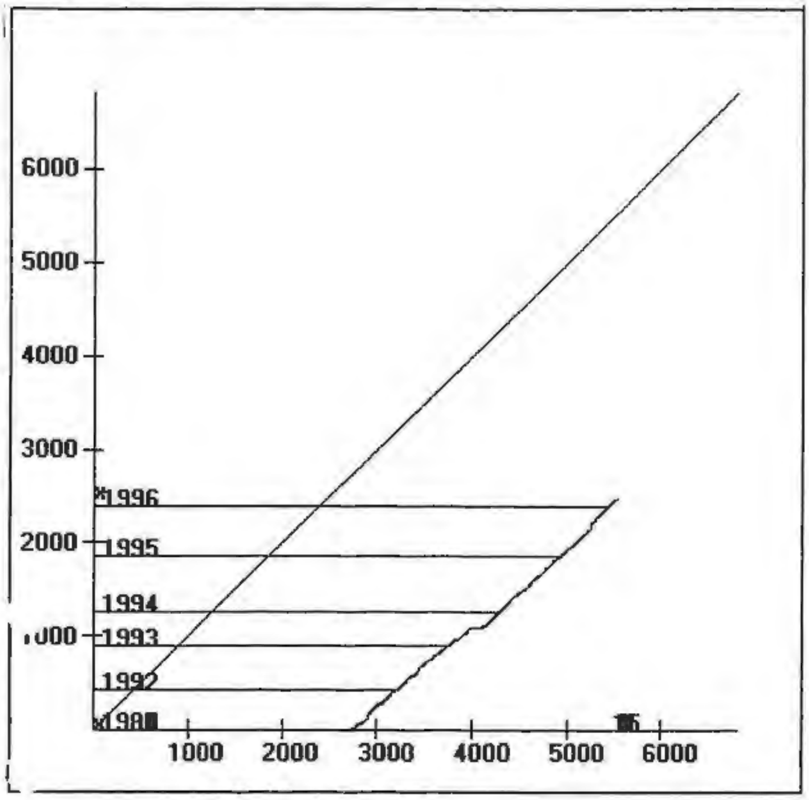

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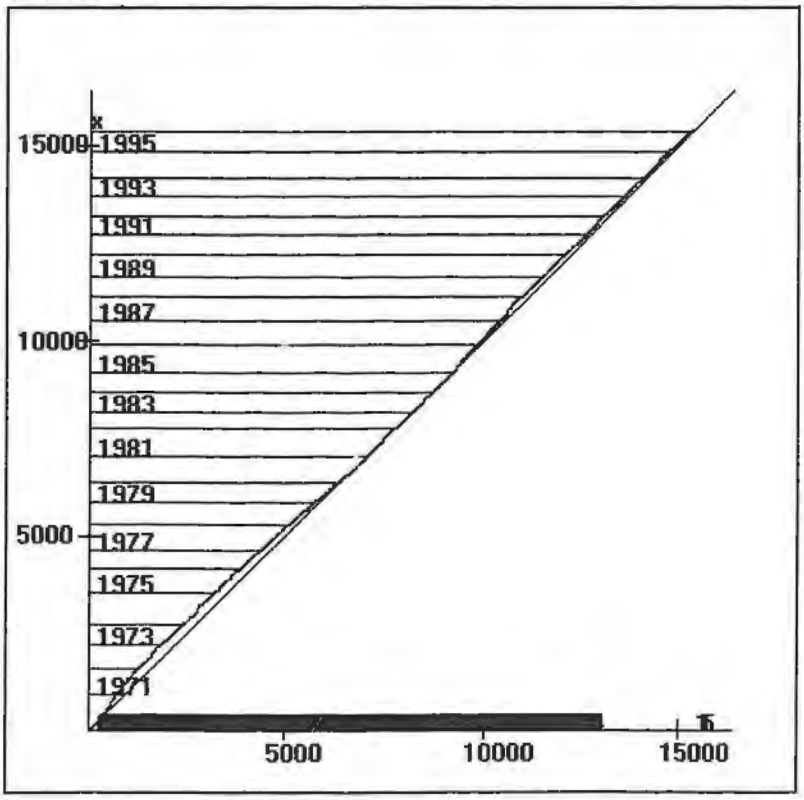

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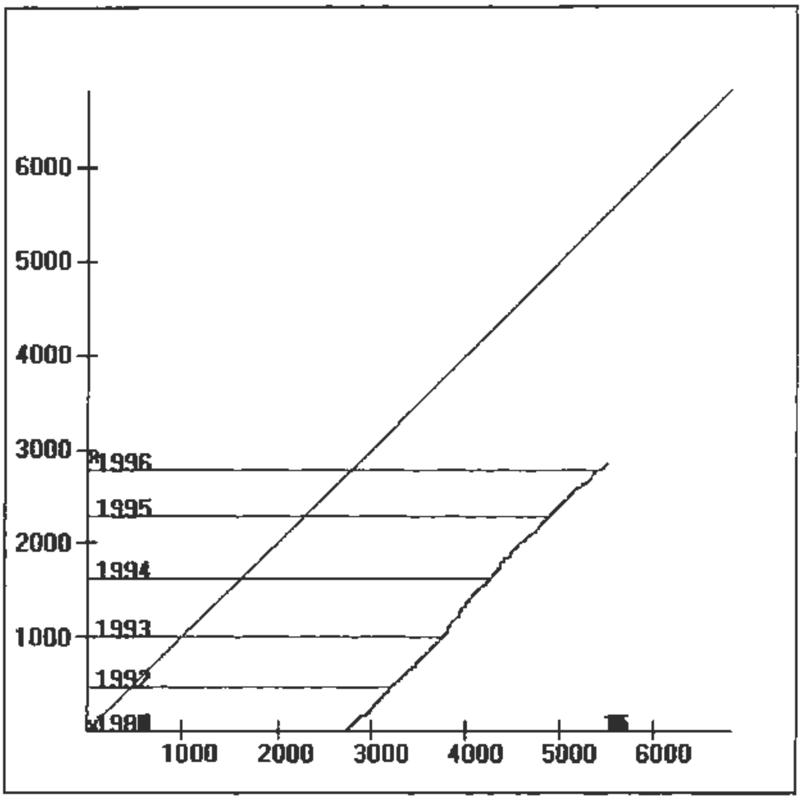

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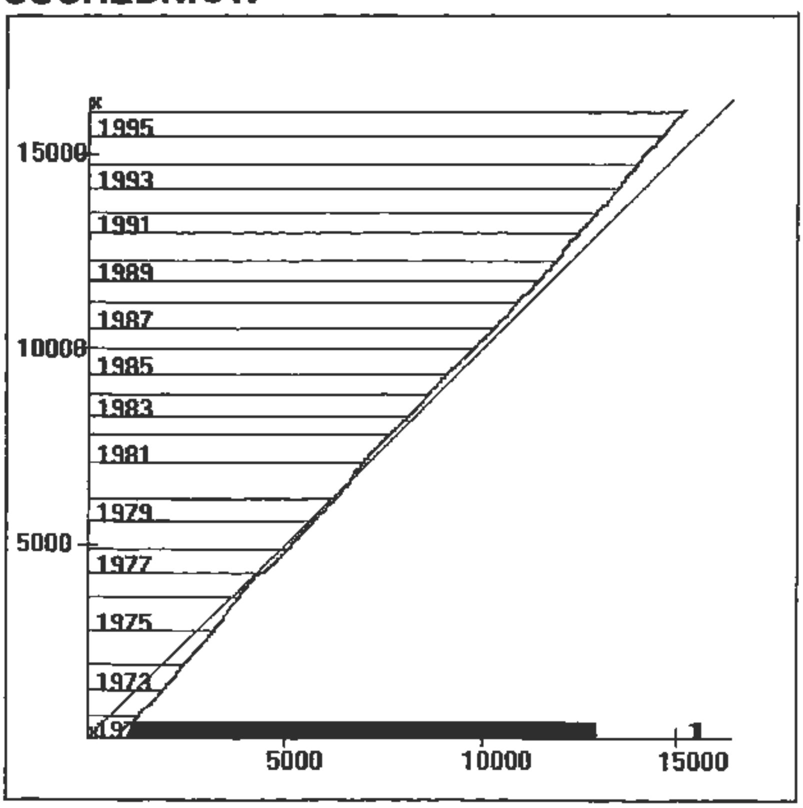

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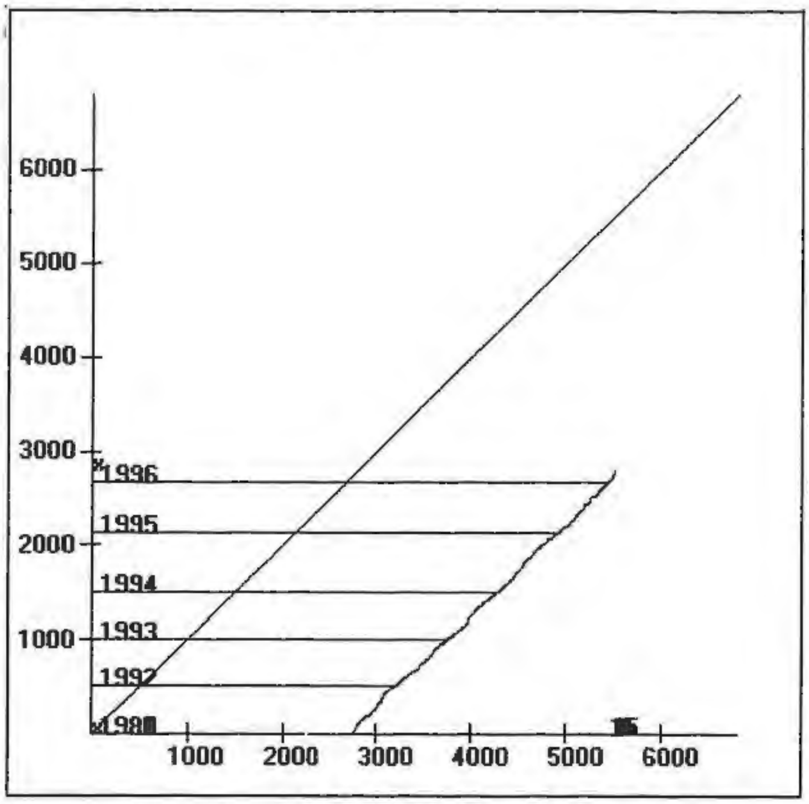

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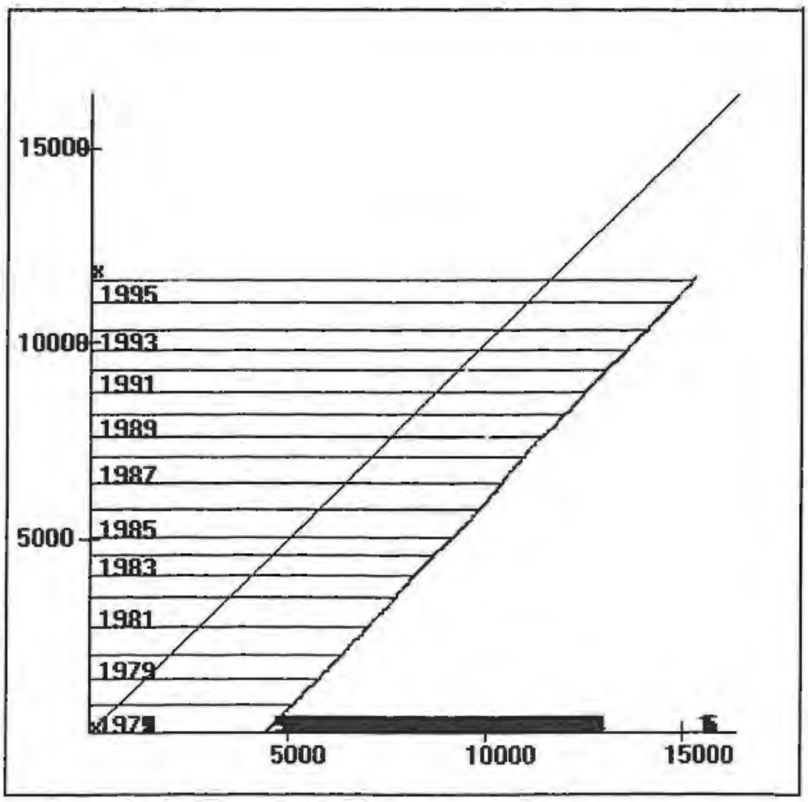

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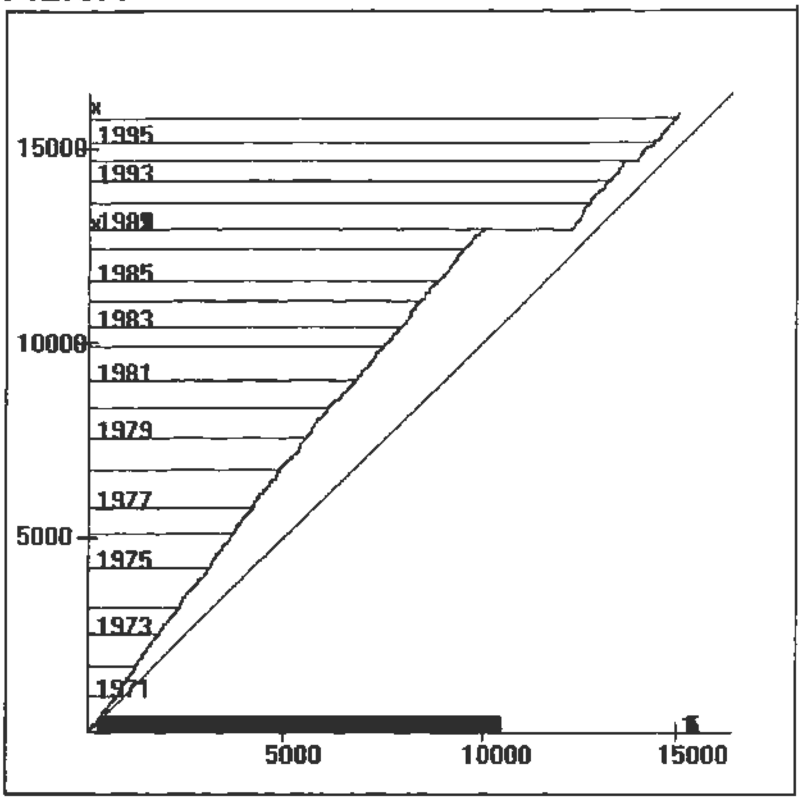

