POLSKA AKADEMIA NAUK
INSTYTUT GEOFIZYKI

PUBLICATIONS OF THE INSTITUTE OF GEOPHYSICS POLISH ACADEMY OF SCIENCES

E – 1 (295)

IMPACT OF CLIMATE CHANGE ON WATER RESOURCES IN POLAND

WARSZAWA 1997

Editorial Office
Instytut Geofizyki Polskiej Akademii Nauk
ul. Księcia Janusza 64, 01-452 Warszawa, Poland

SUBSCRIPTION
Subscription orders should be addressed directly to the Editorial Office. The list of issues to be published in 1997 is on the inside back cover.

ISBN-83-85173-65-X ISSN-0138-0133

Camera ready copy prepared by:
Dział Informacji i Wydawnictw Naukowych
Instytutu Geofizyki PAN
Printed and bound by:
Zespół Wydawniczy Centrum Badań Kosmicznych PAN
Warszawa, ul. Bartycka 18a

PUBLS. INST. GEOPHYS. POL. ACAD. SC., E-1 (295), 1997

IMPACT OF CLIMATE CHANGE ON WATER RESOURCES IN POLAND

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1. Introduction

With 1,500 m^3 of annual availability of per capita water supply, unevenly distributed in time and space, Poland is scarce in water in a large part of the country. A comparison of water availability in Poland and some European countries is shown in Fig. 1. Variations of country's runoff range between 34.4 km^3 in 1952 and 79.5 km^3 in 1981 (Fig. 2). Due to interannual and intra-annual variability (Fig. 3) of hydrologic processes, the reliable water resources, available by 95% of time, are equal to about 22 km^3. Due to environmental constraints only 30% to 40% of these resources may be effectively used by agriculture, industry, or population for residential needs. Despite of natural water scarcity and some improvements in last years, Poland's economy is still water intensive. For example, the efficiency of water use in industry is, at present, three to four times lower in Poland than in most of West European countries. Water demands in various sectors of Poland's economy are shown in Fig. 4. It can be concluded that water shortages observed in some years in several regions of the country are deeply rooted not only in natural scarcity, but also in inefficient water use and in the high level of water pollution.

