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Climate Change Impacts on the Water Supply System in the Warta River Catchment, Poland

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ABSTRACT *The effects of a non-stationary climate on a water management system in the Warta River Catchment in Central Poland which already suffers from seasonal water deficits are examined in this paper. To determine a range of possible implications of global change on the region of interest, two scenarios were selected for the study: the warm–dry scenario predicted by the GFDL model, and warm scenario obtained from the GISS model. It is shown that the basin's water supply and demand are both sensitive and vulnerable to climatic changes. Possible adaptation options to cope with further degradation of domestic, industrial and agricultural water supplies are recommended.*

Introduction

The objectives of this study are to examine the effects of a non-stationary climate on a water management system in Central Poland which already suffers from seasonal water deficits, and to analyse possible adaptation options to cope with further degradation of domestic, industrial and agricultural water supplies. There is no general consensus within the scientific community on the timing and scale of global climate change. In spite of the uncertainties, however, it is largely acknowledged that *if* future climatic processes differ from present conditions, *then* an impact of such disturbances on terrestrial systems and human activities could be very serious. Among the most important implications of climate change may be its effects on the hydrological cycle, which will impact on water availability and use, particularly in regions already scarce in water supply.

Climate is only one of the many influences on water resource systems, but it is the only one which cannot be controlled by humans. Adaptation to long-lasting, unfavourable climatic conditions requires either:

(1) better management of existing facilities;
(2) extension of the system's infrastructure; or
(3) reduction of water use by employing various conservation measures.

Such adaptation actions require timely decisions and the accumulation of necessary investment funds. This paper provides information about possible impacts of climate change on one of the most vulnerable regions in Poland as a basis for policy decisions about actions that will mitigate the adverse regional effects of global warming.

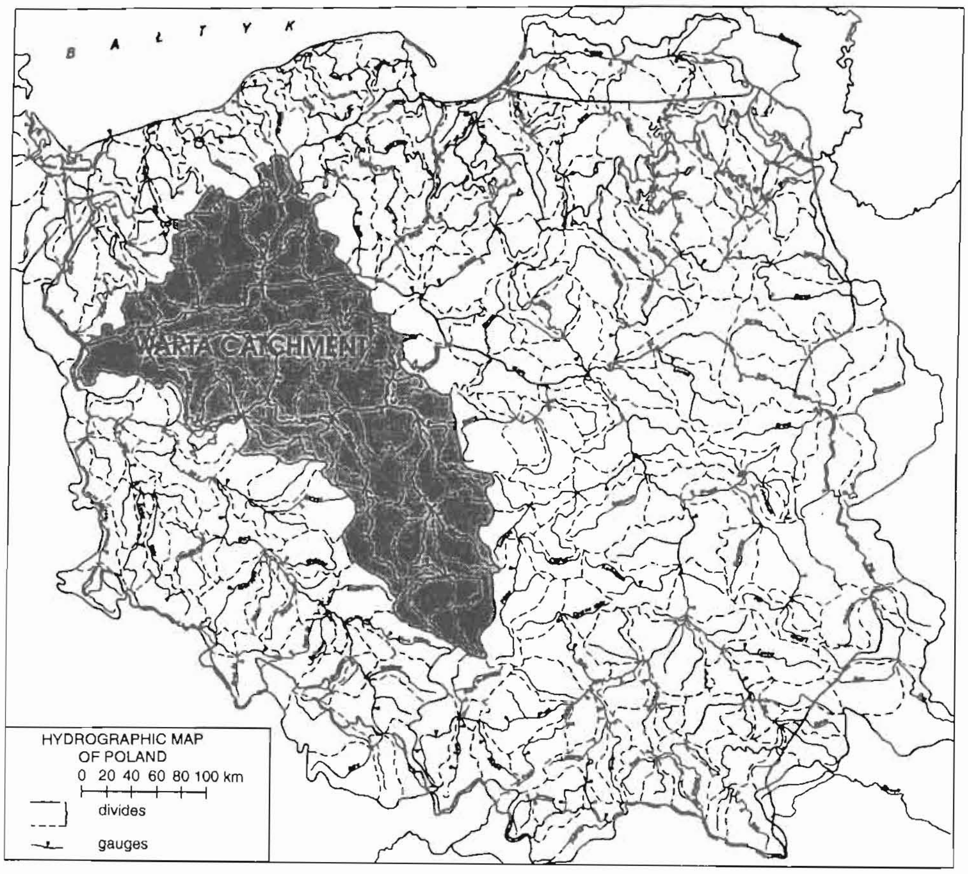

Figure 1. Map of Warta River system.

Warta River Water Resources System

The Warta River catchment (see Figure 1) is located in the western part of the Polish Plateau and is the largest tributary to the Odra River, which forms the border between Poland and Germany. The entire catchment area is 53 710 km^2, and about 17% of the territory of Poland. The region is characterized by a moderate climate with relatively low precipitation (635 mm per year) and a mean annual temperature of 8.1°C. Average monthly climatic data—air temperature, solar radiation, rainfall and potential evapotranspiration—obtained from 1951–90 for a number of stations located along the river catchment are given in Table 1.

The annual mean of discharge (years 1951–90) of the Warta at the mouth of the river is estimated to be 216.7 m^3/s, which gives an average annual catchment runoff of 130 mm. Monthly discharges varied in the above period from 73.0 m^3/s in September 1963 to 729.0 m^3/s in May 1979.