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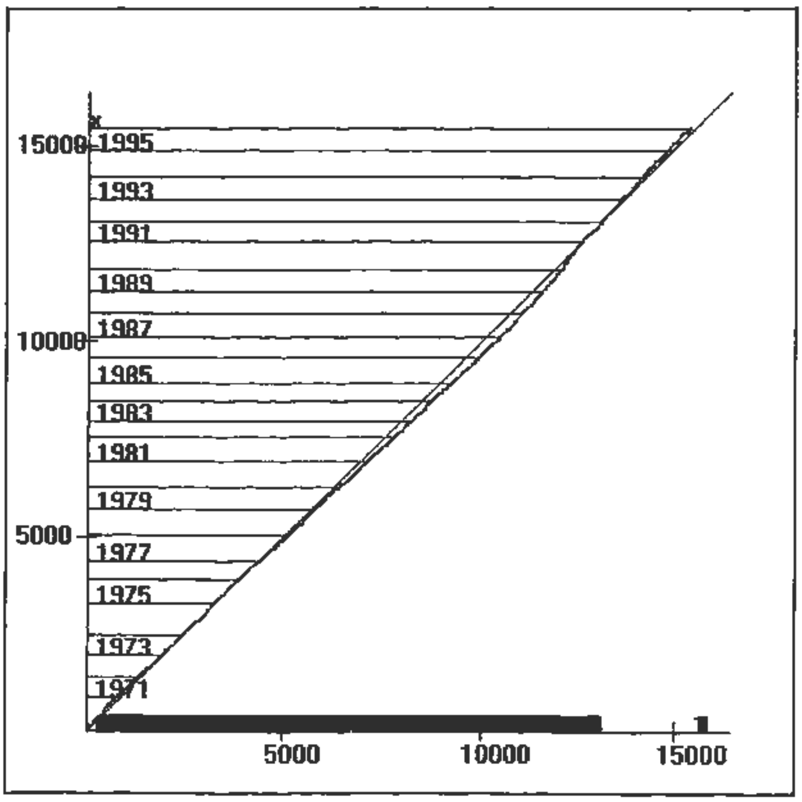

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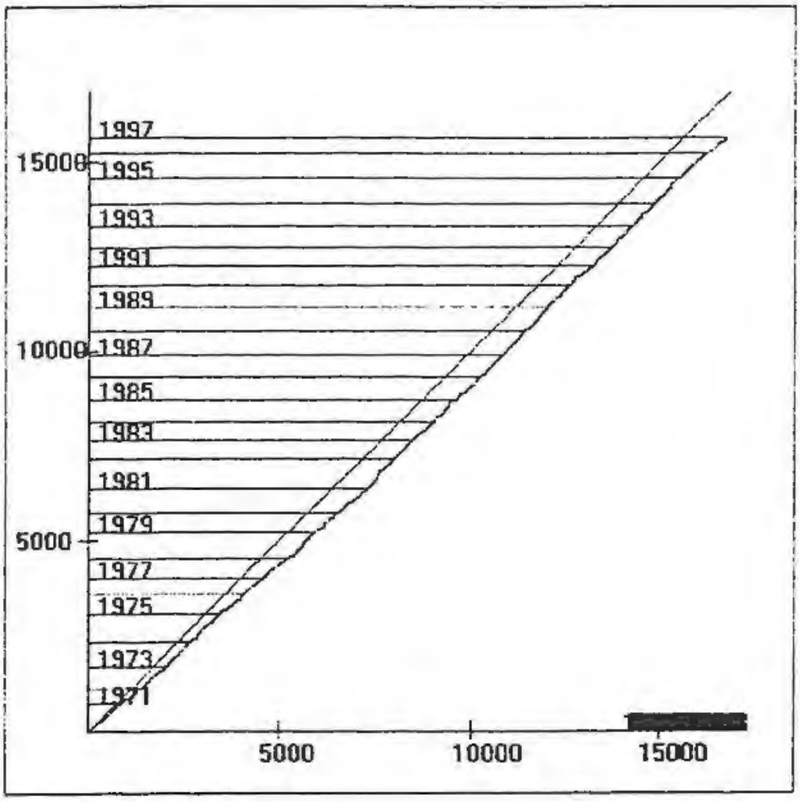

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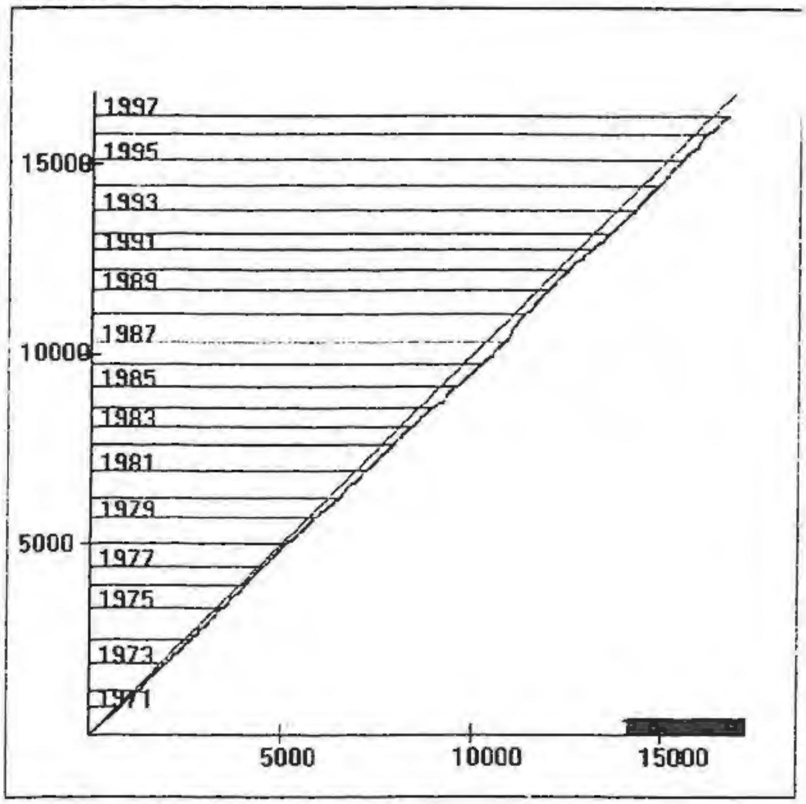

Upper Narew district 1970-01-01—1997-03-05

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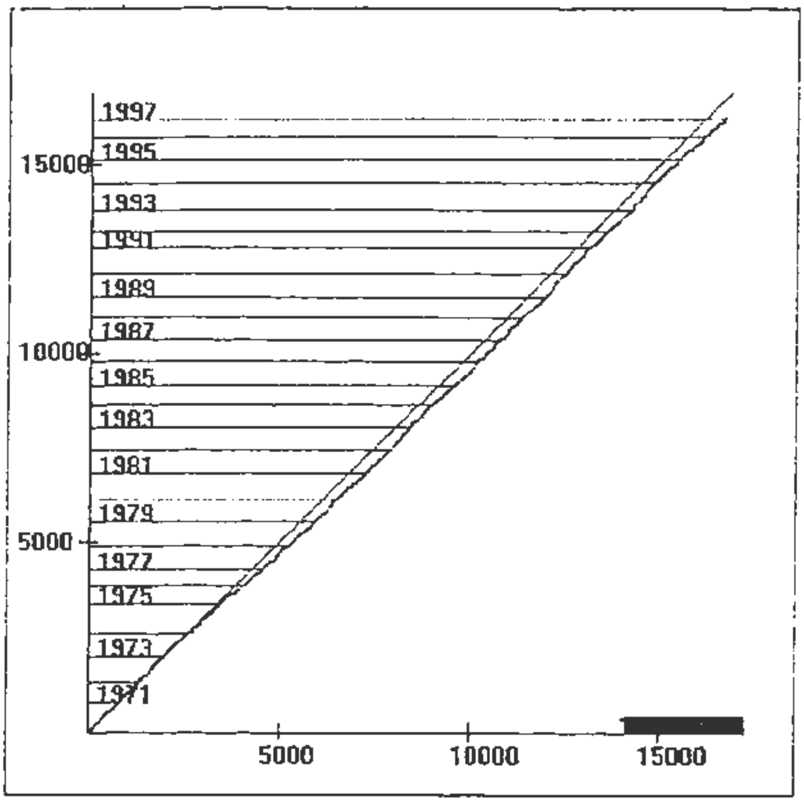

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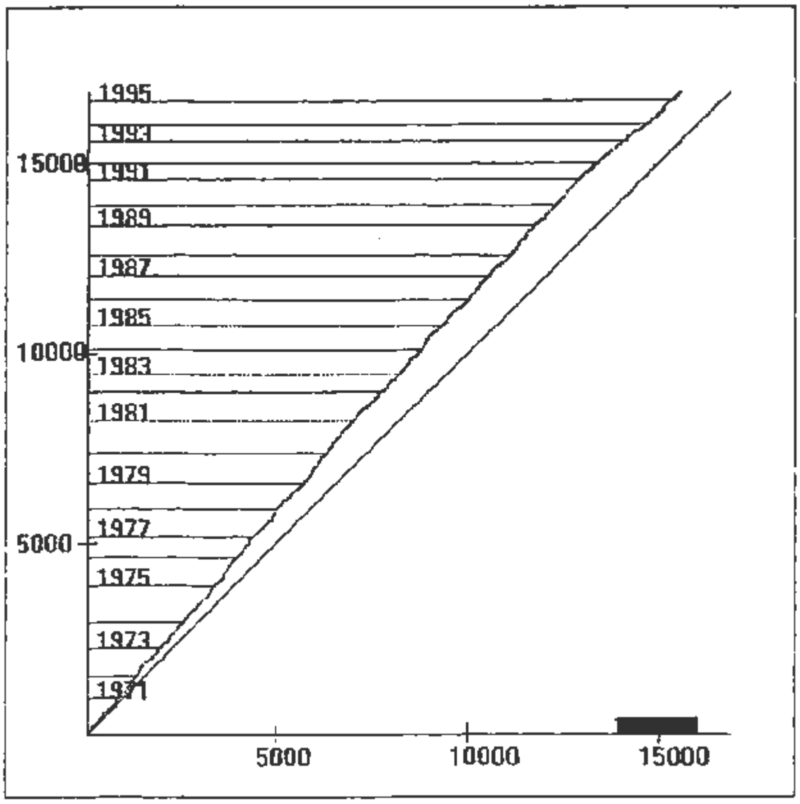

Upper Narew district 1970-01-01—1997-03-05

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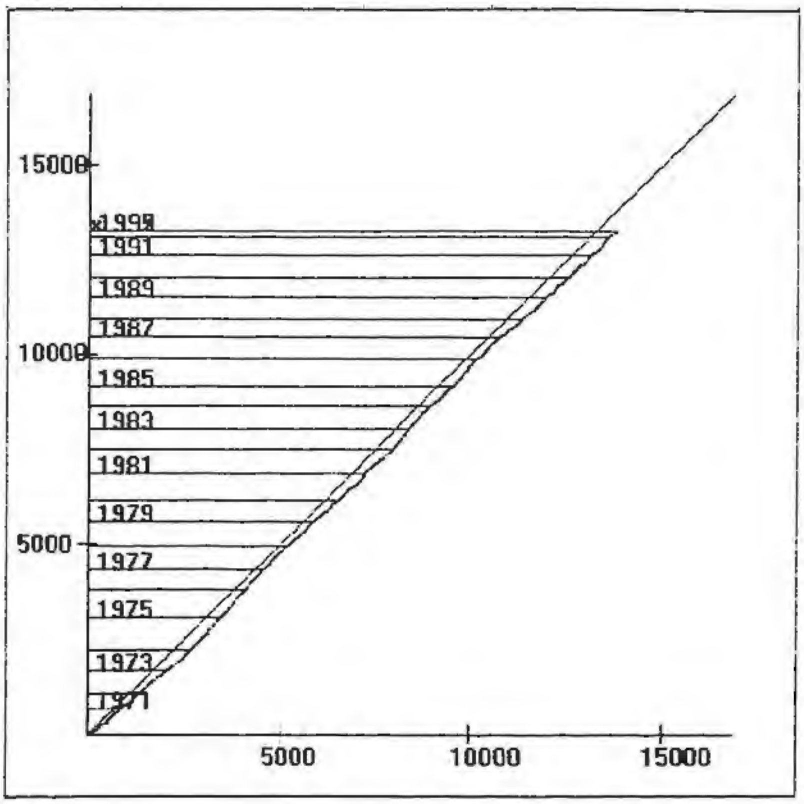

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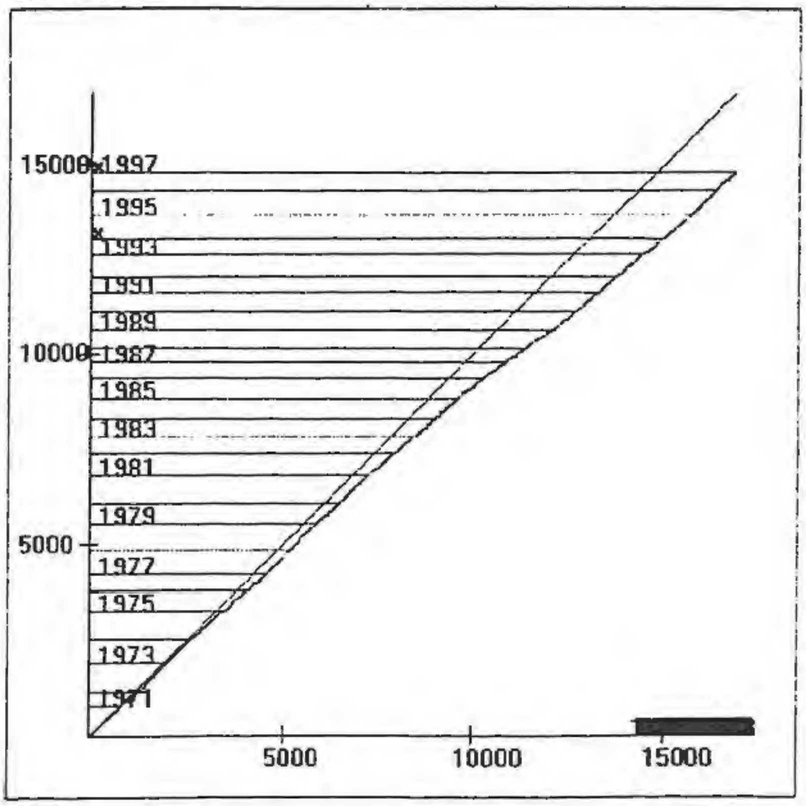