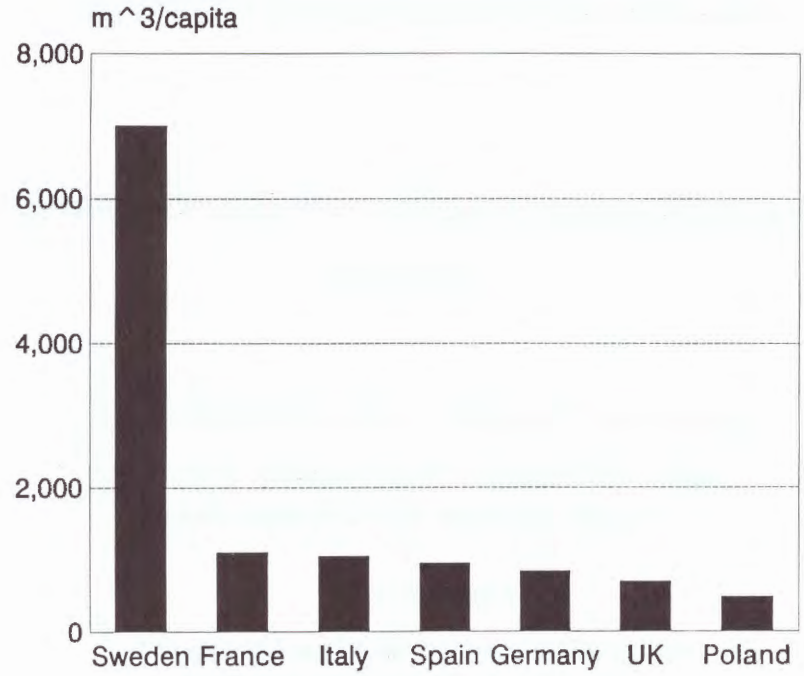

Fig. 1. Water resources *per capita* in selected European countries

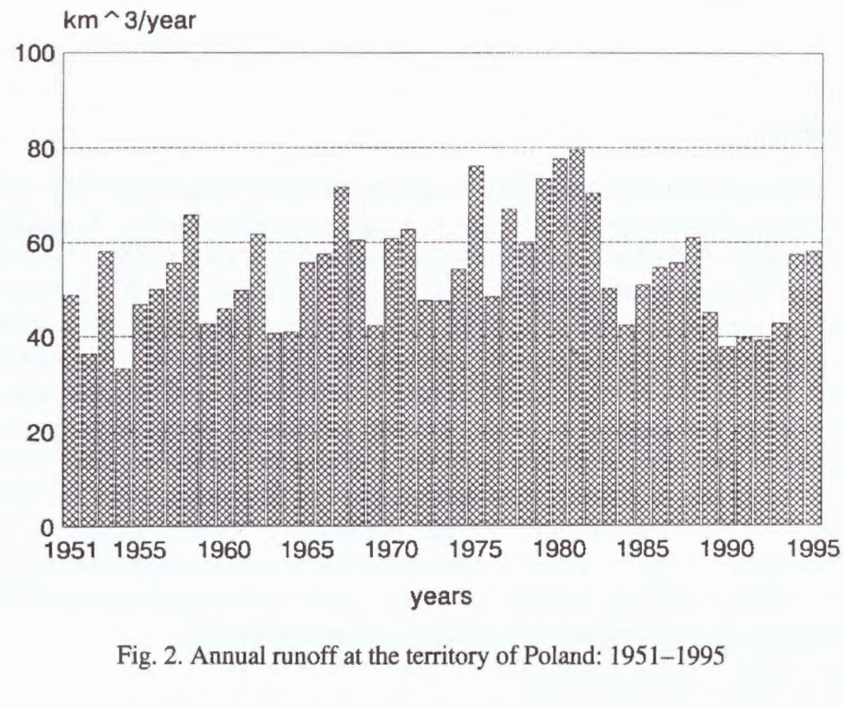

Fig. 2. Annual runoff at the territory of Poland: 1951–1995

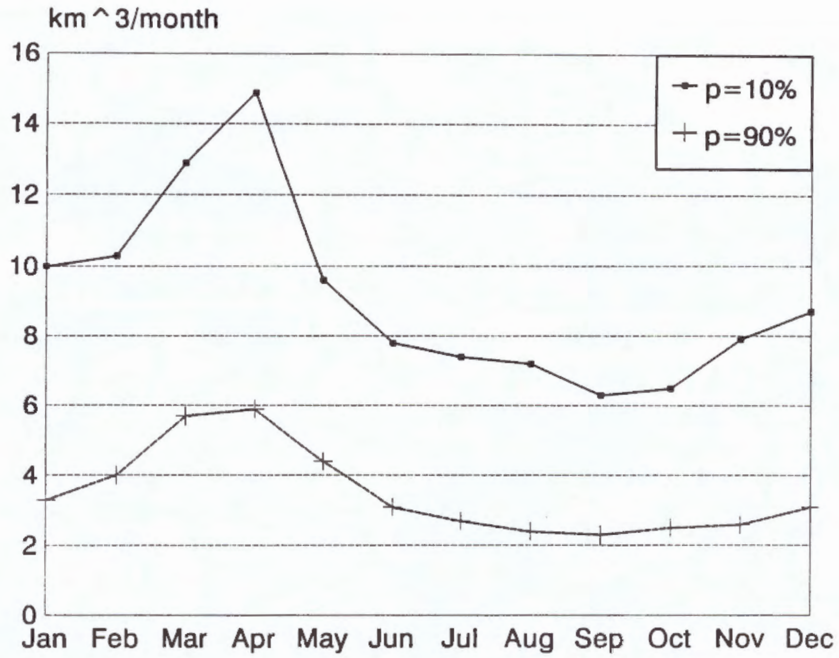

Fig. 3. Monthly runoff in Poland with exceedance probabilities of 10% and 90%

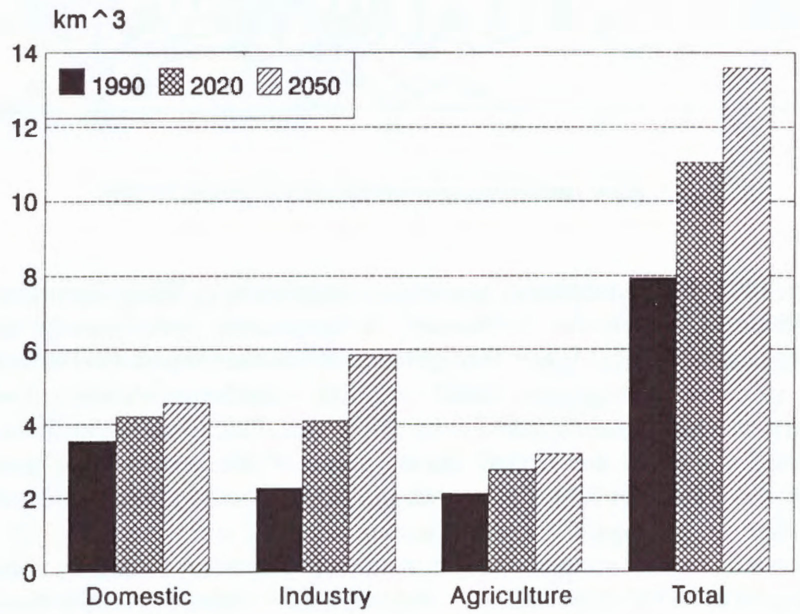

Fig. 4. Water demands in Poland in 1995

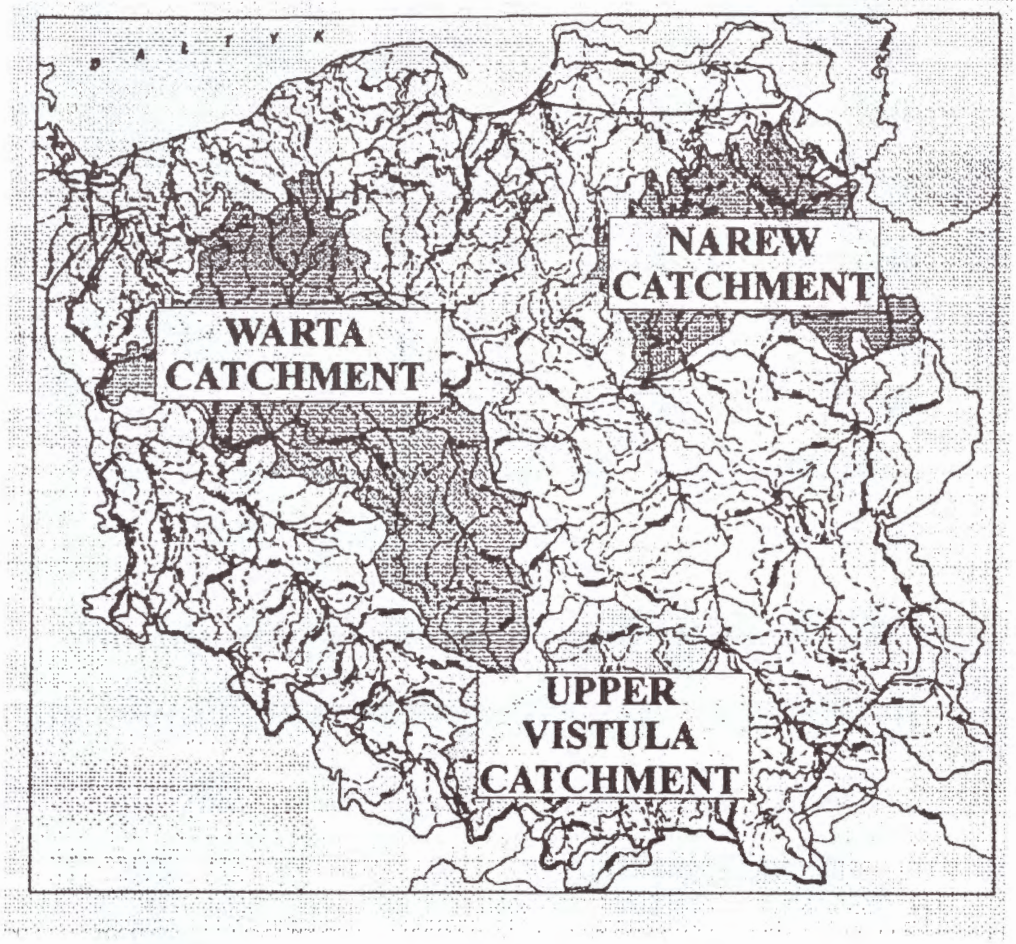

Fig. 5. River catchments selected for climate impact analysis

In years 1992–1995 a number of studies was undertaken by Water Resources Division of the Institute of Geophysics in Warsaw, in cooperation with research staff of the Institute of Meteorology and Water Management, on possible impact of climate change on hydrology and water management, based on 2*CO_2 equilibrium scenarios developed by the Geophysical Fluid Dynamic Laboratory (GFDL) and the Goddard Institute for Space Studies (GISS), both in the United States. Some of the results were published by Kaczmarek and Kindler (1996), Kaczmarek and Napiórkowski (1996), and Jurak (1992). There is, however, no general consensus among scientists and water resources managers in Poland on the possible scale of changes in climatic processes, caused by anthropogenic forcing. In spite of all the uncertainties accompanying the climate issue, the impact of such changes on water resources may create serious environmental and social problems, at least in some vulnerable regions of the country. In the long-term thinking on the future of national water policy, this issue should not be neglected, and the water resources impact of various scenarios of possible trends in geophysical processes should be investigated.

Recently, research staff of both institutes has been involved in a cooperative undertaking of several European institutions, aimed on assessing the impact of climate change on hydrological regimes and water resources in Europe. The study was implemented in years 1993–1997 with financial support of European Union. Its aim was to enhance knowledge on the vulnerability of regional water systems to climate change, based on a new generation of climate scenarios, with the following objectives:

1) Assessment of implications of climate change on hydrological processes in three river basins (Fig. 5) in Poland for time horizon 1990–2050;
2) Assessment of the potential impact of climate change on temperature regimes in Masurian lakes, including stratification patterns;
3) Systematic analysis of the performance and reliability of water resource systems in the face of possible changes in non-climatic and climatic factors.

River basins with different climatic, landscape and socio-economic conditions were selected for investigation. Basic catchment characteristics are provided in Table 1.

Table 1

Characteristics of river basins selected for the European Project

River: Gauging station:	Warta Gorzów	Vistula Sandomierz	Narew Ostrołęka
Catchment area [km^2]	52,404	31,846	21,862
Average catchment height [m]	126	375	136
Geographical coordinates	52.1 N 17.0 E	50.0 N 20.2 E	53.4 N 22.5 E
Mean annual temperature [°C]	8.0	5.3	6.8
Mean annual precipitation [mm/a]	610	840	660
Mean annual PET [mm/a]	690	660	640
Mean annual runoff [mm/a]	130	280	160

Water can become a barrier to sustainable development due to several mutually dependent factors, such as:

* Water scarcity depending on the relation between water supply and demand,
* Pollution of rivers, lakes and groundwater aquifers,
* Technological and economic shortcomings,
* Institutional impediments and low public awareness.