In the year 1990 about 6.4 million people lived in the Warta basin, more than one-third of them in four main agglomerations: Częstochowa, Konin, Łódź and Poznań. Per capita fresh water supply in the entire basin was equal to 1067 m^3/year, just above the 1000 m^3/year benchmark used as an approximate

Table 1. Climatic data for the Warta river catchment

Month	T (°C)	R_s (W/m^2)	*PET* (mm)	*P* (mm)
January	− 2.1	20.6	2.5	26.3
February	− 1.6	43.3	6.8	36.2
March	2.3	92.7	25.2	49.9
April	7.5	148.1	55.6	52.5
May	13.1	204.2	93.8	58.4
June	16.7	291.5	113.4	76.8
July	18.0	208.4	112.1	85.3
August	17.4	184.3	97.9	71.8
September	13.3	123.9	59.0	51.1
October	8.6	67.8	27.8	42.0
November	3.6	25.5	10.2	46.9
December	− 0.1	14.9	3.8	38.6
Avg over year	8.1	118.8	608.1	635.8

indicator of *water scarcity* by the World Bank (Engelman & LeRoy, 1993). Overall water use within the basin in 1990 (Table 2) was still well below available resources, and ranged from 18.7 m^3/s in autumn and winter to about 44.4 m^3/s in summer. These figures do not include water required for a once-through cooling system of two power plants located in the Konin region (Dobrowolski & Jurak, 1995). The cooling system is a closed system, with no impact on the water budget in other parts of the Warta catchment.

Table 2 gives data for the upper and middle part of the Warta catchment, up to the Poznań agglomeration. This sub-basin, with an area of 25 100 km^2, represents one of the most critical water resource regions in Poland because of water scarcity, high population density and high levels of industrial development. Until now, however, most of the region's agriculture is rain-fed, with irrigated lands covering only a small percentage of the entire basin.

The technical infrastructure of the Warta water resource system is very modest (see Figure 2). Only two reservoirs, Poraj and Jeziorsko, are located along the river, of which only the latter has sufficient capacity to impact on flow redistribution. The two reservoirs control only 3.2% of the catchment's runoff. In addition, a storage reservoir was built in Sulejów on the neighbouring Pilica river with the aim of supplying the Łódź agglomeration. Operation rules for both dams under changed climatic conditions have been developed and will be discussed later in this paper. Local water transfers of limited capacity between

Table 2. Water demands (1990) in the Warta River Basin: (a) entire basin and (b) Upper and Middle Warta

Water use sector	Period	D (m^3/s) (a)	D (m^3/s) (b)
Domestic	Jan–Dec	13.9	11.1
Industrial	Jan–Dec	4.8	4.0
Energy (cooling)	Jan–Dec	62.2	62.2
Agricultural	May–Aug	25.7	16.1

Source: Main Statistical Office (1993).