Upper Narew district 1970-01-01—1997-03-05

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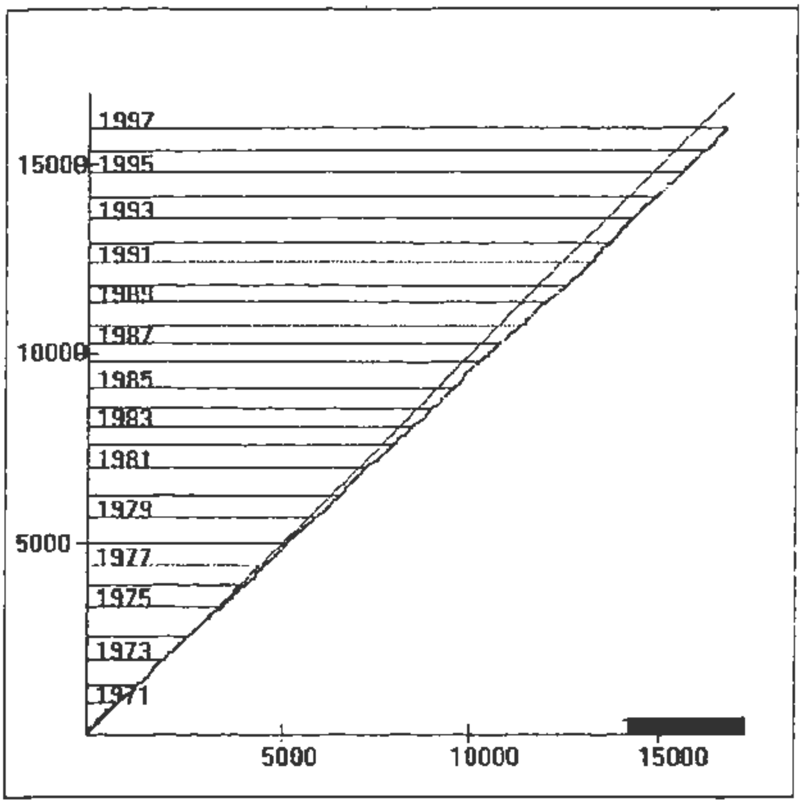

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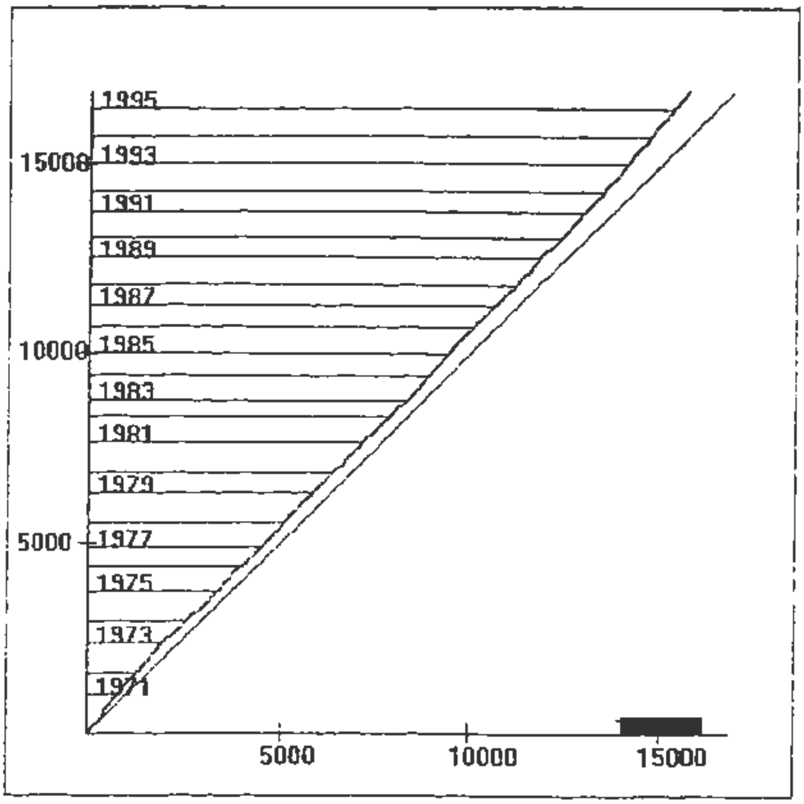

Upper Narew district 1970-01-01—1997-03-05

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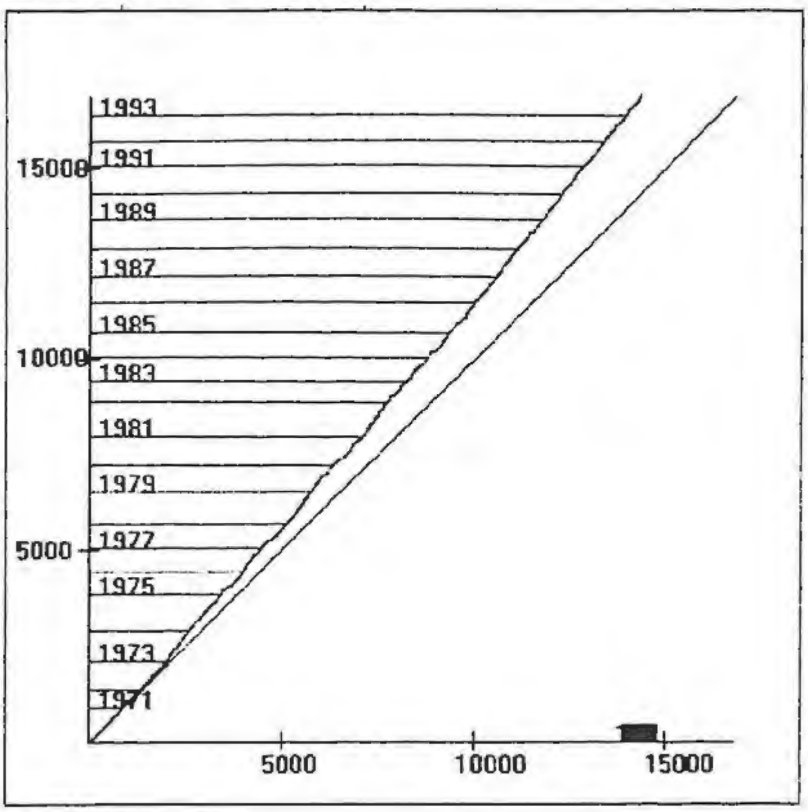

Upper Narew district 1970-01-01—1997-03-05

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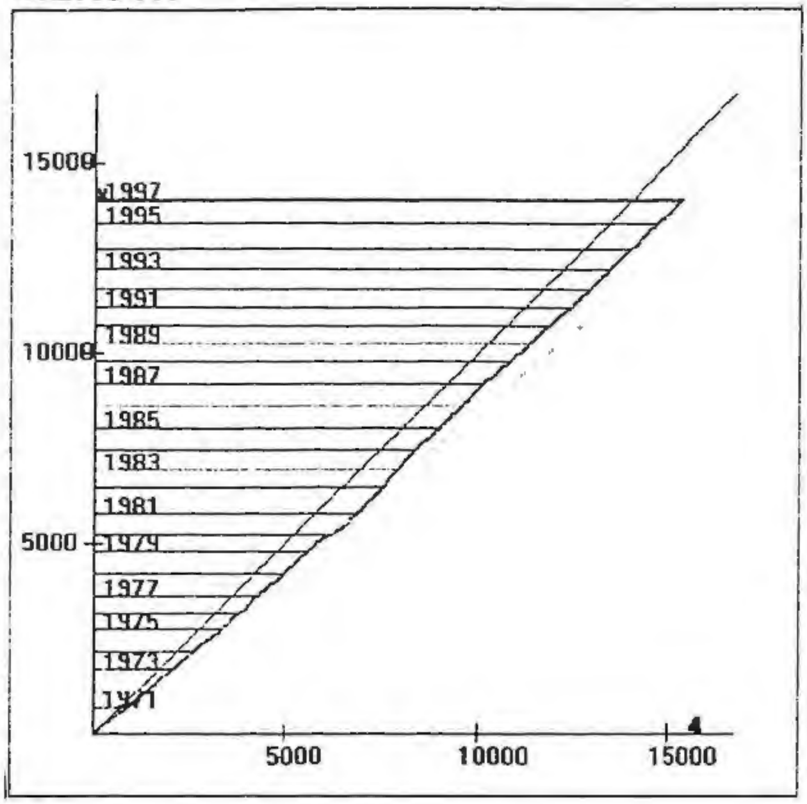

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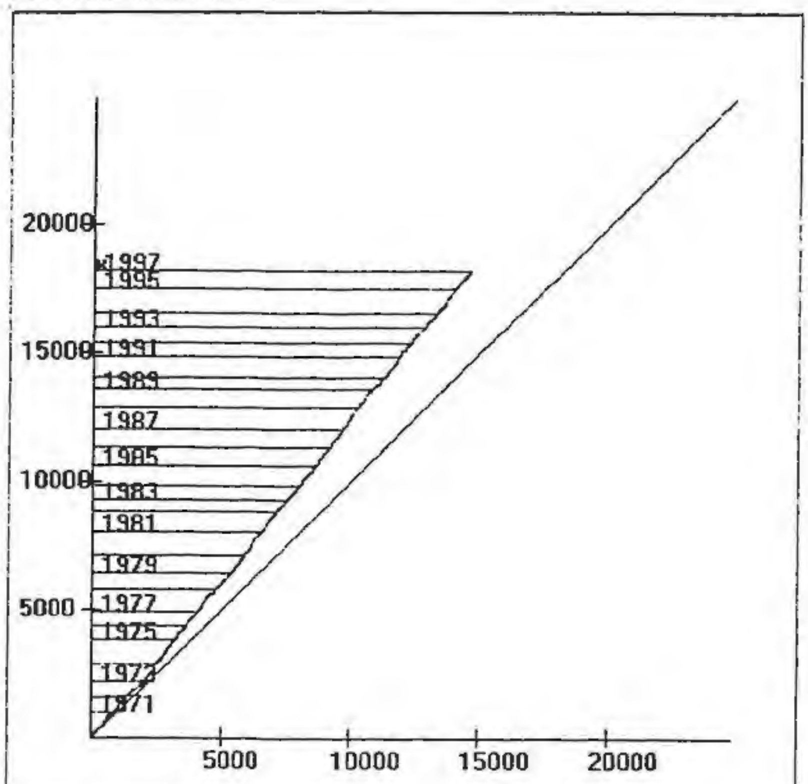

Wkra district 1970-01-01—1997-01-19

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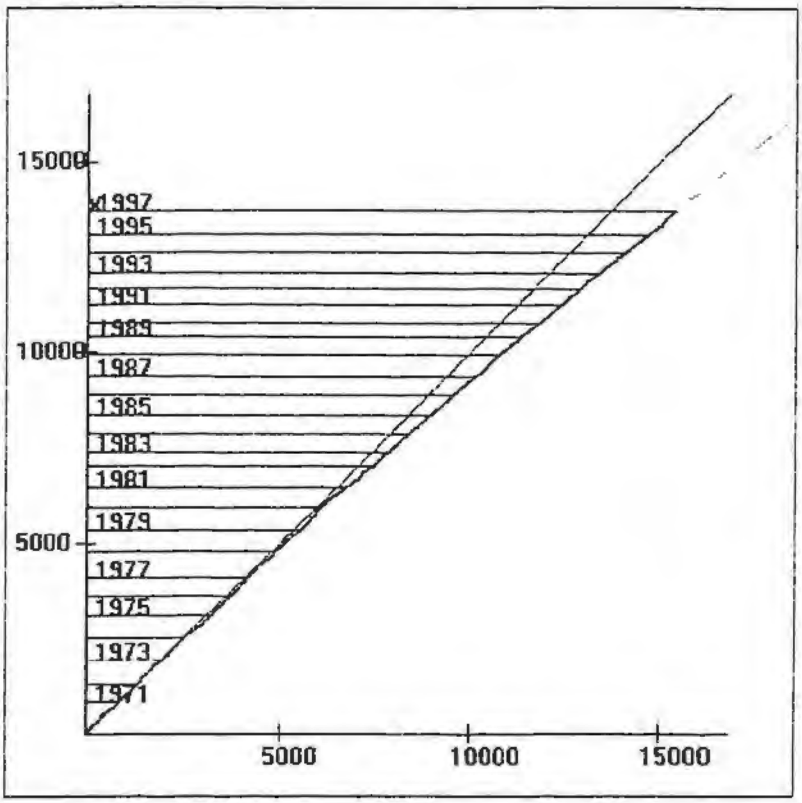