Climate impact assessment was undertaken with the understanding that the main indicators of water economy projected over the next decades will be influenced not only by climate, but also by population and economic growth, and technological progress. Some of these factors are quite removed from physical processes, and only the first two are partly dependent on climate change. Others are subject to policy decisions which, if rationally applied, may help to adapt water resources systems to non-stationarities of geophysical processes.

This paper summarizes methodological approach and main conclusions of the Polish component of the European Study. It also presents some of earlier results gained due to concession of national research grants and in framework of a Country Study Project *Strategies of the GHG Emission Reduction and Adaptation of the Polish Economy to the Changed Climate*, implemented under a contract between the Ministry of Environment, Natural Resources and Forestry, and several governmental organizations in the United States.

2. Climate scenarios

Similarly to most water resources impact studies reported in the literature, our investigations were based on interpolation of changes in some meteorological elements, as predicted by the global-scale climate scenarios. The expected temperature differences ΔT were added to measured temperature data. Similarly, in order to get rainfall characteristics for the year 2050, observed precipitation values were multiplied by the ratios rP of predicted by global circulation models (GCMs) for that year and for the control GCM's rainfall data.

Monthly data from years 1951 to 1990 of observed air temperature, air vapour pressure, wind speed, sunshine duration and precipitation at 21 climatic stations and about 300 precipitation gauges were used to estimate baseline climatic characteristics. Rainfall data were corrected for systematic instrumental errors, and adjusted to snow accumulation and snow melting processes by means of a model developed at the Institute of Geophysics in Warsaw. Mean monthly values of potential evapotranspiration were calculated by means of Penman formula, based on mean monthly data of air temperature, air humidity, wind speed and sunshine duration, using a software developed at the Institute of Meteorology and Water Management.

Potential evapotranspiration for year 2050 was estimated assuming *no change* in relative air humidity rh, wind speed u, sunshine duration S and albedo. The Penman formula was applied to calculate potential evapotranspiration for the year 2050, assuming that the air vapour pressure for that year depends on the temperature change, according to the formula (e_0 is the saturated vapour pressure):

$$e = rh \cdot e_0(T + \Delta T)\,. \qquad (1)$$

According to the agreement reached by scientists participating in the European Study, four climate scenarios were used to assess temperature and precipitation changes for the year 2050, based on the following GCMs:

* Canadian Climate Model (CCCM),
* Geophysical Fluid Dynamics Laboratory (U.S.A.) transient model (GFTR),
* Hadley Centre (U.K.) high resolution model (UKHI),
* Hadley Centre (U.K.) transient model (UKTR).

Temperature increments ΔT and precipitation ratios *rP* predicted for the year 2050 by the above models are given in Tables 2–5. Expected changes in temperature were also used for calculating adjusted winter precipitation due to snow accumulation and snow melting processes.

As can be seen, predicted changes in temperature and precipitation differ substantially among models. No method yet exists of providing confident predictions of future climate (Carter *et al.*, 1994), but the global circulation models are at present the only available tools for assessing the impact of increased concentration of "greenhouse" gases on future climate. They produce *scenarios* which, although highly uncertain, are used to assess a range of possible future situations the water managers may face in coming (Paoli, 1994).

Table 2

Climate change scenario for the year 2050: CCCM model

Month	ΔT			*rP*		
	Warta	Vistula	Narew	Warta	Vistula	Narew
Jan	1.1	1.4	1.4	1.03	1.10	.99
Feb	1.6	1.6	2.1	1.13	1.06	1.12
Mar	1.5	1.9	2.3	1.07	1.01	1.08
Apr	.9	1.1	1.2	1.09	1.02	1.06
May	.8	.8	.7	1.07	.99	1.03
Jun	.8	1.0	.8	1.03	1.01	1.02
Jul	.9	1.1	.9	.95	.97	.98
Aug	.8	1.0	.9	1.02	.94	1.09
Sep	1.1	1.1	1.1	.98	.95	.99
Oct	1.0	1.0	1.0	1.04	1.07	1.03
Nov	1.2	1.2	1.2	1.14	1.10	1.11
Dec	.8	.7	.7	1.13	1.12	1.10
Year	1.0	1.2	1.2	1.05	1.01	1.04

Table 3

Climate change scenario for the year 2050: GFTR model

Month	ΔT			*rP*		
	Warta	Vistula	Narew	Warta	Vistula	Narew
Jan	2.8	2.1	2.1	1.06	.99	.86
Feb	.8	.8	2.0	.99	1.01	1.17
Mar	2.9	3.3	3.7	1.12	1.14	1.29
Apr	2.8	2.5	3.0	1.27	1.25	1.10
May	.5	.1	.6	1.10	1.07	1.12
Jun	.7	.7	.0	1.16	1.19	1.08
Jul	.9	.2	.8	1.10	1.28	1.15
Aug	2.3	1.7	1.6	.90	.75	.82
Sep	3.6	3.5	2.8	.72	.63	.82
Oct	2.3	2.3	2.3	.87	.75	.87
Nov	1.3	.8	1.4	1.04	.93	1.06
Dec	2.3	2.3	3.0	.99	1.06	.93
Year	1.9	1.7	1.9	1.03	1.02	1.01

Table 4

Climate change scenario for the year 2050: UKHI model

Month	*ΔT*			*rP*		
	Warta	Vistula	Narew	Warta	Vistula	Narew
Jan	4.1	3.8	4.0	1.31	1.18	1.29
Feb	4.4	4.4	3.8	1.37	1.31	1.34
Mar	4.2	4.4	4.2	1.20	1.11	1.19
Apr	3.6	4.0	4.3	1.11	1.07	1.12
May	2.2	2.1	2.7	1.05	1.02	1.06
Jun	1.7	1.6	1.8	1.07	1.04	1.11
Jul	1.4	1.3	1.4	1.14	1.04	1.23
Aug	2.0	2.0	1.9	1.00	.94	1.02
Sep	2.0	2.1	1.8	.96	.95	1.00
Oct	2.3	2.6	2.5	1.10	1.06	1.09
Nov	2.2	2.4	2.6	1.06	1.08	1.10
Dec	3.4	3.3	3.6	1.27	1.20	1.29
Year	2.8	2.8	2.9	1.11	1.06	1.14

Table 5

Climate change scenario for the year 2050: UKTR model

Month	ΔT			rP		
	Warta	Vistula	Narew	Warta	Vistula	Narew
Jan	3.8	4.0	3.8	1.17	1.20	1.18
Feb	4.1	4.5	4.4	1.34	1.30	1.36
Mar	5.6	6.8	6.1	1.49	1.46	1.50
Apr	3.0	3.7	4.4	1.30	1.31	1.37
May	2.6	2.3	3.2	1.03	.97	1.09
Jun	1.7	1.5	1.8	1.21	1.10	1.15
Jul	2.2	2.1	2.4	1.11	1.14	1.16
Aug	2.2	2.3	2.0	1.02	.92	1.08
Sep	2.6	3.1	2.1	1.03	.99	1.02
Oct	2.2	2.3	2.7	1.10	1.12	1.09
Nov	3.6	4.3	4.9	1.39	1.30	1.41
Dec	4.3	5.0	4.7	1.24	1.29	1.30
Year	3.2	3.5	3.5	1.18	1.14	1.20

3. Changes in runoff and other water balance components

To assess the impact of climate on water resources, models linking the climatic and hydrological processes must be applied. There is a possibility of applying a range of approaches, from simple empirical relationships to complex conceptual models based on simplified representation of the processes involved in the hydrological cycle. They usually include certain number of parameters which need to be identified by means of calibration procedure, or estimated from empirical relationships with measurable catchment properties.