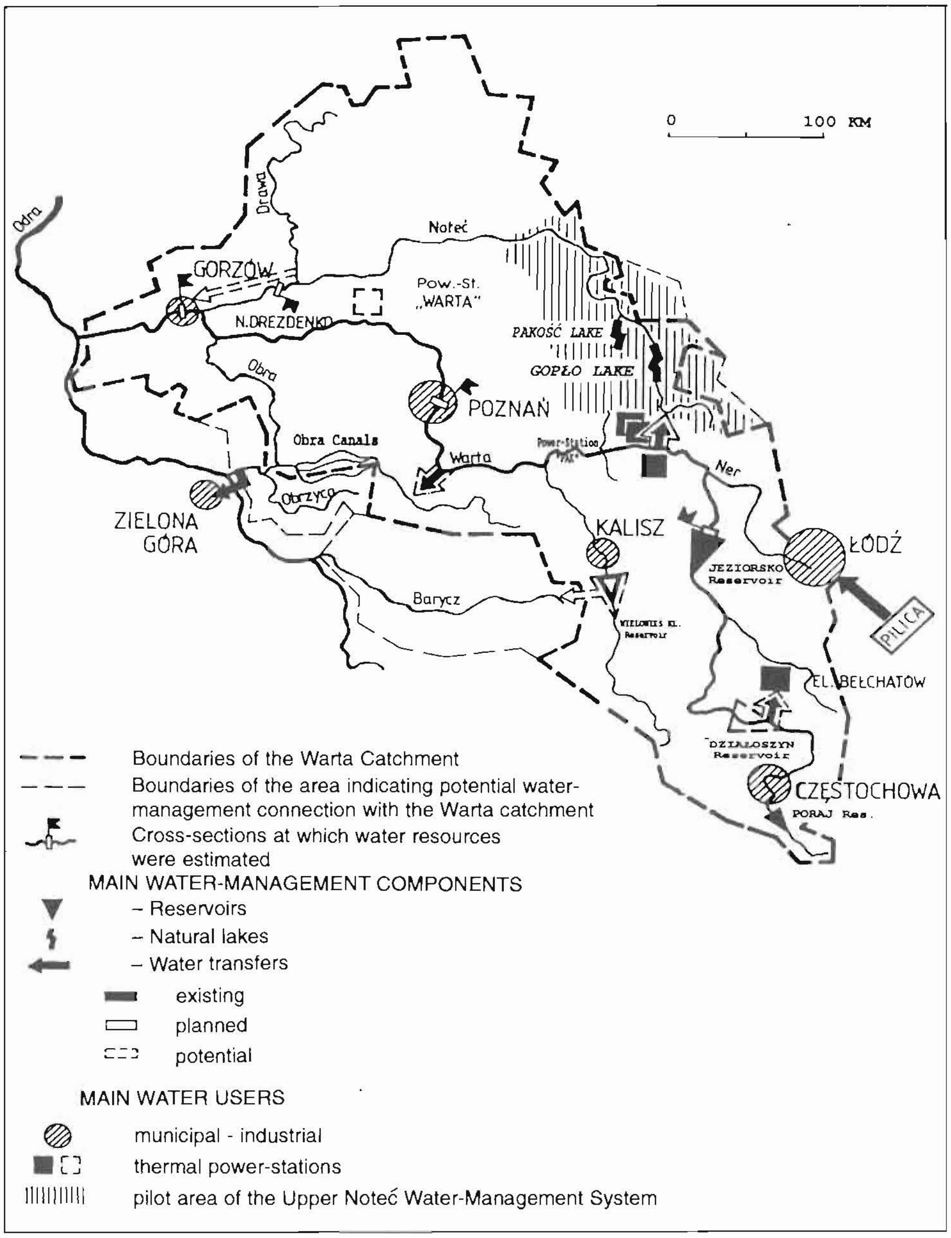

Figure 2. Main elements of Warta Catchment system.

various parts of the basin are also possible, but their role in the catchment's overall water management scheme is rather restricted.

Impact of Climate Change on Water Supply

Assessing the implications of climate change on hydrology is essential for planning future water resources activities on a regional scale. Climate is defined as a *periodic-stochastic process,* whose realizations are states of the atmosphere

Table 3. Temperature and precipitation changes predicted for the Warta Basin

	Temperature difference				Precipitation ratio			
Month	GFDL R–15	GFDL R–30	GISS	CCCM	GFDL R–15	GFDL R–30	GISS	CCCM
I	5.2	2.5	5.3	3.3	1.05	1.07	1.16	1.09
II	5.3	4.7	6.5	4.7	1.01	1.34	1.26	1.28
III	5.9	4.0	3.5	5.2	1.12	1.16	1.26	1.10
IV	3.8	5.6	4.6	2.8	1.01	1.22	1.36	1.25
V	5.0	4.5	3.0	2.3	1.27	1.07	1.18	1.07
VI	4.4	5.1	2.4	2.5	0.87	0.89	1.10	1.06
VII	5.6	5.3	2.4	2.7	0.73	0.89	1.17	0.89
VIII	5.3	3.4	2.0	2.6	0.87	1.06	1.07	1.01
IX	5.7	2.5	4.4	3.2	1.03	1.24	0.79	0.93
X	4.2	3.8	2.9	3.0	1.09	1.48	1.25	1.13
XI	4.8	5.4	4.9	3.6	0.96	1.46	1.28	1.41
XII	4.1	5.8	5.7	2.4	0.86	1.20	1.06	1.36
Average over year	4.9	4.4	4.0	3.2	0.99	1.17	1.16	1.13

(*weather*), and can be described by a set of quantifiable attributes. Also, realizations of a *hydrologic stochastic process* are states of the hydrosphere, such as catchment runoff, soil moisture, evaporation, etc. The two processes are linked by a number of *transfer functions*. Shifts in the shape and/or parameters of multivariate probability distributions of climate variables lead to more or less substantial changes in hydrologic statistics, which form the basis for many of the water resources design decisions.

Alternative climate statistics were estimated on the basis of measurements made in a number of climatic stations located in the Warta basin and from predictions by Global Circulation Models (GCMs). Alternative temperatures were derived by adding the predicted changes from the GCMs to the 'historical' temperatures (IPCC Scientific Assessment, 1990, 1992). Similarly, the measured rainfall values were multiplied by precipitation change indicators which are predicted by the GCM scenarios. Of the six analysed scenarios, two were rejected because of poor agreement between observed data and the results of control runs implemented for $1 \times CO_2$ conditions. The other four scenarios are based on the equilibrium-type atmospheric models developed by the Geophysical Fluid Dynamics Laboratory (versions GFDL-R15 and GFDL-R30), the Goddard Institute for Space Studies and the Canadian Climate Center.

The temperature increments and precipitation ratios for the Warta catchment were obtained by interpolating grid values predicted by these models of the difference between simulated characteristics for $2 \times CO_2$ and $1 \times CO_2$ conditions. Results averaged over the whole basin are given in Table 3.

It can be seen that a large amount of uncertainty is associated with climate predictions. Differences among models in assessing changes in precipitation are particularly high with regards to the direction and magnitude of change. To determine a range of possible implications of global climate change on the region of interest, two scenarios were selected for the study: the *warm–dry* scenario predicted by the GFDL-R15 model, and the *warm–wet* scenario obtained from the GISS model.

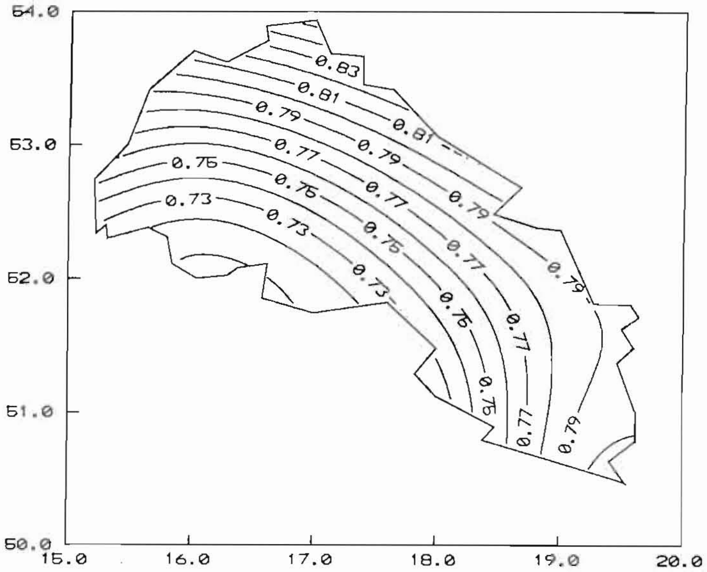

Figure 3. Percentage change of annual runoff for Warta River catchment (GFDL $2 \times CO_2$ scenario).