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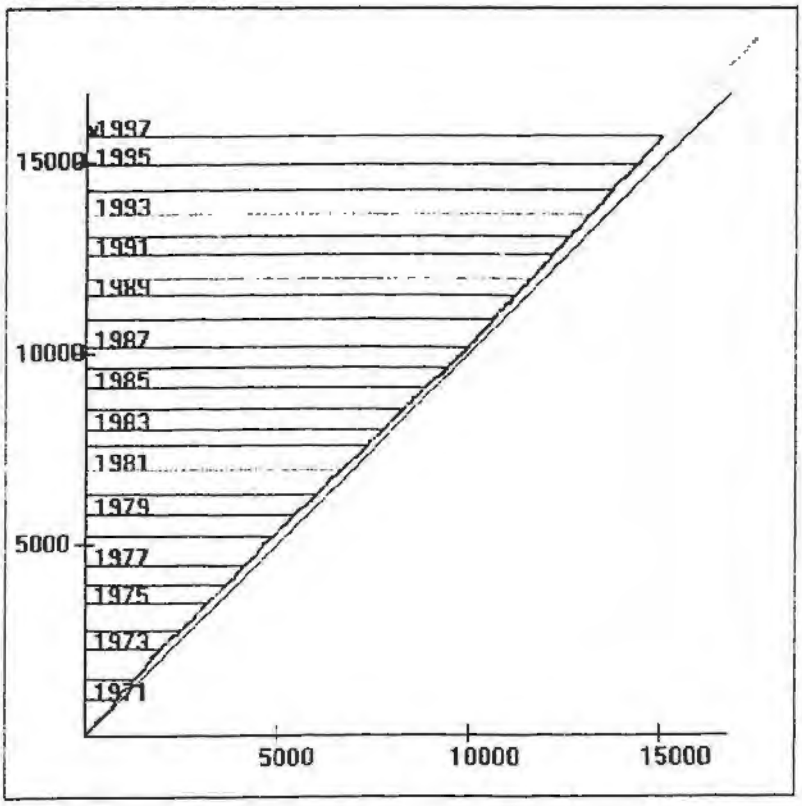

Wkra district 1970-01-01—1997-01-19

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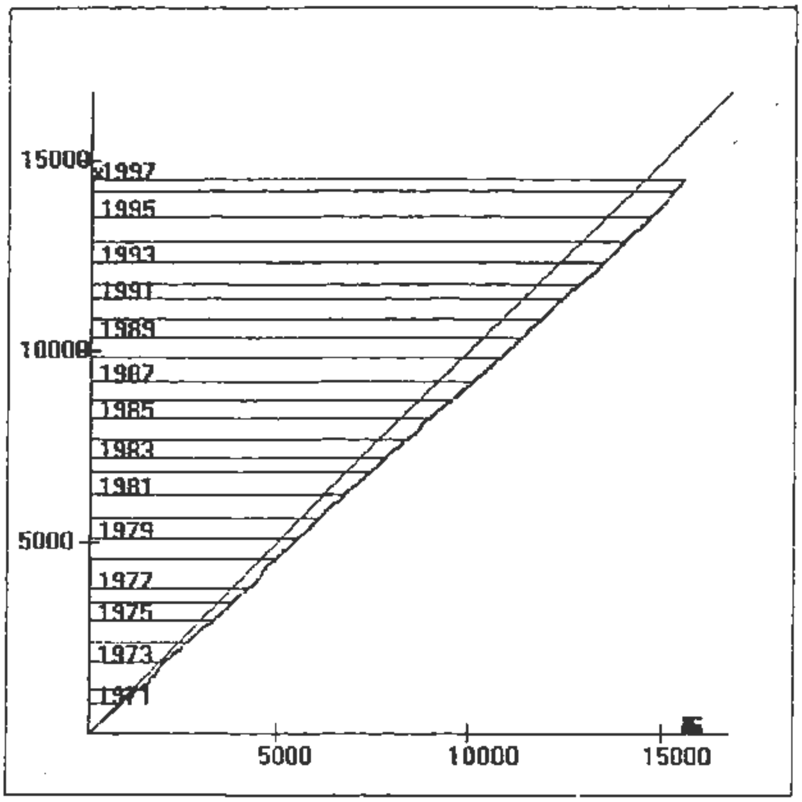

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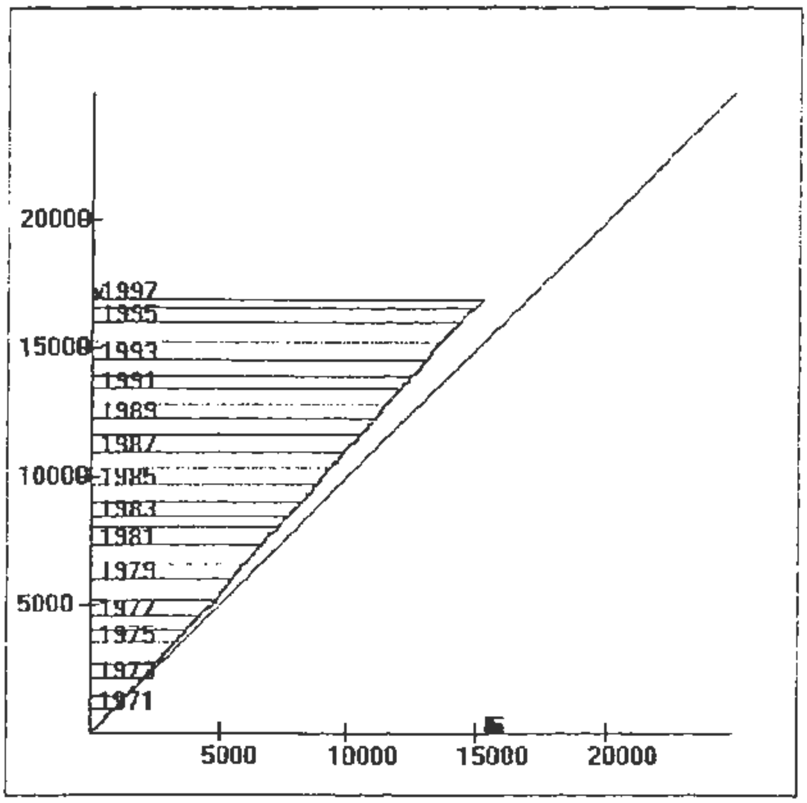
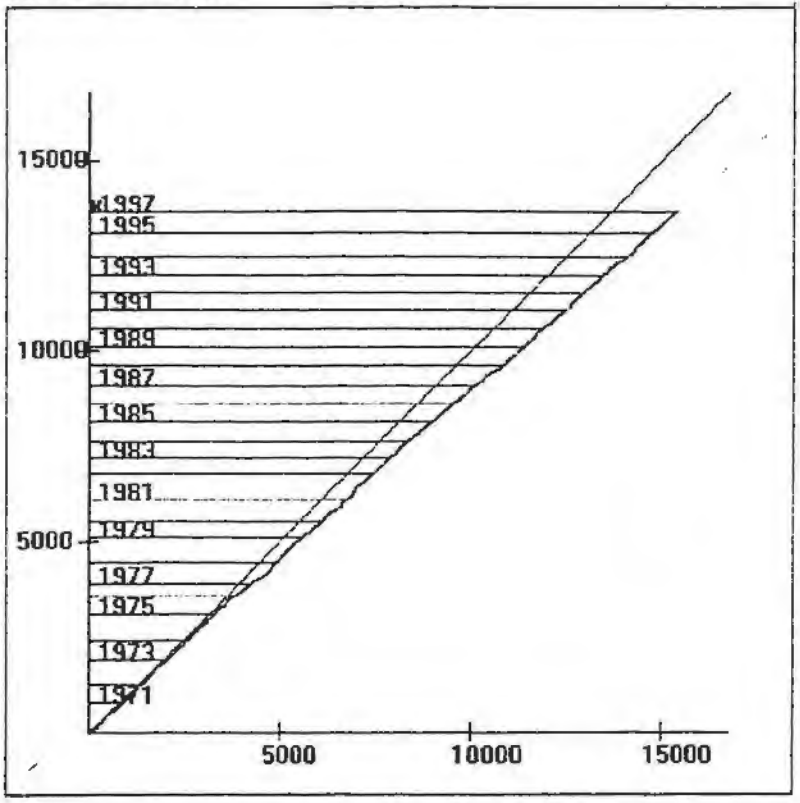


Wkra district 1970-01-01—1997-01-19

WARSZAWA



Wkra district 1970-01-01—1997-01-19

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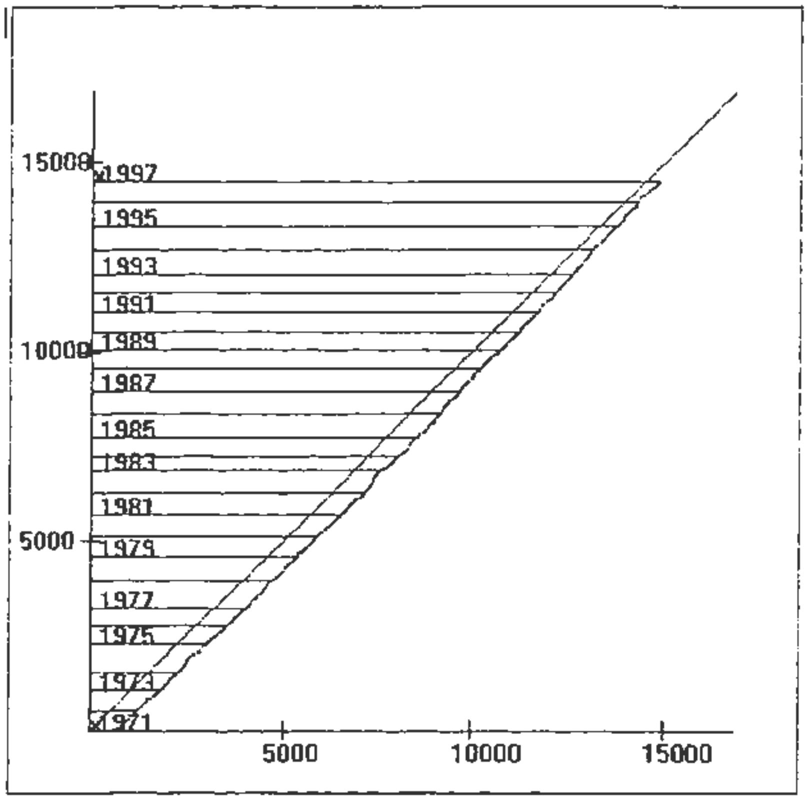

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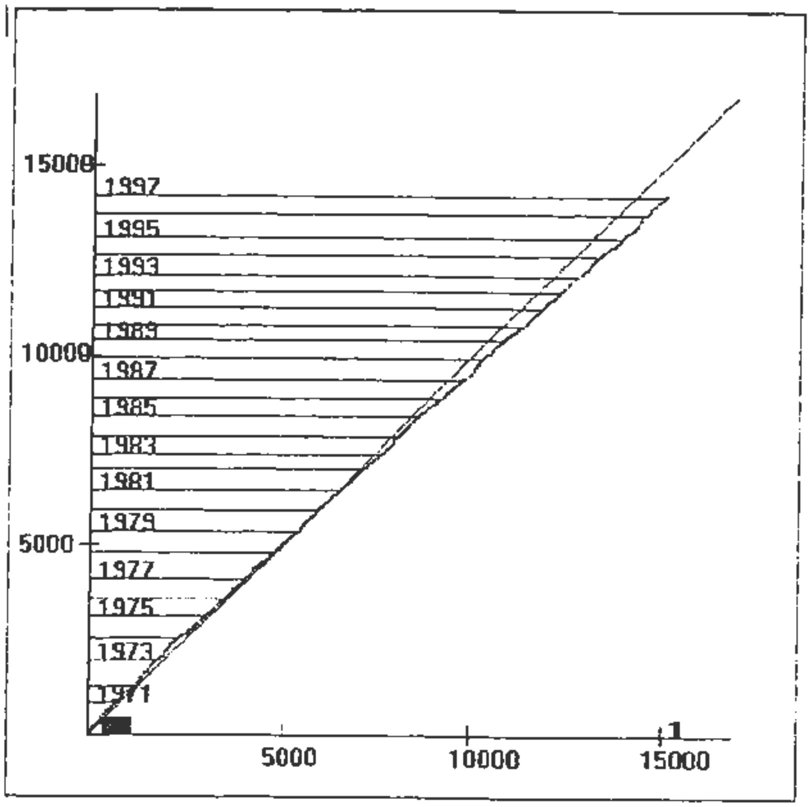
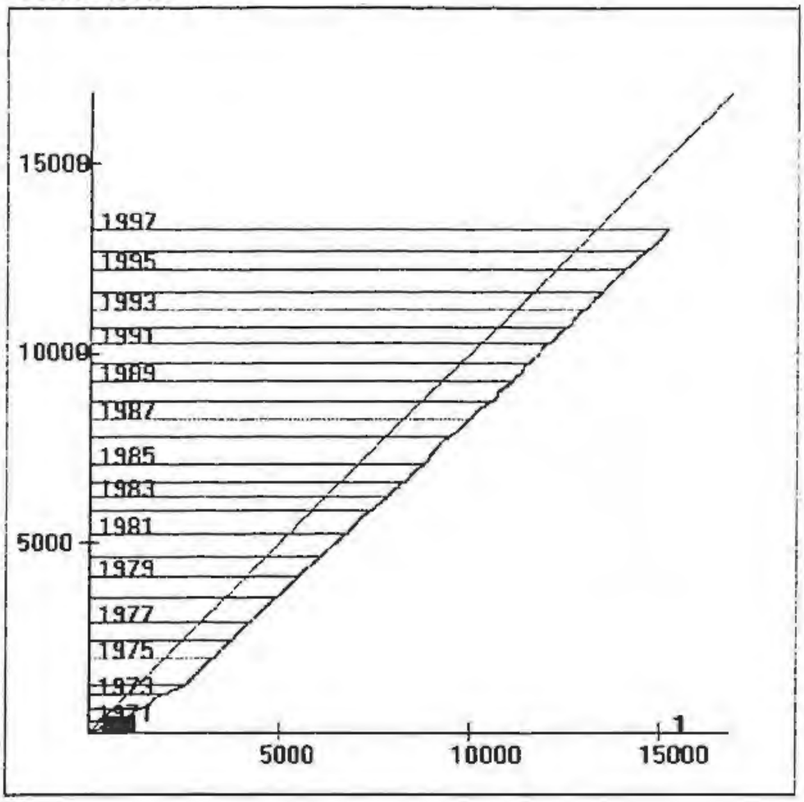