Authors of most of the climate change impact assessment studies applied conceptual hydrologic models, for which the important assumption is that the calibration done for current climatic conditions remains appropriate for changed climate. Although such an approach has been strongly criticized by some authors (e.g. Klemeš, 1996), the effect of this assumption can be, at least partly, evaluated by examining the performance of the model under consideration during extreme periods in the currently available data sets. It may be possible to evaluate how a particular model parameters might change (e.g. those reflecting vegetation cover), but very few studies have so far attempted this. The physical background of some conceptual models (e.g., the mass conservation law) means that their implied sensitivity to climate change is not as much dependent on current conditions as in the case of purely empirical (statistical) methods.

Time series of monthly values of catchment water storage, runoff and actual evapotranspiration were simulated in selected river basins and for assumed climate scenarios (current climate inclusive) by means of a conceptual hydrological model CLIRUN_3, elaborated at the Institute of Geophysics (Kaczmarek, 1994). The model is founded on monthly-step water balance equation:

$$S_{\max}\frac{dz}{dt} = P - R_s - R_g - R_b - E \qquad (2)$$

where $z = S/S_{\max}$, $S_{\max}$ is the total catchment capacity, $R_s(z,P)$ the immediate (surface and subsurface) runoff, $R_b(z)$ the delayed runoff, R_b the base flow, and $E(z,PET)$ the evapotranspiration. Substituting the above functional relationships into equation (2), one obtains after integration:

$$\int_{z_0}^{z_t}\frac{dz}{\Phi(z,P,PET,R_b)} = \frac{t}{S_{\max}} \qquad (3)$$

In the case of CLIRUN_3.1 version of the model, water balance components are conceptualized as follows:

$$R_s = \varphi_1(z,P) = \frac{\varepsilon P}{1+\varepsilon - z}; \quad R_g = \varphi_2(z) = \alpha z^2; \quad E = \varphi_3(z,PET) = \frac{PET}{3}(5z - 2z^2)$$

$$\Phi(z,P,PET,R_b) = \frac{(1-z^{\mu})P}{1+\varepsilon - z^{\mu}} - z^2\left[\alpha - \frac{2}{3}PET\right] - \frac{5}{3}z\,PET - R_b \qquad (4)$$

Parameters ε, α, $S_{\max}$ and μ have to be identified by means of model calibration. Solving equation (3) for given z_0, precipitation P, potential evapotranspiration PET, and R_b, one gets:

$$z_t = \phi(z_0, P, PET, R_b, S_{\max}, t) \qquad (5)$$

(for next time interval z_t becomes z_0). Average values of water balance variables for the time interval <0, t> are:

$$\overline{\varphi}_i(..) = \frac{1}{t}\int_0^t \varphi_i(..)dt \qquad (6)$$

or after replacing dt by dz:

$$dt = S_{\max} \frac{dz}{\Phi(z, P, PET, R_b)} \tag{7}$$

one gets:

$$\overline{\varphi}_i(..) = \frac{S_{\max}}{t} \int_{z_0}^{z_t} \frac{\varphi_i(..)}{\Phi(z, P, PET, R_b)} dz \tag{8}$$

For example:

$$\overline{R}_s = \frac{S_{\max}}{t} \int_{z_0}^{z_t} \frac{\varphi_1(z, P)}{\Phi(z, P, PET, R_b)} dz \tag{9}$$

Input data for each of the investigated catchments contain mean monthly values of precipitation and potential evapotranspiration for years 1951–1990, and for climatic conditions in the middle of next century as predicted by four scenarios. Mean monthly runoff (1951–1990) was used in the calibration procedure in order to identify model parameters. Output files include 40-year long time series of monthly catchment storage, immediate, delayed and total runoff, and actual evapotranspiration.

Table 6

Results of discharge simulation [m^3/s]: river Warta – station Gorzów

Month	hist			CCCM		GFTR		UKHI		UKTR	
	mean	σ	ρ	mean	σ	mean	σ	mean	σ	mean	σ
Nov	202	70	–	209	73	183	61	209	76	241	92
Dec	237	107	.89	262	155	221	84	294	249	338	291
Jan	250	98	.83	276	110	248	88	322	144	351	154
Feb	271	89	.69	308	109	263	85	373	179	408	206
Mar	296	104	.68	325	115	284	92	372	161	436	237
Apr	276	75	.61	294	80	269	72	309	87	353	109
May	235	64	.84	248	70	235	67	253	73	279	83
Jun	200	53	.76	209	56	211	59	212	58	240	69
Jul	187	59	.54	190	60	203	70	204	71	223	82
Aug	175	59	.75	176	60	178	63	184	67	198	74
Sep	166	52	.88	165	53	153	49	168	55	181	61
Oct	173	62	.82	173	63	152	53	178	69	190	73
Year	222	–	–	236	–	216	–	256	–	286	–

Table 7

Results of discharge simulation [m³/s]: river Vistula – station Sandomierz

Month	hist			CCCM		GFTR		UKHI		UKTR	
	mean	σ	ρ	mean	σ	mean	σ	mean	σ	mean	σ
Nov	253	127	–	272	146	195	76	266	140	325	185
Dec	232	99	.51	262	125	235	106	327	170	408	209
Jan	208	74	.51	255	101	216	73	322	135	355	154
Feb	250	119	.18	335	185	238	104	447	264	473	272
Mar	356	204	.37	413	198	385	169	420	161	543	228
Apr	429	155	.10	392	132	392	143	351	107	428	142
May	361	152	.21	342	140	353	153	323	126	338	126
Jun	367	132	.31	352	128	436	181	346	130	388	150
Jul	369	227	.34	342	204	552	426	360	227	435	307
Aug	323	166	.62	289	143	291	134	294	148	309	157
Sep	245	91	.67	220	79	179	52	219	79	234	85
Oct	244	180	.45	234	177	166	83	231	174	249	198
Year	303	–	–	309	–	303	–	325	–	374	–

Table 8

Results of discharge simulation [m³/s]: river Narew – station Ostrołęka

Month	hist			CCCM		GFTR		UKHI		UKTR	
	mean	σ	ρ	mean	σ	mean	σ	mean	σ	mean	σ
Nov	115	65	–	124	74	103	51	132	80	161	110
Dec	122	85	.89	137	105	121	82	179	144	210	162
Jan	114	49	.82	129	56	110	44	177	97	183	95
Feb	123	52	.71	153	77	124	52	204	114	223	124
Mar	153	69	.49	189	147	172	124	221	165	263	189
Apr	158	70	.25	151	53	137	46	161	57	188	79
May	122	34	.75	122	35	118	35	126	37	139	45
Jun	107	25	.67	108	26	109	28	113	28	122	32
Jul	97	31	.57	95	30	106	37	113	42	113	41
Aug	91	35	.79	94	38	87	32	101	43	104	45
Sep	90	41	.79	91	44	79	31	96	47	99	50
Oct	103	83	.76	105	87	84	51	119	128	121	130
Year	116	–	–	125	–	112	–	145	–	160	–

Based on results of CLIRUN_3 calculations, mean values and standard deviations of simulated monthly discharges for three river basins and analyzed scenarios are presented in Tables 6–8 (coefficients of correlation were estimated based on observed discharge data, and refer to a given month and the preceding month).

For example, Fig. 6 shows a comparison between observed and simulated (for the current climate) average discharges for Warta river basin. Figure 7 presents ratio Q_{sce}/Q_{hist} of Upper Vistula average monthly discharges for some scenarios.

Simulated discharge statistics differ highly depending on the climate model applied. For some scenarios a slightly decreasing trend in runoff and soil moisture in Central Poland during the drought period has been noticed. A shift in floods occurrence from March–April to January–February may be observed, probably due to changes in snow accumulation and melting processes. The above conclusions should be, however, interpreted as a preliminary assessment of possible changes of hydrological regime in Poland due to climate change. Further studies are evidently needed to evaluate a range of expected disturbances in water resources supply, for making improved versions of global atmospheric models.