For the sensitivity assessment of Warta water resources to climate change, a conceptual lumped hydrologic model CLIRUN3 (climate/runoff model) was used (Kaczmarek, 1993). The model is based on the differential equation:

$$S_{\max} \frac{dz}{dt} = P - R_s(z, P) - R_g(z) - R_b - Ev(z, PET) \tag{1}$$

where $S_{\max}$ is the catchment water-holding capacity, z is a ratio of actual catchment moisture to $S_{\max}$, P and PET are average precipitation and potential evapotranspiration values for the current time-period, R_s represents the immediate (storm-induced) runoff, R_g is the delayed (soil-moisture-induced) runoff, and R_b is the baseflow independent of climatic fluctuations. All input variables are taken as uniformly distributed throughout the catchment. The CLIRUN3 model depends on three parameters: $S_{\max}$ and two parameters α and ε contained in non-linear relationships linking R_s and R_g with precipitation and with relative values of soil moisture. Parameters of the model were calibrated for more than 30 middle-size catchments all over Poland, and then interpolated to a grid of 1° resolution.

The water balance variables runoff, actual evapotranspiration and soil moisture were first calculated for each grid cell in the Warta catchment, and then averaged for monthly time-steps. Input data consisted of the 'historical' (1951–90) climatic statistics and the two selected $2 \times CO_2$ scenarios. Figures 3 and 4 show the spatial distribution of changes in annual runoff for the GFDL and GISS scenarios for the whole Warta catchment. Figure 5 shows the mean monthly runoff data from observation and for two climate scenarios at the Gorzów cross-section.

It can be seen that the *warm–dry* scenario may induce a serious decrease in the freshwater volume of the region, particularly for summer months. The mean annual discharge at the river mouth is estimated to be from 172 m^3/s (GFDL)

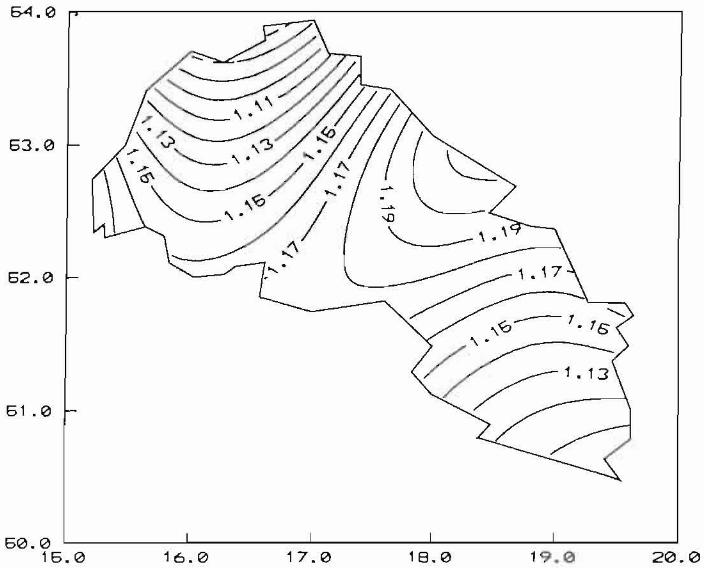

Figure 4. Percentage change of annual runoff for Warta River catchment (GISS $2 \times CO_2$ scenario).

to 256 m^3/s (GISS). For the Poznań gauging station (Upper and Middle Warta), the calculated annual discharge is approximately 74 m^3/s (GFDL) to 121 m^3/s (GISS). Time series of monthly inflows to the Jeziorsko and Sulejów Reservoirs were also generated by means of the CLIRUN3 model for 'historical' climatic data and for the GFDL and GISS scenarios. These results will be discussed later, in connection with the optimal operating rules for both dams under various climatic conditions.

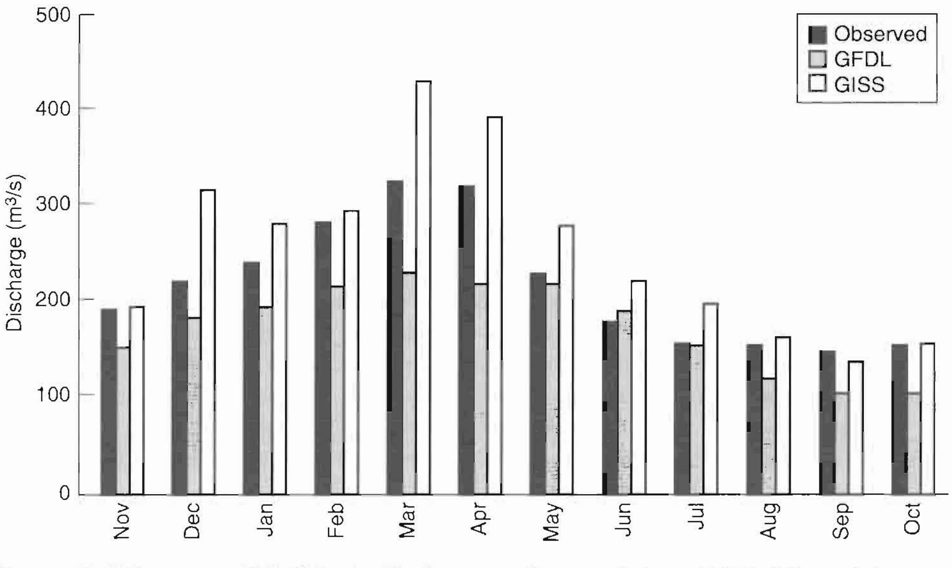

Figure 5. Mean monthly Warta discharges: observed data (1951–90) and for two climate scenarios with CO_2 doubling.