Bzura district 1970-01-01—1997-03-05

SULEJOW



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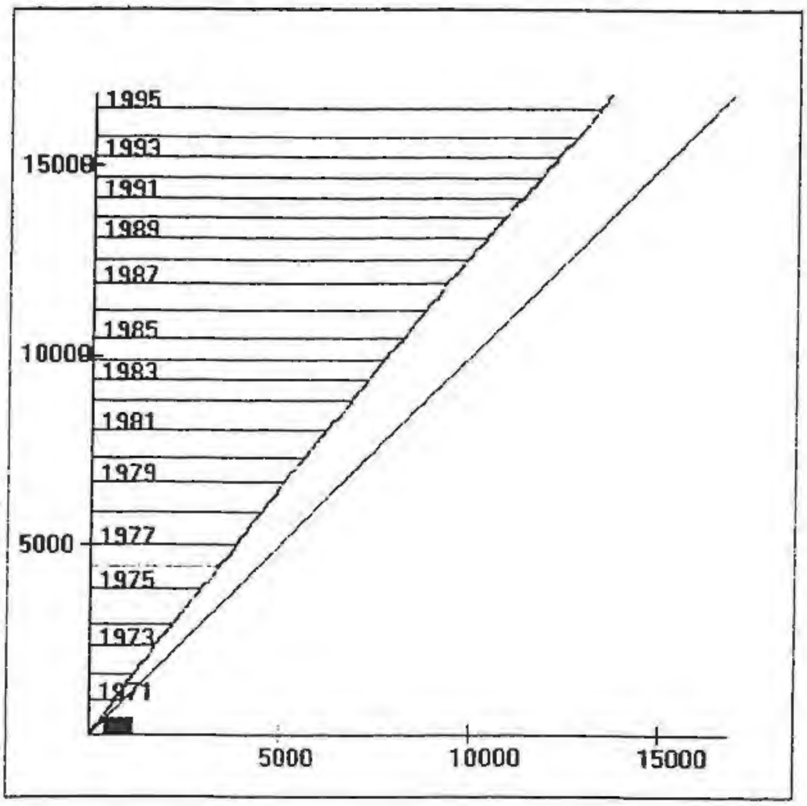

Bzura district 1970-01-01—1997-03-05

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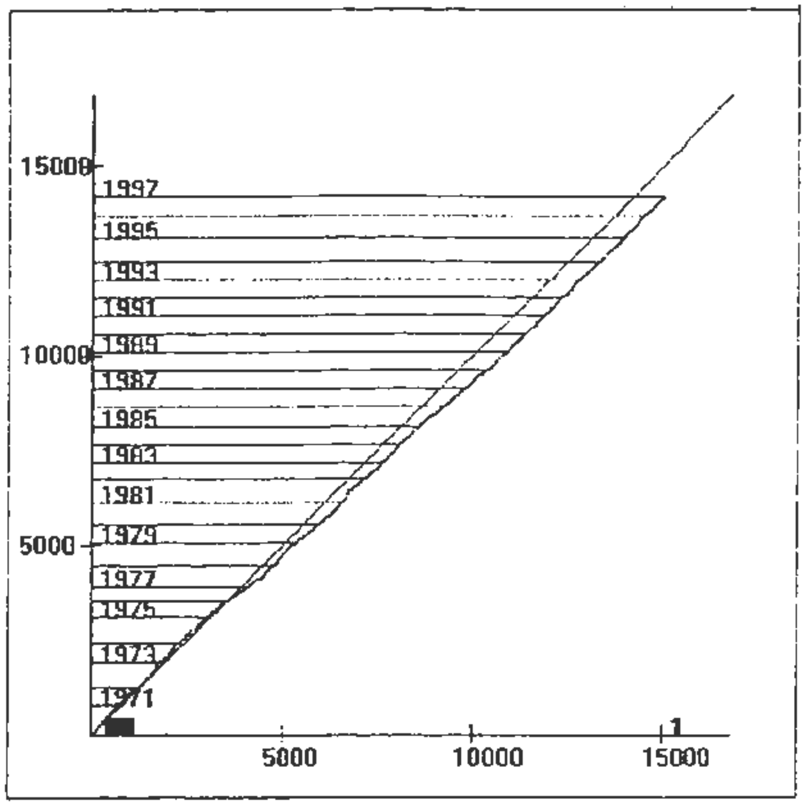

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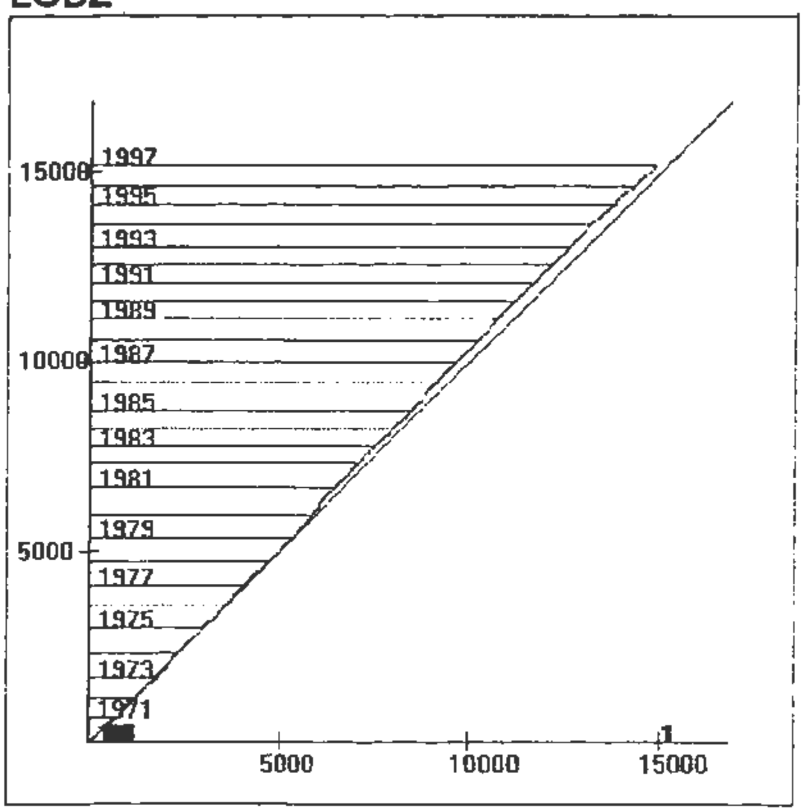

Bzura district 1970-01-01—1997-03-05

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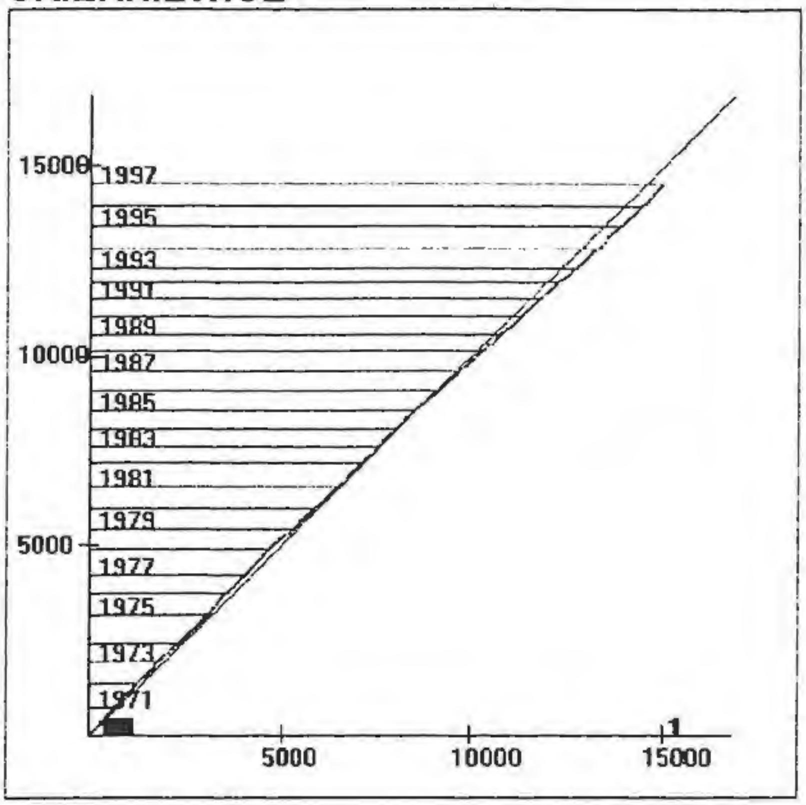

Bzura district 1970-01-01—1997-03-05

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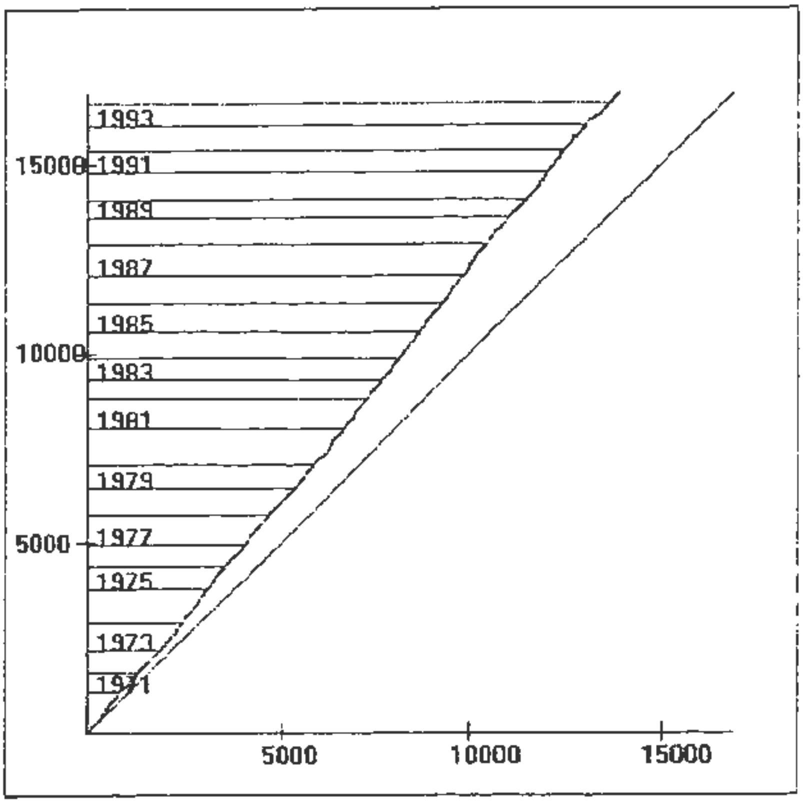

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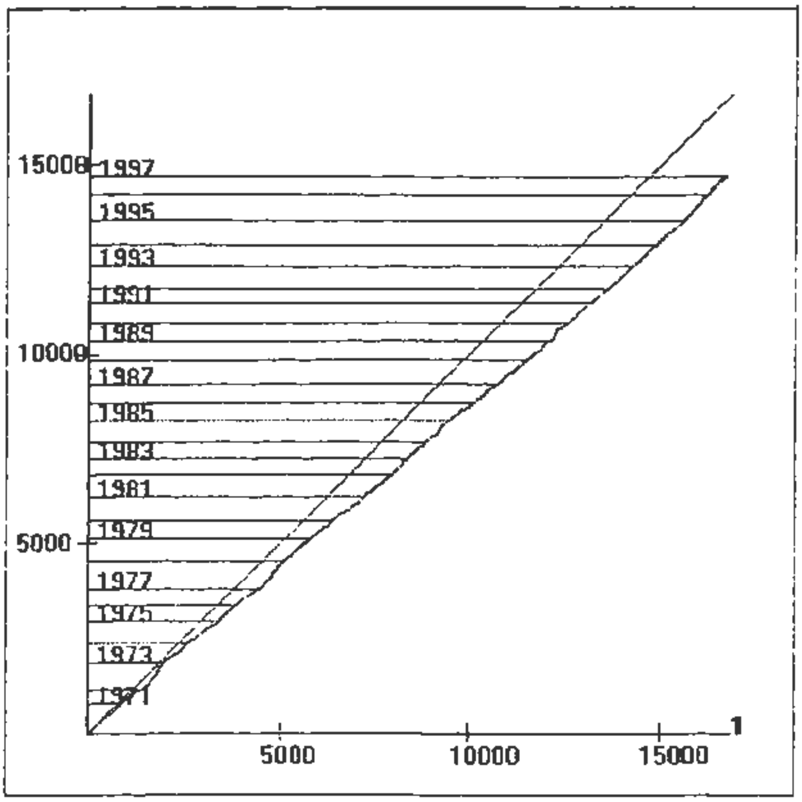

Drweca district 1970-01-01—1997-03-05

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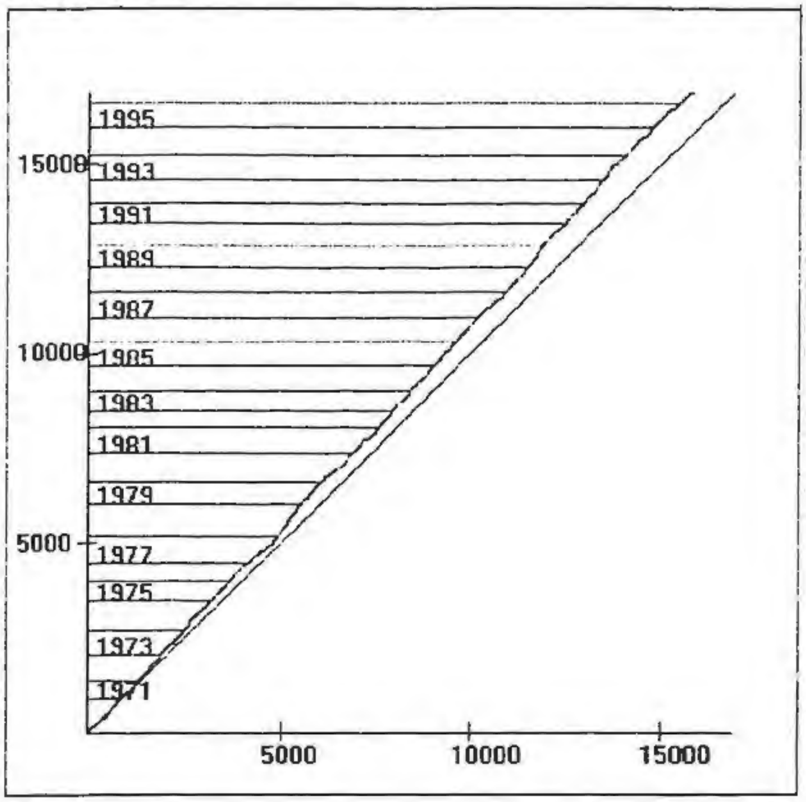