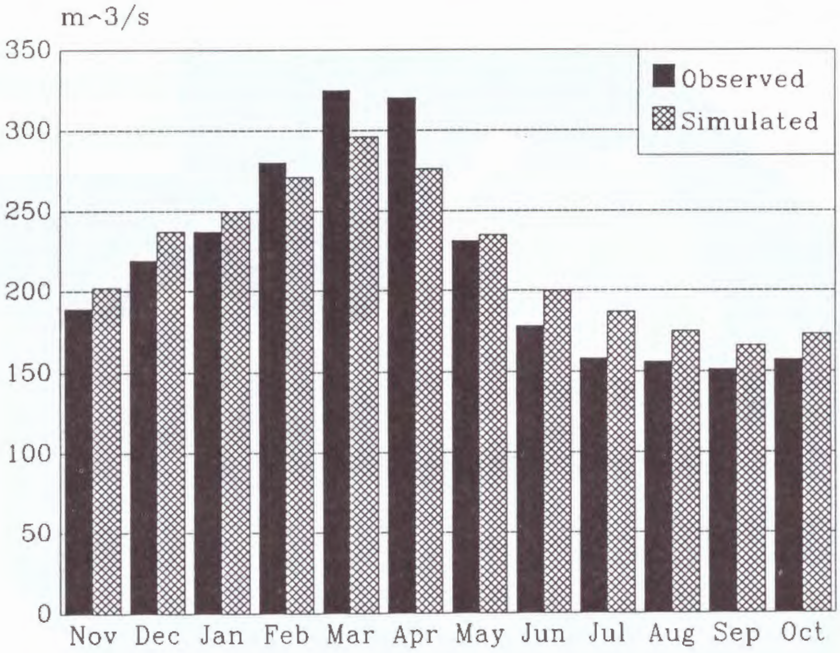

Fig. 6. Comparison of observed and simulated discharges for Warta river

For some climate scenarios a significant increase of discharge variance has been detected. In order to assess a possible effect of this phenomenon on reliability of water supply, a sensitivity analysis of an impact of changes in precipitation and potential evapotranspiration *variability* on guarantied runoff was done. Assuming that monthly discharges may be represented by the Markowian stochastic process, the joint probability:

$$P_s(q) = Prob(Q_1 \geq q, \ldots Q_s \geq q) = P(Q_1 \geq q)\prod_{2}^{s-1} P(Q_i \geq q \mid Q_{i-1} \geq q) \qquad (10)$$

was calculated for Warta river, Upper Vistula river, and Narew river, using the following arbitrary scenarios:

A. Baseline climatology $\sigma(P)$ and $\sigma(PET)$ observed in 1951–1990,

B. $\sigma(P)$ increased by 20%, and *PET* observed,

C. $\sigma(P)$ observed, and $\sigma(PET)$ increased by 20%,

D. Both $\sigma(P)$ and $\sigma(PET)$ increased by 20%.

Results are shown in Figs. 8–10. It can be concluded that the increase of rainfall variability may have a significant impact on reliability of water supply, while the latter is relatively insensitive to changes of *PET* variability.