Climate and Water Requirements in the Warta River Basin

Water demands should be predicted in a way compatible with climate scenarios. Water planners usually assume growing requirements for reasons of population growth and economic development, but in many cases the resulting projections have not been realized (Stakhiv, 1993). In a water resources Master Plan (Hydroprojekt, 1976), estimates of water demands in the Warta river basin for 1990 were forecast to be 2.5 *times higher* than actual water use in that year. This example explains the level of uncertainty associated with non-climatic factors which determine water use on the national scale. The addition of one more uncertain factor—climate change—further complicates water resources planning procedures.

The results are reported in the literature of only a few studies on possible implications of global warming for domestic and industrial water use. Hanaki (1993) refers to a study on urban water demand in one city in Japan, where the planners predict a 3.3% increase in water use as a result of a +3.0°C change in annual air temperature. Kulshreshtha (1993) assumes that domestic and industrial water use per capita would increase by 5% in the warmer climate. In the present study we shall assume that:

- domestic water use will increase proportionally to population growth: i.e. 0.3% yearly;
- water demands in industry (excluding cooling waters) will increase according to expected GNP growth: about 3.0% yearly.

Predicting future irrigation demands in the Warta basin is a complex issue. First, it is the opinion of many authors (Szpindor & Piotrowski, 1986) that the present percentage of irrigated agricultural lands in Poland is much too low, even for the current climate conditions. Second, climate warming may necessitate an expansion of irrigated land and may also cause an increase in the water demand per unit of irrigated land, even in the case of enhanced precipitation. Finally, the increased concentration of CO_2 in the atmosphere may reduce irrigation demands owing to the antitranspirant effect of increased stomatal resistance. For the purpose of this study we assume that in Central Poland 15% of arable lands and 40% of greenlands should be irrigated. These are slightly lower figures than those proposed by water resource planners (Hydroprojekt, 1976) and agricultural scientists (Szpindor & Piotrowski, 1986).

Water requirements for one hectare of irrigated land were calculated for the GFDL and GISS climate scenarios by means of the CLIRUN3 model, following the approach of McCabe & Wolock (1992). We assume that irrigation should be applied during the months of intensive vegetation, i.e. from May to August, in order to sustain soil moisture storage at a level of 75% or greater of the catchment water-holding capacity. The amount of additional water needed for the vegetative season was estimated for each grid cell of the Warta catchment (1° resolution). Results of the calculations, averaged over the whole basin, led to the following water demands:

- 1400 m^3/hectare for current climate conditions,
- 2670 m^3/hectare for the GFDL $2\times CO_2$ climate, and
- 1460 m^3/hectare for the GISS $2\times CO_2$ climate.

Table 4. Water demands (m^3/s) in Warta Basin: (a) entire basin, (b) Upper and Middle Warta

	(a)			(b)		
Months	1990	2050 GFDL	2050 GISS	1990	2050 GFDL	2050 GISS
I–IV	18.7	44.9	44.9	15.1	36.9	36.9
V–VIII	44.4	110.7	80.9	31.2	74.2	57.3
IX–XII	18.7	44.9	44.9	15.1	36.9	36.9

The agricultural water demands for the entire basin could then be obtained by multiplying the above values by the required acreage of irrigated lands.

In conclusion, the estimated 1990 and 2050 water requirements for domestic use, industry and agriculture in the entire catchment and its upper and middle part are given in Table 4. The 2050 values were estimated under the assumption that CO_2 doubling will result in a 'new' equilibrium climate before that year. This hypothesis is disputable in light of possible mitigation actions aimed at reducing CO_2 emissions.

Comparison of water supply and demands for various climate conditions clearly shows that the latter would hardly be met in 2050, particularly for the upper and middle part of the basin for the GFDL scenario. Figure 6 shows the ratio of water requirements to mean monthly discharges in Poznań for this particular case. It should be remembered, however, that water withdrawn to meet domestic and industrial needs in most cases will be returned to the river (sometimes of deteriorated quality), and may be used again after treatment. Water used for irrigation will, however, evaporate or return delayed to the river network.