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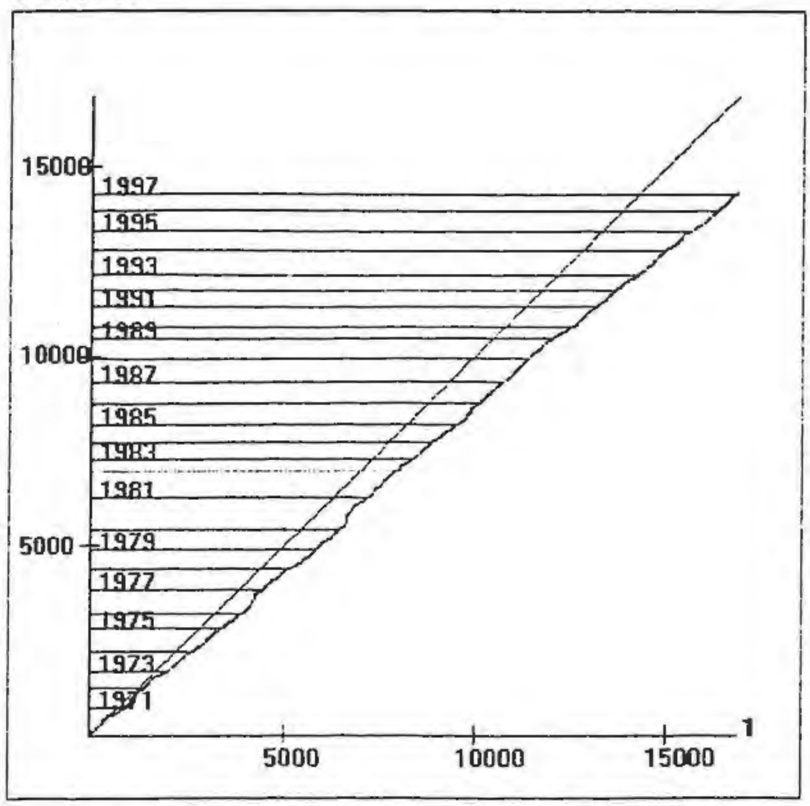


Drweca district 1970-01-01—1997-03-05

Appendix 3

Meteorological and hydrological tables

Meteorological data

Table 1. Precipitation and temperature stations used in the HBV model application for Vistula river basin.

Station	Station (Type)	Annual average precipitation (mm)
Piotrkow	p	562.3
Spala	p	658.4
Bialobrzegi	p	497.7
Sulejow	p, t	491.4
Lodz	p, t	560.5
Chelsty	p	550.3
Plucice	p	510.0
Silniczka	p, t	597.8
Stanowiska	p	588.5
Suchedniow	p	651.3
Bonowice	p	565.5
Pilczyca	p	614.0
Pilica	p	716.7
Kielce	p, t	596.4
Kozienice	p, t	521.7
Wielka Wies	p	580.9
Starachowice	p	573.6
Brody	p	533.7
Bodzentyn	p, t	594.4
Swiety Krzyz	p, t	765.7
Sandomierz	p, t	541.6
Radzyn	p, t	534.7
Wlodawa	p, t	512.2
Deblin	p	562.7
Annopol	p	569.0
Wysokie	p	550.0
Lublin	p, t	569.7
Zamosc	p, t	554.0
Tomaszow Lubelski	p, t	604.5
Ketrzyn	p, t	578.1
Mikolajki	p, t	602.5
Suwalki	p, t	598.5
Bialowieza	p	660.7
Sztabin	p	597.7
Osowiec	p	549.2
Sokolka	p	663.1
Ostroleka	p, t	581.1
Bialystok	p, t	589.8
Banie Mazurskie	p	703.2

Station	Station (Type)	Annual average precipitation (mm)
Mlawa	p, t	543.9
Cieksyn	p	536.1
Plock	p, t	526.7
Dzialdowo	p	599.9
Olsztyn	p, t	629.2
Warszawa	p, t	529.9
Nowe Miasto	p	693.6
Laziska	p	516.6
Skierniewice	p	536.6
Lowicz	p	556.4
Torun	p, t	528.9

Table 2. Mean evapotranspiration (mm/day) data used in the HBV model application for Vistula river basin.

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Kamienna	0.38	0.64	1.90	3.10	4.00	4.50	4.30	3.80	2.50	1.40	0.78	0.45
Wieprz	0.30	0.50	1.50	2.70	3.70	4.20	4.10	3.50	2.10	1.10	0.68	0.37
Radomka	0.37	0.59	1.70	2.90	3.90	4.80	4.30	3.70	2.30	1.20	0.76	0.43
Pilica	0.35	0.60	1.80	2.90	4.20	4.60	4.30	3.80	2.30	1.20	0.73	0.41
Up.Narew	0.34	0.47	1.30	2.80	4.5C	4.80	4.30	3.70	2.20	1.10	0.63	0.35
Wkra	0.30	0.53	1.60	2.80	4.40	4.80	4.30	3.60	2.10	1.10	0.67	0.35
Bzura	0.33	0.53	1.70	3.00	4.60	5.00	4.60	3.70	2.10	1.10	0.74	0.39
Drweca	0.28	0.53	1.60	2.70	4.20	4.50	4.00	3.50	2.00	0.99	0.60	0.31

Hydrological data

Table 3. Discharge stations used in the HBV model application for Vistula river basin.

Station (Name)	Runoff area (km^2)	Mean flow (m^3/s)	Mean flow ($l/s,km^2$)
Bzin	276.8		
Wachock	476.0	3.17	6.66
Michalow	586.0		
Brody	630.1	3.88	6.16
Nietulisko	405.1	1.99	4.91
Kunow	1106.0	6.08	5.50
Czekarzewice	1878.4	8.67	4.62
Nielisz	134.9		
Krasnystaw	3001.0	11.8	3.93
Sobianowice	1264.9	5.02	3.97
Lubartow	6363.5	22.4	3.52
Tchorzew	2341.0	8.31	3.55
Kosmin	10230.6	36.4	3.56
Rogozek	2060.4	9.40	4.56
Szczekociny	352.8	2.32	6.56
Bonowice	129.2	0.54	4.18
Przedborz	2535.9	15.9	6.27
Dabrowa	941.3	6.05	6.43
Sulejow	3908.4	24.2	6.19
Kludzice	505.7	3.03	5.99
Spala	5955.2	33.2	5.57
Bialobrzegi	8664.2	46.0	5.31
Narew	1978.0	9.81	4.95
Suraz	3376.5	15.5	4.59
Fasty	1816.6	8.73	4.81
Strekowa Gora	7180.6	33.3	4.64
Osowiec	4365.1	22.4	5.13
Burzyn	6900.4	33.6	4.87
Wizna	14307.7	67.9	4.75
Trzciniec	1928.0	10.8	5.60
Cieksyn	4879.0	20.1	4.12
Kwiatkowek	350.2		
Sochaczew	6281.4	24.4	3.88
Nowe Miasto	2724.6	16.9	6.20
Elgiszewo	4959.4	28.5	5.75

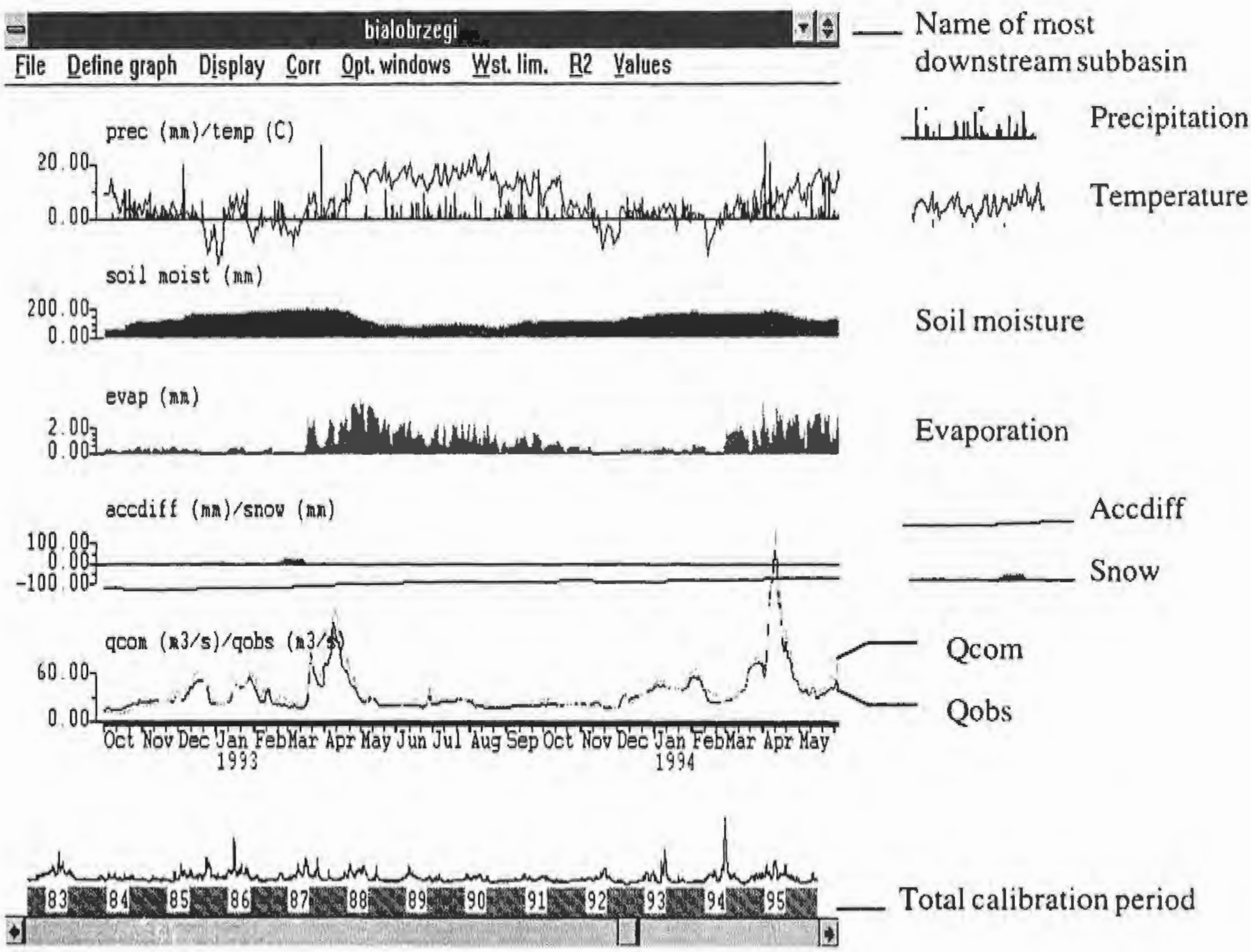
Remark: The stations for which no mean flow is given have too short observation periods to calculate reasonable mean on.