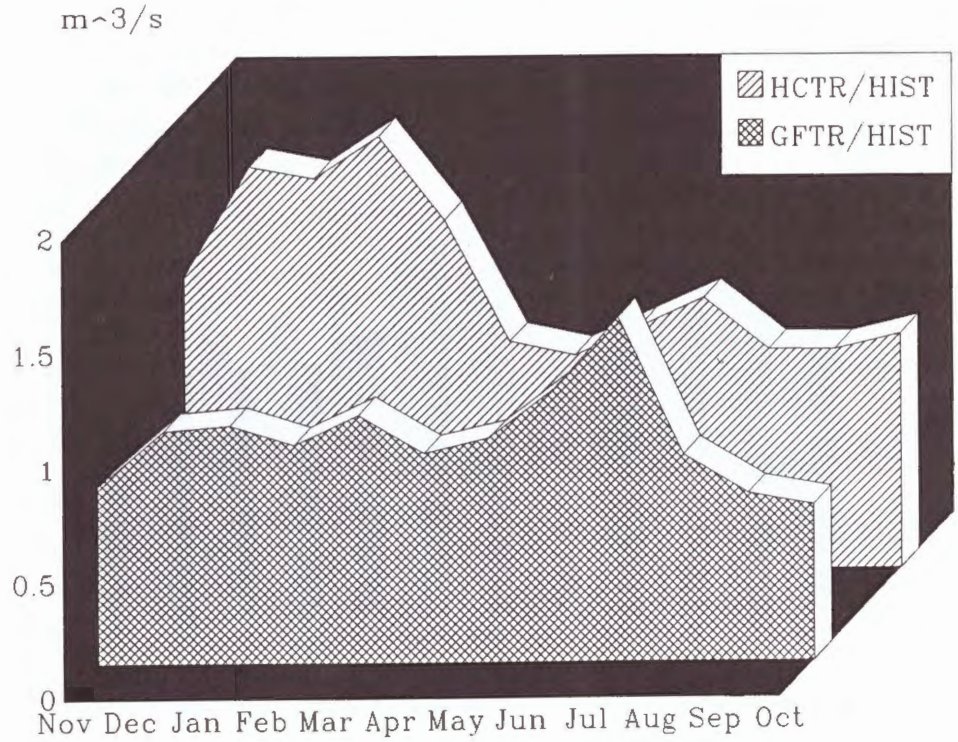

Fig. 7. Expected discharge changes in Upper Vistula basin

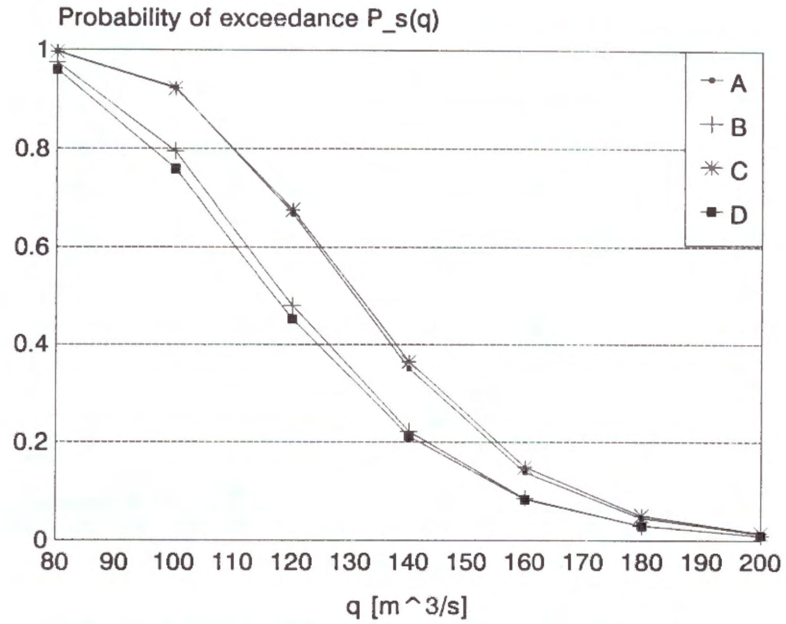

Fig. 8. Sensitivity of runoff to variability of *P* and *PET*: Warta river

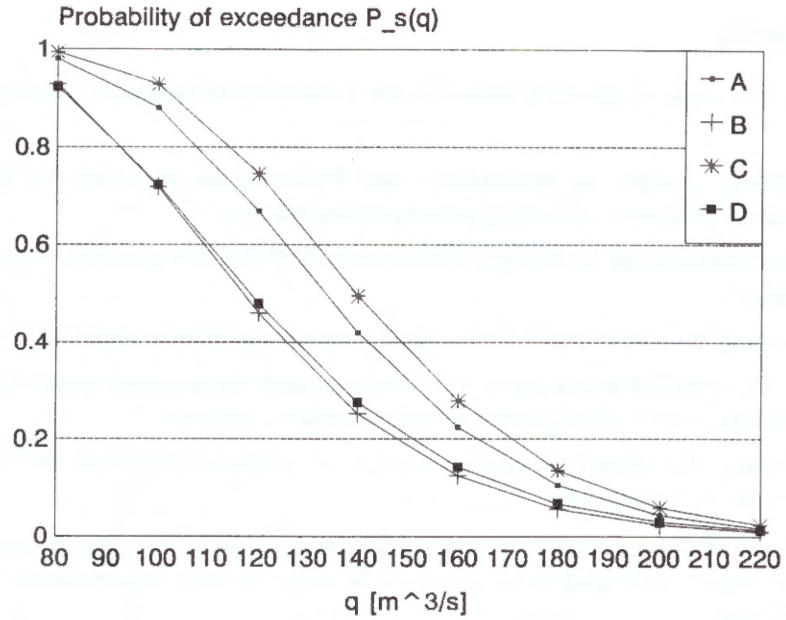

Fig. 9. Sensitivity of runoff to variability of *P* and *PET*: Upper Vistula river

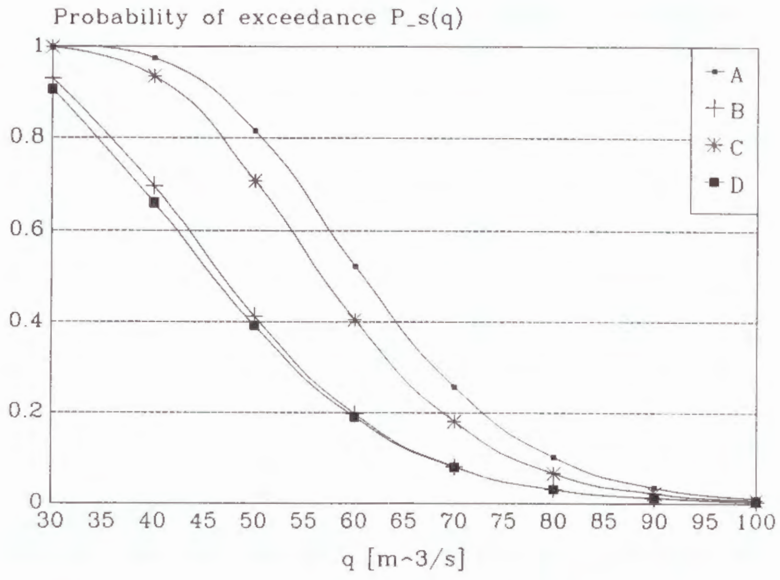

Fig.10. Sensitivity of runoff to variability of *P* and *PET*: Narew river

4. Impact of climate change on water management

4.1. Introduction

At least five areas of research related to the climate/water resources interface may be identified:

a) Detecting changes in atmospheric and hydrological variables by means of measured indicators, including paleohydrological data;
b) Parameterization of hydrologic components of global and mesoscale atmospheric models;
c) Assessing the sensitivity of land surface processes to climate characteristics;
d) nalyzing possible implications of climate change on regional water supply and Ademand, and on management of water resources systems;
e) Assessing the impact of climate change on physical, chemical and biological processes in water bodies.

The progress in all these directions in the last decade is evident, but most of the relevant theories and models still need to be improved in order to meet requirements of water resources practice.

Any climate/water resources impact assessment study should allow to answer a number of questions important for policy decision making. These are:

a) Does the water system under consideration is able to fulfil all required tasks for the current socio-economic, climatic and hydrologic conditions?
b) If not, what action should be taken to improve the situation?
c) Will the system be able to meet all instream and offstream water requirements 20 to 50 years from now, assuming stationarity of natural (geophysical) processes? How certain are the predictions?
d) If not, what kind of structural and non-structural measures must be foreseen to enhance system's ability to cope with water deficits and/or with floods?
e) To what extent a water resource system may be affected as a result of climate change? How to deal with uncertainties accompanying the issue?
f) What are the adaptation options? How the analysts should communicate with decision makers in order to demonstrate that there is a problem to be addressed, conveying at the same time the list of uncertainties attached to climate predictions?

Clarification of some of these questions was the main purpose of our study in the framework of the European Project on Climate and Water Resources.

The 1990 and 1992 Intergovernmental Panel on Climate Change published two Assessment Reports, outlining extensive difficulties in conducting meaningful analyses of climate change impacts on hydrology and water resources (Shiklomanov *et al.*, 1990; Stakhiv *et al*, 1992). Since then, many studies have been implemented for different river basins - almost exclusively in developed countries. Their results were summarized in the third IPCC Report (Kaczmarek *et al.,* 1996a). Uncertainties of climate change impact analysis, especially at the catchment scale, remain large. It is necessary to distinguish between the physical effects of climate change, and the impacts which reflect a societal value placed on a change in some physical quantity. The impact highly depends on the characteristic of the water use system: in some cases a large climate change effect may have a small impact while in water scarce regions a small change may have a dramatic impact.

Several possible effects of global warming on water supply and demand within a catchment or water supply area may be distinguished. The relative importance of them varies considerably among catchments, depending not only on the hydrology, but also on the characteristics of the supply system. For example, a conjunctive use system involving several reservoirs, river regulation and groundwater boreholes will be affected differently than a supply system based on direct abstractions from an un-regulated river.

Studies that have considered possible changes in water supply in specific areas fall into three groups. The first infers changes in potential supply directly from modelled changes in the catchment water balance. Problems in maintaining summer supplies from direct river abstractions may be inferred, for example, if summer river flows are simulated to decline (Arnell and Reynard, 1993). The second group of research has considered the sensitivity of supply systems - usually single reservoirs - to changes in inputs. The third group of studies consists of investigations into specific water supply systems. Some have looked at individual reservoirs or groundwater resource systems; others have examined entire integrated water supply systems including real system operating rules.

In order to analyze possible water management adaptation measures, necessary in Poland in the case of expected changes in global geophysical processes, the following steps were implemented:

a) Water demands (domestic, industry, agriculture) for years 1990 and 2050 due to *non-climatic* factors were estimated for the whole country, and for Warta and Vistula river basins;
b) An impact of climate change scenarios on irrigation water requirements has been estimated by means of two models: CROPWAT, developed by the UN Food and Agriculture Organization, and IRDEM, developed by the Institute of Geophysics);
c) An impact of climate change on reservoir management in the upper part of Vistula basin (Goczałkowice - Tresna system), and in the Warta basin (Jeziorsko reservoir) has been analyzed.

4.2. Assessment of future water demands

To date, trends in water demands caused by demographic and socio-economic factors were, in most cases, identified without reference to possible changes in environmental conditions, including climate. The experience of water management agencies in various countries demonstrates that socio-economic processes influencing water use cannot be accurately predicted for long time horizons. In most of the past studies done in Poland to formulate long-term Poland's water strategy, future demands were highly overestimated. It may be expected that even more difficult will be to assess possible implications of climatic change on future water requirements.