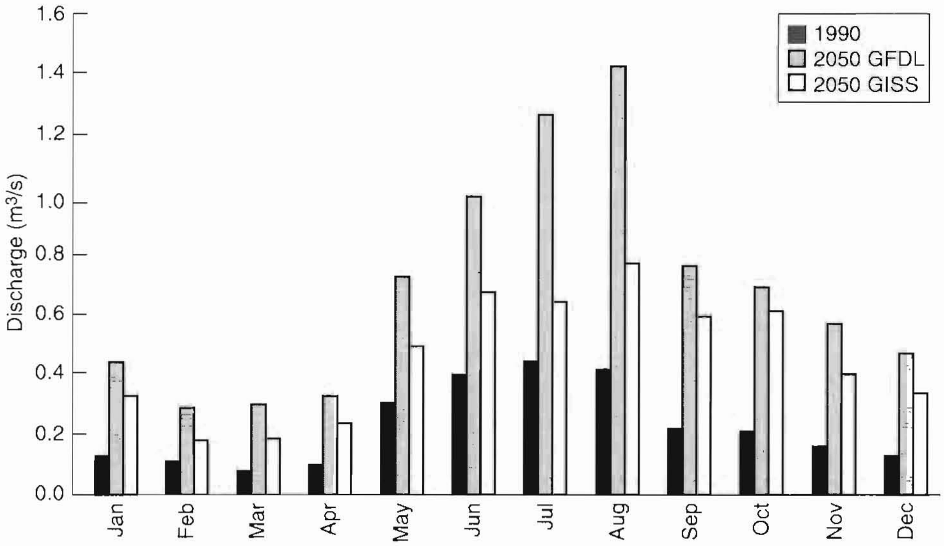

Figure 6. Ratio of water demands to water supply for Upper and Middle Warta basin for various climatic scenarios.

Table 5. Characteristics of reservoirs

Reservoir characteristic	Sulejów	Jeziorsko
Catchment area	4925 km^2	9063 km^2
Total storage capacity	75 MCM	192 MCM
Dead storage	14.5 MCM	19 MCM
Environmentally protected flow	9.3 m^3/s	10.3 m^3/s
Maximum allowed flow capacity	150 m^3/s	200 m^3/s

Table 6. Water demands to be met by Sulejów and Jeziorsko Reservoirs

	Sulejów		Jeziorsko	
	1990	2050	1990	2050
Water sector:				
Domestic use (I–XII)	4.37	5.55	0.54	0.80
Industry (I–XII)	0.70	2.28	1.17	3.81
Agriculture:				
May	0.11	0.19	2.67	18.5
June	0.11	0.19	2.67	22.2
July	0.11	0.19	2.67	18.5
August	0.11	0.19	2.67	14.8

A separate analysis was performed to estimate the required outflow from Jeziorsko and Sulejów Reservoirs to meet regional demands. In both cases it was required to release some amount of water to meet the environmental requirements of the river, as established by the Polish environmental legislation for protected flow Q_{env}.

Operation of Storage Reservoirs

The Sulejów Reservoir is located on Pilica River and its primary purpose is to supply the Łódź agglomeration. The Jeziorsko Reservoir on the Warta River operates with the aim of meeting water requirements in the Konin region (see Figure 2). The characteristics of these reservoirs are given in Table 5.

The outflow from both reservoirs in m^3/s that is required to meet current water demands, and that for the 2050 climate conditions (determined according to the discussion presented in earlier sections) are given in Table 6.

Assuming uniformly distributed annual water demands for the Łódź area and taking into account the environmentally protected flow, the total demands were estimated to be 14.4 m^3/s and 17.3 m^3/s in 1990 and 2050, respectively. The required total outflow from Jeziorsko for the non-vegetative period is equal to 10.0 m^3/s in 1990 and 14.9 m^3/s in 2050, while the average water demand for summer months is 14.7 m^3/s in 1990 and 33.4 m^3/s in 2050. These values were used as required outflow from the two dams in the optimization of their operation.

The water supply systems of Sulejów and Jeziorsko reservoirs were analysed by means of an optimization technique. The object of control, in both cases, is the retention S, the *inflow* denoted by d, and the *outflow* denoted by u. The downstream discharge and the water withdrawal from the reservoir are considered to be one variable and are therefore treated jointly in our model. The quantities d and u are considered as piece-wise constant functions and represented by sequences of average monthly values.

The reservoirs' performances were examined for several years, over a 12-month time horizon (May to April). A 40-year time series of monthly inflows to the reservoirs was used, based either on 'historical' data (1951–90), or on inflow values simulated by means of the CLIRUN3 model for the assumed climate scenarios. The objective function of the optimization problem under consideration can be written:

$$Q(u, S) = \sum_{j=1}^{12} [a_j^+(u_j^* - u_j)^2 + b_j(S_j^* - S_j)^2] \tag{2}$$

The performance index Q depends explicitly on controls u_j and the state trajectory S_j (reservoir contents). Other quantities which occur in its formulation are treated as parameters. These are:

(1) Water user demands u^*; the general aim of control is to satisfy them if possible.
(2) The reference state trajectory S_j^*; it was assumed that the operation of the reservoirs is carried out on annual bases in the following way:
  - By late December, the reservoirs normally are returned to low level to prepare the systems for the next flood season.
  - The storage reserve for flood control on 1 January was determined for controlling the flood. During the filling period, January–April, the reservoirs should be filled completely.
  - During May–November the water stored is used to meet municipal, industrial and irrigation needs.
(3) Weighting coefficients $a, b_j > 0$. In the optimization problem the following values of these parameters were used: $a_j = 1$ if demands are greater than outflow and $a_j = 0.2$ otherwise for $j = [1,12]$. One then avoids the eventuality of planning outflows exceeding demands. As far as the second coefficient is concerned, $b_j = 0.001$ for $j = [1,10]$, $b_{11} = 0.005$ and, $b_{12} = 0.01$. This conforms with the general objective of the control problem, which is aimed at the rational protection against water deficits and at reaching the 'minimal desired state' at the end of the water resources year in October.