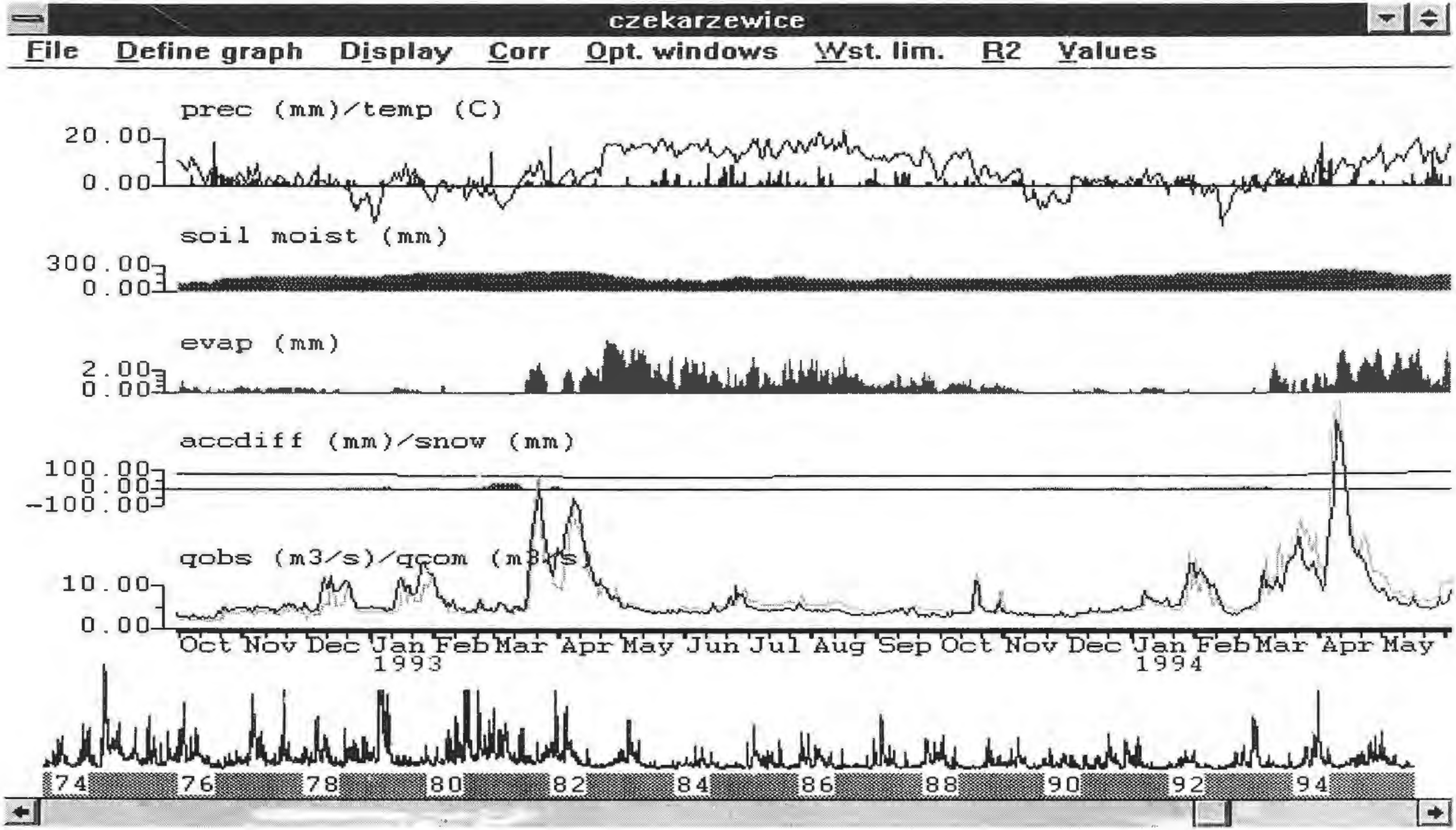
Appendix 4

Model results

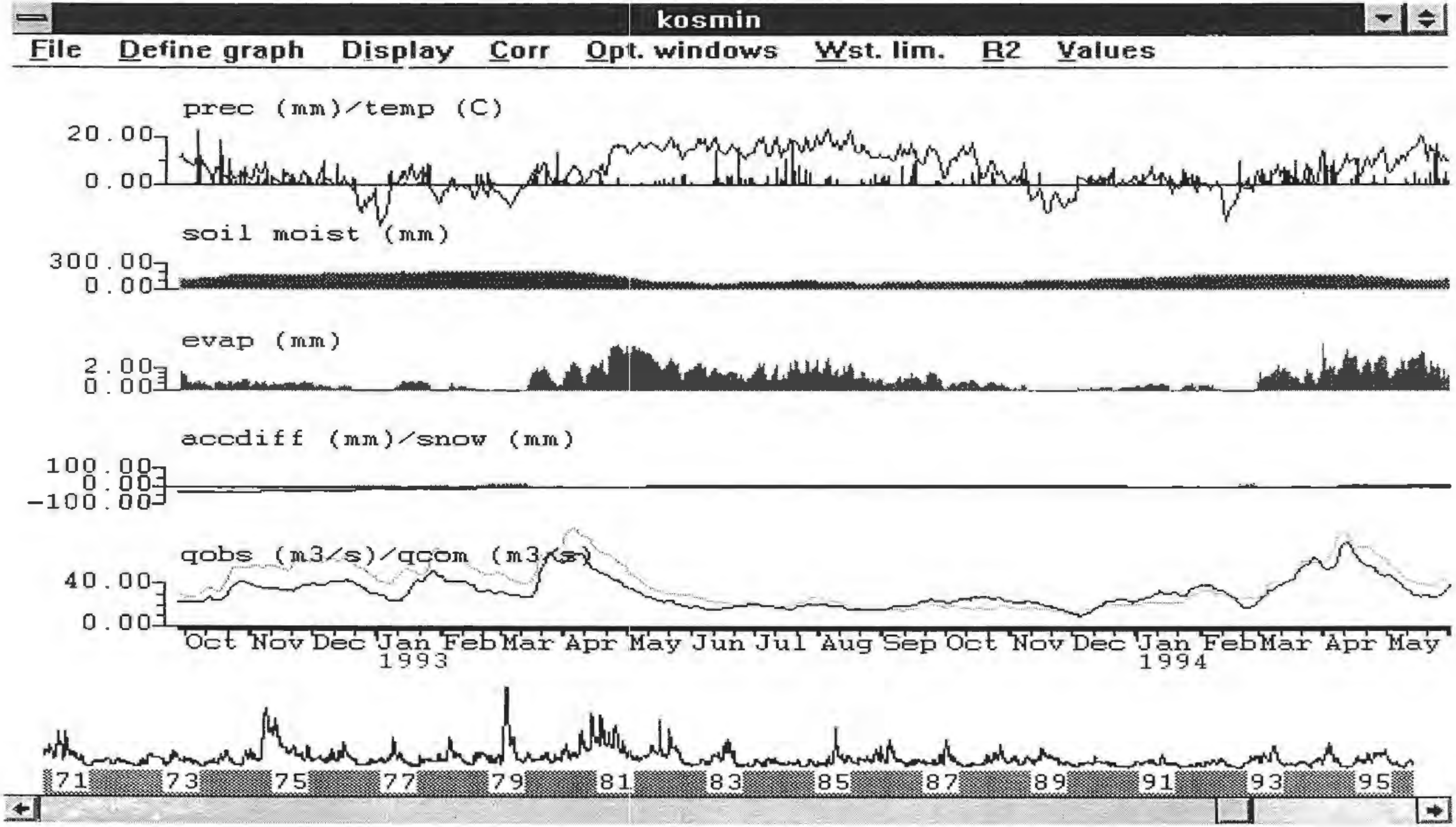
Graphs for the period October 1993 to May 1994

Legend

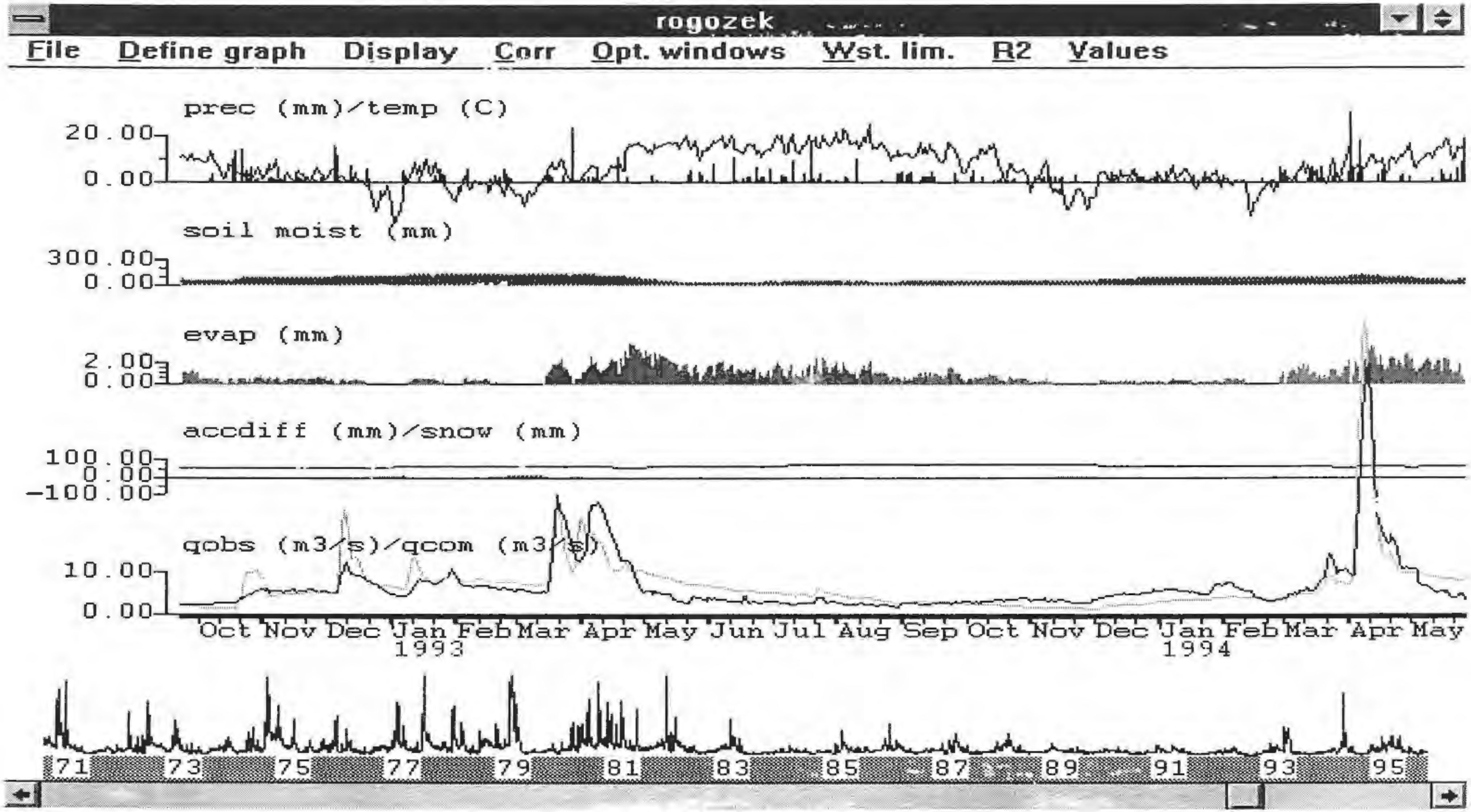

bialobrzegi
File Define graph Display Corr Opt. windows Wst. lim. R2 Values
prec (mm)/temp (C)
20.00
0.00
soil moist (mm)
200.00
0.00
evap (mm)
2.00
0.00
accdiff (mm)/snow (mm)
100.00
0.00
-100.00
qcom (m3/s)/qobs (m3/s)
60.00
0.00
Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan Feb Mar Apr May
1993
1994
83 84 85 86 87 88 89 90 91 92 93 94 95
Name of most downstream subbasin
Precipitation
Temperature
Soil moisture
Evaporation
Accdiff
Snow
Qcom
Qobs
Total calibration period