Table 9

Annual water demands [km^3] in Poland

Sector	1990	2020 GFDL	2020 GISS	2050 GFDL	2050 GISS
domestic	2.54	3.25	3.22	3.78	3.71
industry	2.27	4.09	4.09	5.84	5.84
agriculture	2.12	3.00	2.77	3.81	3.19
others	1.00	1.09	1.09	1.12	1.12
total	7.93	11.43	11.17	14.55	13.86

Water withdrawal in Poland in 1990 was equal to 7.93 km^3, distributed among sectors as shown in Table 9. According to our estimates, water demands in the middle of next century may increase due to non-climatic factors by about 70 percent. There is limited information on the possible effect of temperature and precipitation changes on water requirements in various sectors of Poland's economy. Preliminary guess, based mostly on literature, leads to a conclusion that temperature increase will have a moderate impact on industrial and domestic water use. A highly uncertain user is agriculture, which at present uses for irrigation relatively small proportion of total withdrawals. The situation may, however, change because a present threshold between irrigated and non-irrigated agriculture may be surpassed in most of Poland's territory in warmer climate.

In the frame of the Country Study Project (see the Introduction) it was assumed that the area of irrigated agriculture in Poland may increase from the present value of 1.5% to about 4.0% in 2050. The latter figure corresponds to the current level of irrigation in some West-European countries where the average temperature is about 2°C higher than in Poland. To estimate water requirement for one hectare of irrigated land, a model IRDEM was developed at the Institute of Geophysics and applied in various regions of the country. The key assumption of IRDEM is that the amount of water used for irrigation should allow to sustain the catchment storage level equal or higher than 75% of the catchment capacity. The output files from the water balance model CLIRUN_3 were used as input files to IRDEM. Calculations were implemented for "historical" data (1951–1990), and for two equilibrium GCMs: Geophysical Fluid Dynamic Laboratory of NOAA, and Goddard Institute for Space Studies.

According to the above assumptions, water demands were estimated for years 2020 and 2050, for the whole Poland (Table 9) and for selected river basins (Kaczmarek and Napiórkowski, 1996). Similar calculations were repeated for CCCM, GFTR, HCHI and HCTR scenarios, but only for two water resource systems: Upper Vistula and Jeziorsko, details of which are described below.

4.3. Upper Vistula water supply system

Structure and objectives

The Upper Vistula water resources system consists of two aggregated reservoirs located on two rivers (Soła river and Vistula river) and of five main water users. The scheme of the system is presented in Fig. 11, and reservoir characteristics are given in Tables 10 to 12.

Table 10

Characteristics of Tresna and Goczałkowice reservoirs

Reservoir	Tresna	Goczałkowice
catchment area [km^2]	1095.0	522.0
total storage capacity V_{max} [mln m^3]	139.7	202.8
dead storage V_{min} [mln m^3]	13.6	20.0
flood control zone [mln m^3]	27.0	30.4

Major objectives of the Upper Vistula system are: to secure water supply for the industrial and municipal water users, namely Katowice and Bielsko agglomerations; to supply the steel works "Katowice" via the Dziećkowice reservoir, and to supply water to the chemical plant Oświęcim and fish farms around the town of Kęty. At the same time, concentration of pollutants discharged mainly to the Vistula river downstream of the outlet of the Przemsza river should be maintained at the levels compatible with water quality standards.

Table 11
Inflow statistics [m^3/s] to Goczałkowice reservoir for various scenarios

Month	HIST mean	HIST s.dev.	CCCM mean	CCCM s.dev.	GFTR mean	GFTR s.dev.	UKHI mean	UKHI s.dev.	UKTR mean	UKTR s.dev.
Nov	4.2	2.7	4.6	3.1	3.1	1.9	4.5	3.0	5.7	4.1
Dec	7.4	4.3	8.8	5.3	7.9	4.7	12.0	7.6	15.3	10.0
Jan	5.8	3.8	8.0	6.1	6.6	5.0	11.0	10.2	11.8	11.0
Feb	6.7	4.3	9.0	6.0	6.0	3.8	11.7	8.2	12.1	8.5
Mar	10.0	4.8	10.8	5.6	10.7	5.6	10.9	7.0	14.0	9.5
Apr	11.0	5.9	9.4	4.6	10.1	4.9	8.4	3.9	10.4	4.8
May	8.0	5.2	7.5	4.7	8.1	5.1	7.3	4.5	7.2	4.3
Jun	10.1	8.7	9.7	8.4	12.8	11.6	9.8	8.5	10.8	9.7
Jul	11.3	10.6	10.5	9.8	17.3	16.9	11.5	10.9	13.5	13.2
Aug	7.7	8.7	6.8	7.6	6.3	6.5	7.2	8.0	7.1	7.8
Sep	5.3	3.9	4.6	3.4	3.3	2.3	4.7	3.5	4.9	3.7
Oct	5.9	6.8	5.7	6.7	3.6	3.6	5.7	6.7	6.1	7.2
Year	7.8	–	7.9	–	8.0	–	8.7	–	9.9	–

Table 12
Inflow statistics [m^3/s] to Tresna reservoir for various scenarios

Month	HIST mean	HIST s.dev.	CCCM mean	CCCM s.dev.	GFTR mean	GFTR s.dev.	UKHI mean	UKHI s.dev.	UKTR mean	UKTR s.dev.
Nov	8.7	6.3	9.5	7.1	6.3	4.1	9.4	6.8	11.7	9.0
Dec	13.7	8.1	16.2	10.0	14.6	8.9	21.8	13.8	27.6	17.9
Jan	9.5	7.7	13.1	11.6	10.6	9.1	17.4	16.9	18.7	18.3
Feb	10.8	8.9	14.2	11.2	9.4	7.2	17.6	13.3	18.2	13.7
Mar	20.3	9.5	21.6	9.4	21.4	10.2	21.3	11.5	27.6	17.9
Apr	24.9	13.2	21.2	9.7	22.6	10.3	18.7	7.5	23.1	9.5
May	16.3	8.3	15.3	7.7	16.4	8.3	14.7	7.3	14.6	7.0
Jun	18.9	10.9	18.1	10.4	23.8	14.3	18.5	10.8	20.1	11.8
Jul	21.9	19.7	20.3	18.2	33.5	31.4	22.2	20.3	26.1	24.6
Aug	13.9	10.5	12.4	9.2	11.5	7.8	12.9	9.6	12.9	9.4
Sep	10.7	7.2	9.4	6.2	6.7	4.0	9.6	6.3	10.0	6.7
Oct	9.4	8.9	9.1	8.8	5.7	4.5	9.1	8.7	9.6	9.4
Year	14.9	–	15.0	–	15.2	–	16.1	–	18.3	–

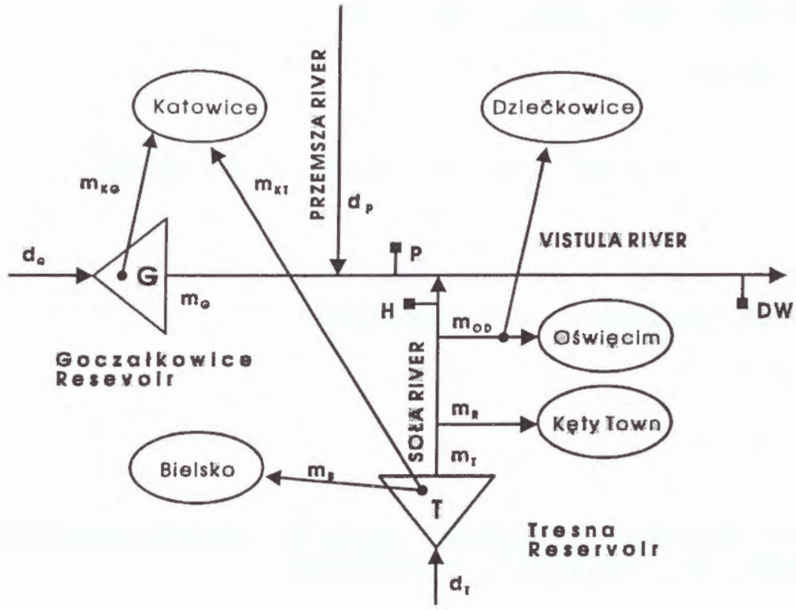

Fig.11. Upper Vistula water resources system

Formulation of optimization problem

The purpose of the Upper Vistula optimization model was to analyze relationships between flow rates in the rivers and in the conduits delivering water to users over a long time horizon (one year) with the discretization period of one month. Therefore, only the dynamics of the storage reservoirs is considered, while effects of dynamics of flow in the river channels are neglected. The following notation will be used:

j - number of month

V^j - state of the reservoir at time j

d^j - natural inflow to the reservoir or to the river at time j

u^j - flow in a given cross-section

z^j - water demands at time j

m^j - outflow from the reservoir or water supply, a control variable at time j

S^j - pollutant load discharge at time j (kg/m^3)