Some initial calculations and tests were performed in order to calibrate the parameters, which were then fixed in simulation. In particular the value of the final reference state was chosen in an experimental manner. The objective function therefore assumes the form of a penalty function, taking the minimum value for $u_j = u_j^*$ and $S_j = S_j^*$ and and being subject to the following constraints:

(1) The reservoir state equation (mass balance)

$$S_{j+1} = S_j + d_j - u_j \tag{3}$$

(2) Initial condition of the system. We assume the upper limit of the reservoir as the initial condition (reservoir is filled after winter) for the first year. For subsequent years, the initial condition is equal to the state of the reservoir at the end of the previous year.

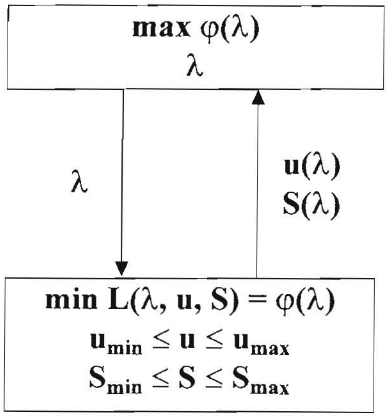

Figure 7. Two-layer optimizing control structure using price coordination.

(3) Constraints on the state of the system

$$S_{\min} \leq S_j \leq S_{\max} \tag{4}$$

in which $S_{\min}$ is the lower limit of the state variable and $S_{\max}$ is its upper limit.

(4) Flow constraints, the flow u during each month should be:

$$u_{\min} \leq u_j \leq u_{\max} \tag{5}$$

Application of the Hierarchical Optimizing Control scheme to solve the aforementioned problem requires adjoining the equality constraints (3) with Lagrange multiplier sequence 1 (prices)

$$L(u,S,\lambda) = \sum_{j=1}^{12} [a_j^+(u_j^* - u_j)^2 + b_j(S_j^* - S_j)^2] + \lambda_j(S_j - S_{j-1} - d_{j-1} + u_{j-1}) \tag{16}$$

To include the state-variable and outflow constraints the above problem is solved by means of the two-layer optimization method (Findeisen *et al.*, 1977; Salewicz & Terlikowski, 1981; Malinowski *et al.*, 1983; Terlikowski, 1993).

The Lagrangian function has a saddle point which can be assigned by minimizing $L(\lambda, S, u)$ with respect to S and u, and then maximizing with respect of λ. Finally, the optimization problem can be expressed in the form:

$$\max_{\lambda} \left[\min_{S,u} L(\lambda, S, u) \right] \tag{7}$$

and solved in a decentralized (coordinated) fashion. At this stage we make use of the additivity of the Lagrangian function (7) and the possibility of separating the decision variables. Figure 7 illustrates how the optimal control method works.

Simulation was performed for:

- historical monthly inflows to Sulejów reservoir (1950–90);
- synthetic monthly inflows for *warm–dry* scenario predicted by the GFDL-R15/CLIRUN3 models;
- synthetic monthly inflows for *warm–wet* scenario predicted by GISS/CLIRUN3 models.

Table 7. Mean monthly inflows to Sulejów Reservoir (m^3/s)

	Sulejów Reservoir			Jeziorsko Reservoir		
Month	Hist	GFDL	GISS	Hist	GFDL	GISS
May	23.4	21.8	24.2	46.3	48.5	67.4
June	22.6	20.2	22.6	41.1	41.8	59.7
July	22.9	16.2	29.7	38.7	35.5	59.7
August	23.2	13.2	28.8	41.2	32.5	49.5
September	19.0	12.1	23.6	35.4	28.7	39.5
October	22.1	11.3	21.9	39.2	28.1	40.2
November	23.9	16.2	18.2	45.5	33.5	49.2
December	26.2	15.9	19.5	51.7	33.2	48.5
January	26.1	17.2	21.3	52.3	35.2	51.9
February	30.3	18.2	22.4	62.3	42.2	59.3
March	36.8	20.1	25.1	70.6	48.8	68.2
April	32.5	22.0	25.5	60.1	46.9	74.9

The average monthly inflows to the reservoirs are given in Table 7.

In addition to the objective function, the control effects were evaluated by means of various performance criteria, namely:

- total deficit time during a year;
- maximum length of continuous deficit period;
- maximum relative (percentage) deficit;
- average relative deficit.

It should be emphasized that these quality criteria do not occur explicitly in the control algorithm. The results are described below.

For the Sulejów Reservoir no water deficit was observed for the GISS scenario. For historical data a deficit was noticed in two separate years, of 10 and 11 months' duration. For the GFDL scenario the longest deficit lasted 72 months. The probability of maximum and average relative water deficiencies, for historical and GFDL-based inflows, are shown in Figure 8. It can be seen that the *warm–dry* scenario may induce a serious decrease in freshwater supply for the Łódź region.

For the Jeziorsko Dam all needs are fulfilled 100% of the time for the three discussed cases. So, the question arises, can the surplus water be transferred to the catchment of the Noteć river through the existing channel? Earlier studies have shown that the irrigation water deficit in the Noteć catchment can be as large as 30 m^3/s. Hence a transfer of water to that catchment of up to 20 m^3/s during the summer months has been investigated. It seems (Figure 9) that during the summer months, about 15 m^3/s can be reallocated without causing any problems.

Adaptation Options and Conclusions

There are generally no accepted procedures for formulating regional water resource policies for adaptation to climate change. One reason is that the adaptation process involves *value judgement,* which is subjective and can be controversial (Carter *et al.*, 1994). The Warta study clearly shows that the basin's water supply and demand are both sensitive and vulnerable to climatic changes.