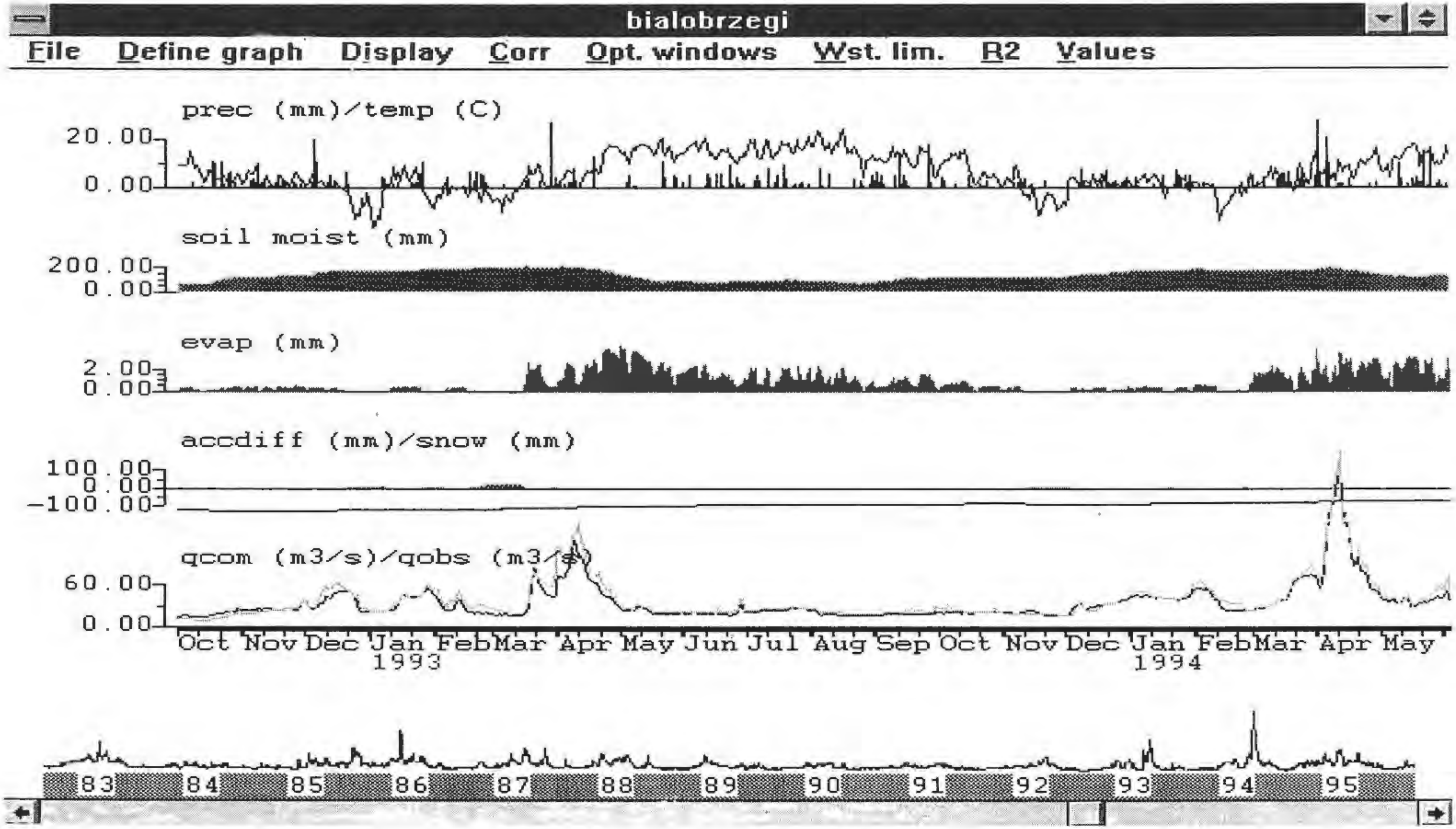
Kamienna district



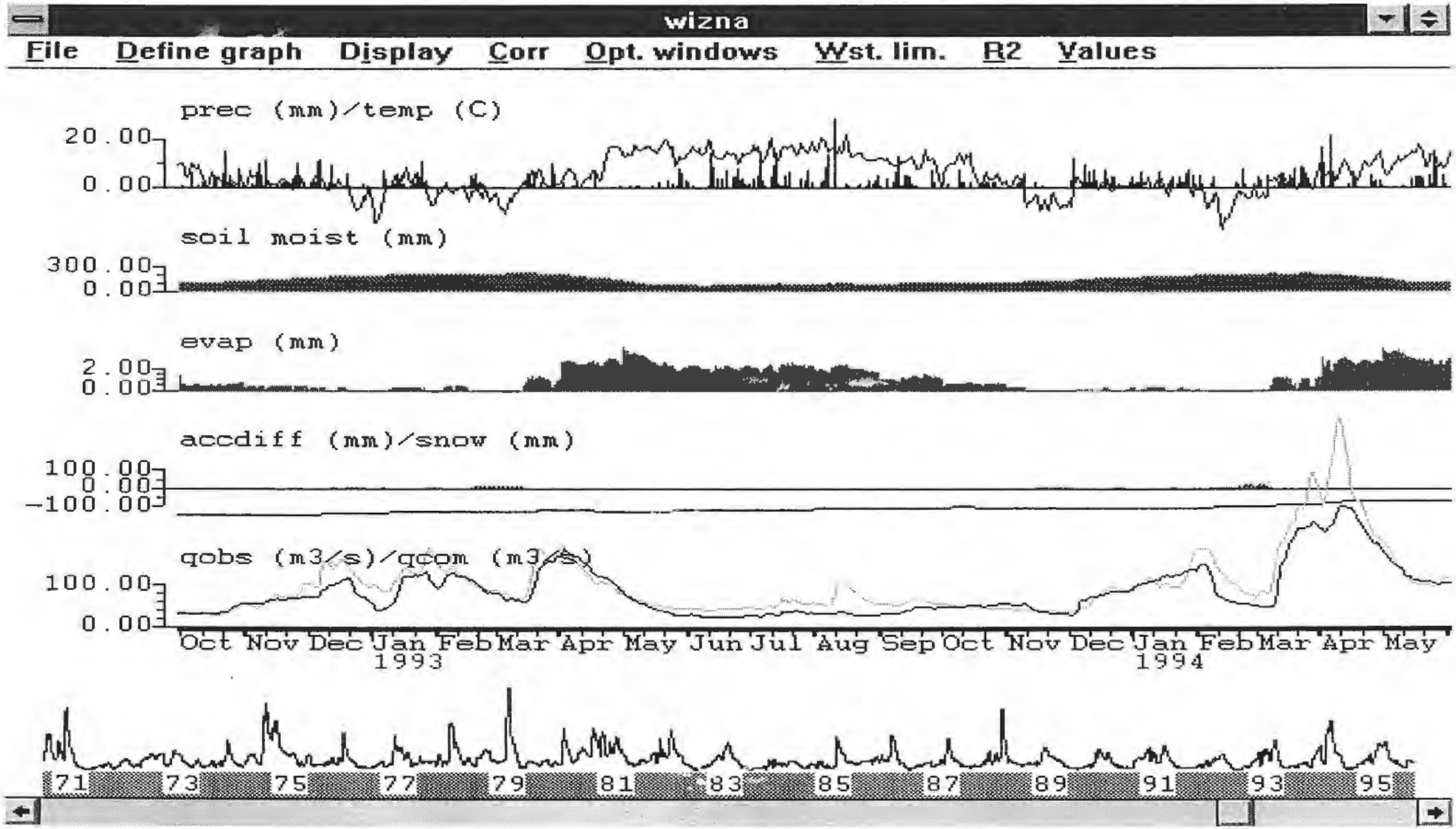
Wieprz district



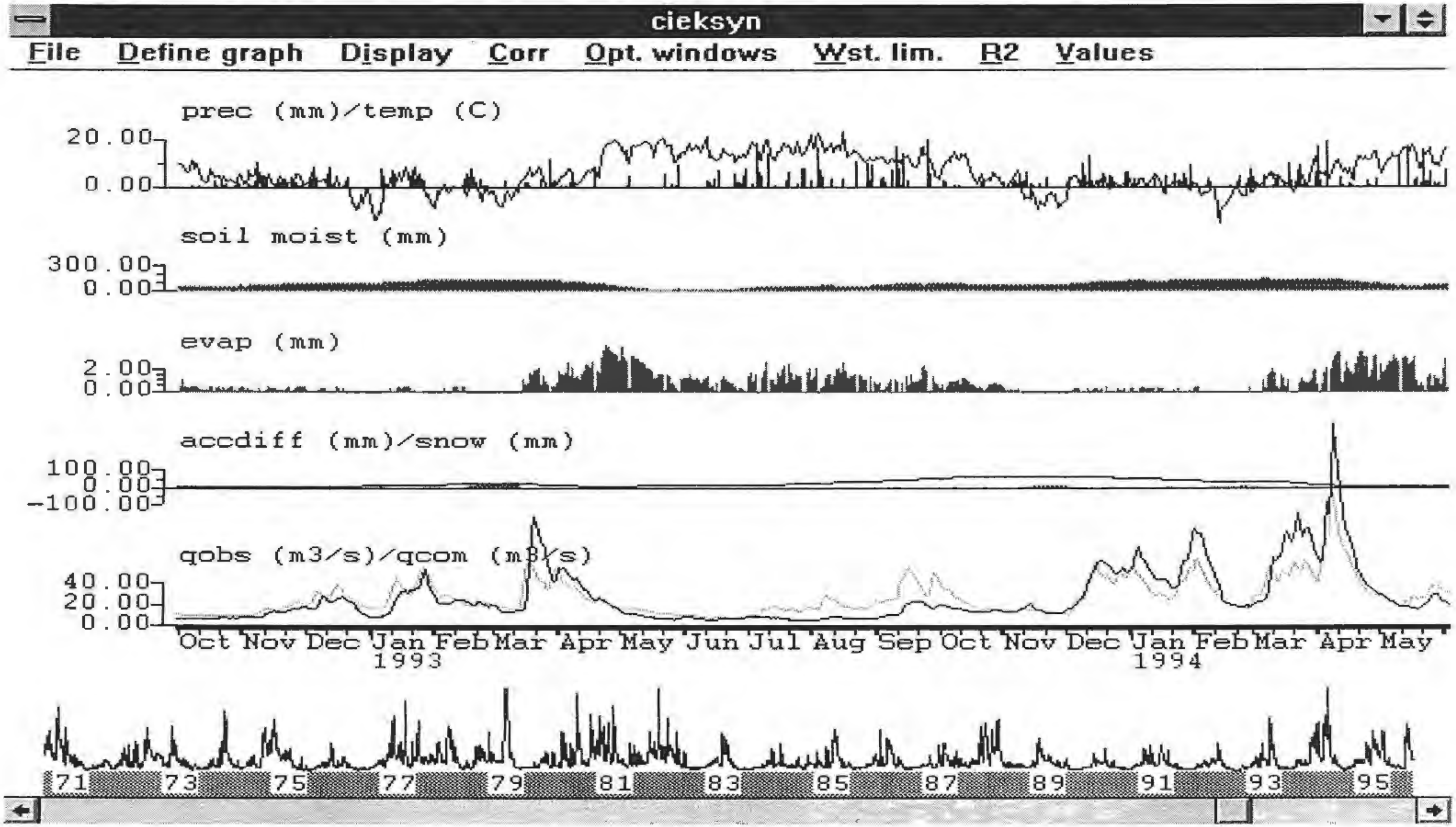
Radomka district



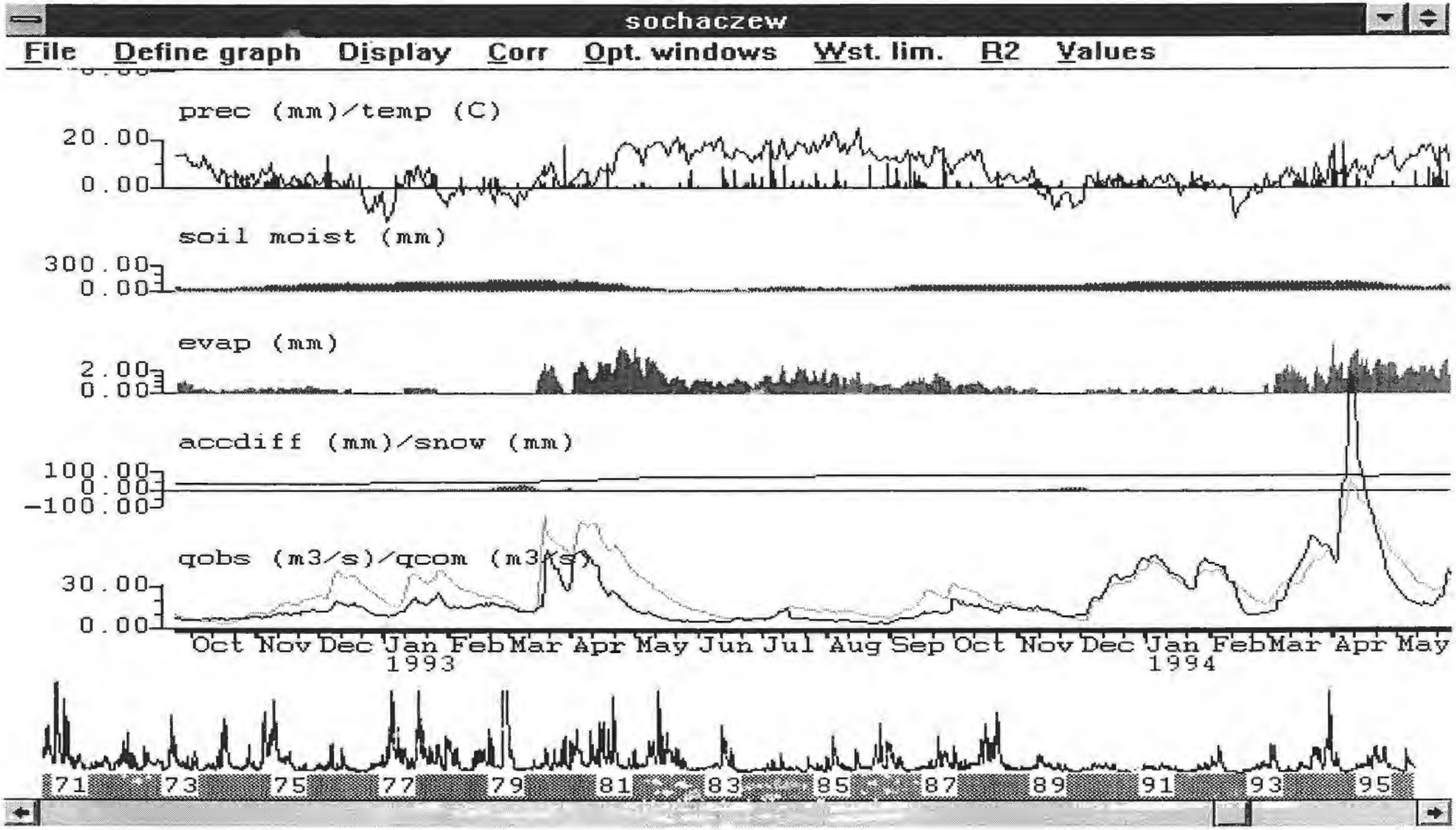
Pilica district



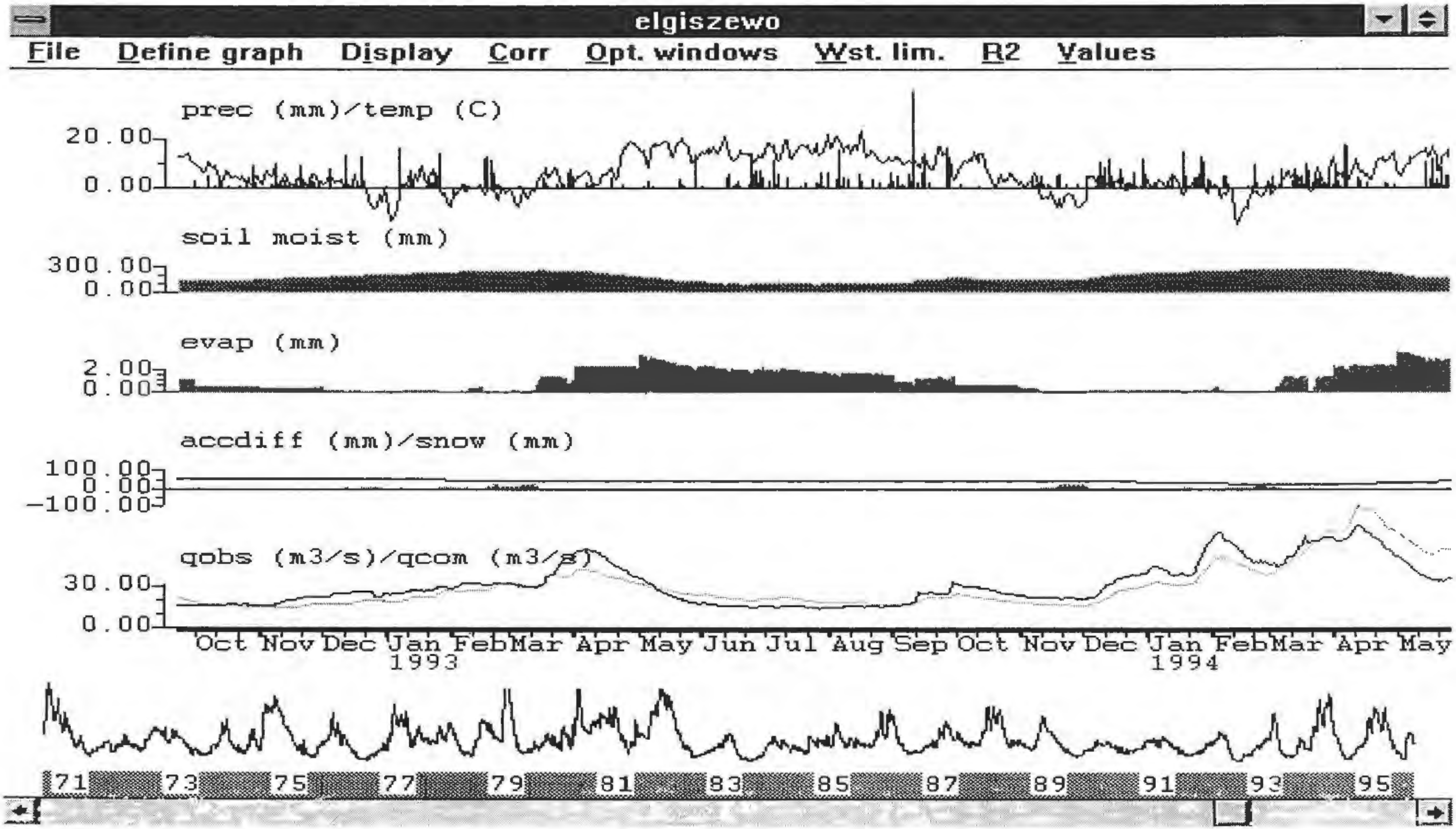
Upper Narew district



Wkra district



Bzura district



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