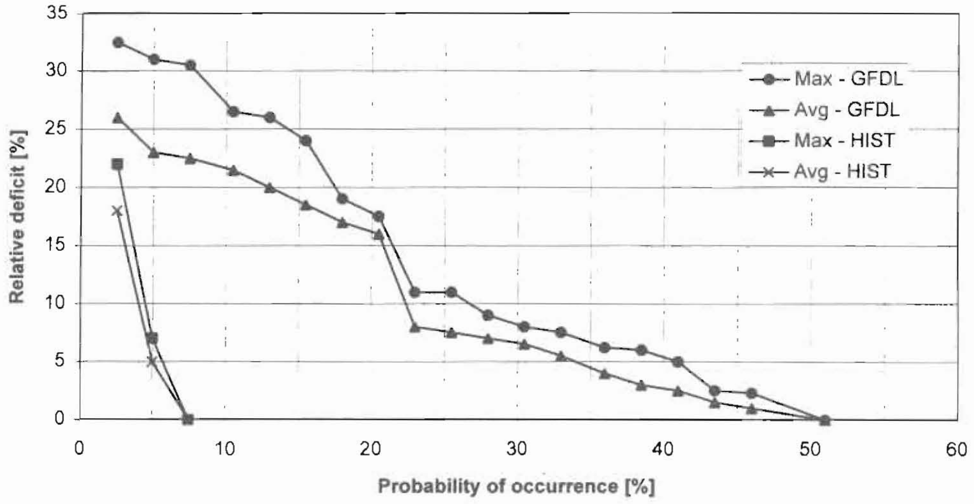

Figure 8. Relative maximum and relative annual water deficit versus probability of occurrence—Sulejów Reservoir.

Burton *et al.* (1993) have listed a number of approaches for coping with negative effects of climate change, such as *prevention of losses, tolerating loss, changing activity or location,* etc. All such actions require extensive social and economic analyses and long-term planning.

A comparison of supplies and demands for the whole Warta water resource system leads to the conclusion that available freshwater may be insufficient in the middle of the next century to meet various requirements. While demands for domestic and industrial use are likely to show only modest change, the expected increase of water used for irrigation may be dramatic, particularly for the GFDL

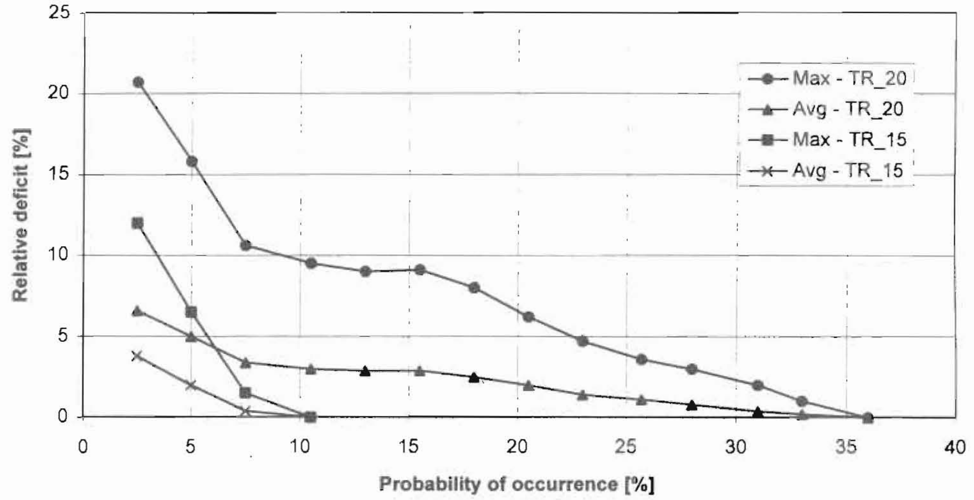

Figure 9. Relative maximum (MAX) and average (AVE) deficit in case of water transfer of 15 m^3/s (TR-15) and 20 m^3/s (TR-20) to Noteć catchment—Jeziorsko Reservoir.

scenario. Even optimal operation of existing reservoirs will not improve the situation in the basin as a whole, although reservoirs are likely to be able to secure reliable supply for the local sub-systems of the Łódź and Konin regions.

The list of possible adaptive responses that might be used to cope with future water deficits includes:

- conservation of water by various sectors of the economy;
- infrastructure development, e.g. constructing new storage reservoirs;
- transfer of water from other river basins; and
- improved management of existing resources.

There is strong social opposition in Poland to new, large-scale hydraulic investments. The reasons are the relatively high population densities, lack of land which could be used for creating additional water storage, environmental concerns and insufficient investment funds. All this leads to the conclusion that the most rational approach in adapting to future situations would be water conservation and improved management. One possible option is to reduce the acreage of irrigated lands and introduce drought-resistant crops. Food imports might be another solution. The experience of several European countries shows that water conservation measures are efficient and economically justifiable means of controlling domestic and industrial water use.

The critical part of this water resource system is the Upper and Middle Warta basin, extending up to the Poznań gauging station. For the GFDL-based hydrologic scenario, water in this part of the basin is able to support no more than 40% to 50% of the estimated demands in the summer months, and about 90% for the remainder of the year. While a 10% reduction in water use by cities and industry seems attainable, the agricultural sector would be seriously affected by changing climate conditions. This may be true also for other parts of the Polish Lowlands. The key recommendation resulting from the Warta study is to undertake an intensive research programme on the vulnerability of the national agricultural sector to climate change, with a particular emphasis on irrigation strategies.

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