C^j - admissible pollutant concentration at time j

and the subscripts refer to: B – Bielsko; D – Dziećkowice reservoir; DW – control cross-section at Vistula river; G – Goczałkowice reservoir; H – control cross-section at Soła river; O – Oświęcim; P – control cross-section at Vistula river (down Przemsza river); R – fish farms; T – Tresna reservoir.

State equations for the system of reservoirs are:

$$V^{j+1} = V^j - B \times m^j + C \times d^j \tag{11}$$

where:

$$V = [V_T, V_G]; \qquad m = [m_T, m_G, m_B, m_{KT}, m_{KG}]; \qquad d = [d_T, d_G] \tag{12}$$

$$B = \begin{bmatrix} 1 & 0 & 1 & 1 & 0 \\ 0 & 1 & 0 & 0 & 1 \end{bmatrix}; \qquad C = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}. \tag{13}$$

and flow balance equations for control cross-sections:

$$u_p^j = m_G^j + d_P^j, \tag{14}$$

$$u_H^j = m_T^j - m_R^j - m_{OD}^j, \tag{15}$$

$$u_{DW}^j = u_P^j + u_H^j. \tag{16}$$

The objective function of the optimization problem for any month and for annual time horizon can be written in the form of a penalty function:

$$\begin{aligned} Q(m,V) = \sum_{j=k}^{k+T} \Big[& a_B^{+j}(m_B^j - z_B^j)^2 + a_R^{+j}(m_R^j - z_R^j)^2 + a_{OD}^{+j}(m_{OD}^j - z_{OD}^j)^2 \\ & + a_K^{+j}(m_{KT}^j + m_{KG}^j - z_K^j)^2 + a_P^{+j}(u_P^j - S_P/C_P)^2 + a_{DW}^{+j}(u_{DW}^j - S_{DW}/C_{DW})^2 \\ & + a_H^{+j}(u_H^j - z_H^j)^2 + b_T^j(V_T^j - V_T^{*j})^2 + b_G^j(V_G^j - V_G^{*j})^2 \Big] \end{aligned} \tag{17}$$

In equation (17) symbols a and b with respective subscripts denote weighting coefficients, while C_P and C_{DW} denote values of pollutant concentration which should not be exceeded at the cross-sections P and DW. Inserting relations (14), (15) and (16) into (17) the performance index Q can be expressed explicitly on controls m^j and the state trajectory V^j (reservoir contains):

$$Q(m,V) = \sum_{j=k}^{k+T} Q(m^j, V^j). \tag{18}$$

Other quantities are treated as parameters. The following data were used for economic and demographic conditions of the year 1990:

* water demands of Oświęcim, Bielsko, Katowice and at H cross-section are $z_{OD} = 5.0$ m^3/s, $z_B = 3.5$ m^3/s, $z_K = 9.0$ m^3/s and $z_H = 5.0$ m^3/s;
* the fish farm water demands vary from 6.0 m^3/s in spring and summer to only 1.0 m^3/s in winter;
* at the cross-sections P and DW concentration of pollutants should not exceed $C_P = 0.016$ kg/m^3 and $C_{DW} = 0.014$ kg/m^3.

Water demands in industry for the year 2050 were evaluated according to expected GNP growth, with assumed rationalization of water use, and in domestic sector proportionally to the population growth in the area.

4.4. Jeziorsko reservoir system

Structure and objectives

Jeziorsko reservoir is located on the Warta river (Fig. 12) and operates with the aim to meet water requirements in the Konin region, as well as to limit flood losses in the middle and lower stretches of Warta river. Reservoir characteristics are given in Table 13. In order to estimate the agricultural water demands in five administrative regions belonging to the upper and middle part of the Warta catchment it was assumed that the current irrigation level of 1.7% of arable lands (1.97 mln ha) will increase to 4.0% in 2050. To estimate water requirement per hectare of irrigated land, the IRDEM model was applied for summer months.

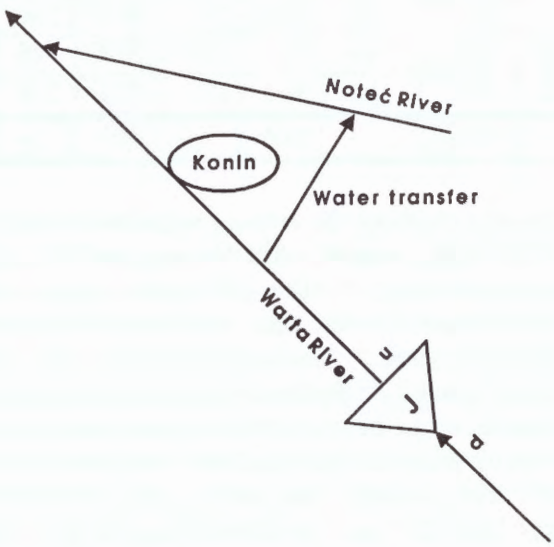

Fig. 12. Jeziorsko reservoir system

Table 13

Characteristics of Jeziorsko reservoir

catchment area [km^2]	9063.0
arable land [km^2]	1967.0
total storage capacity S_{max} [mln m^3]	202.8
dead storage S_{min} [mln m^3]	30.2

Table 14

Inflow statistics [m^3/s] to Jeziorsko reservoir for various scenarios

Month	HIST mean	HIST s.dev.	CCCM mean	CCCM s.dev.	GFTR mean	GFTR s.dev.	UKHI mean	UKHI s.dev.	UKTR mean	UKTR s.dev.
Nov	46.6	19.8	48.7	21.4	42.4	17.1	49.9	23.3	60.4	32.2
Dec	52.4	28.7	58.1	35.5	50.6	24.5	69.5	49.9	79.6	58.8
Jan	51.6	20.5	57.5	24.2	54.2	22.7	77.0	43.4	79.5	42.0
Feb	60.0	26.4	71.3	36.7	57.4	23.8	88.6	44.8	92.6	46.7
Mar	68.0	27.8	73.3	28.4	66.0	24.8	84.3	33.3	98.4	44.0
Apr	63.5	20.6	67.0	21.7	63.1	22.2	70.2	21.7	80.9	27.7
May	56.9	21.4	60.5	24.1	58.5	24.7	61.8	24.2	66.6	27.1
Jun	50.5	15.4	53.0	16.4	55.5	18.3	54.7	16.7	62.0	19.6
Jul	48.4	16.7	47.7	16.2	53.9	20.2	55.2	21.2	58.9	22.7
Aug	45.0	18.7	45.1	18.8	45.8	19.1	48.7	21.6	51.8	23.4
Sep	39.7	14.2	38.9	14.0	35.3	12.0	40.9	15.0	43.6	16.4
Oct	39.7	18.3	39.3	18.3	34.4	14.7	42.3	21.9	44.4	23.2
Year	51.9	–	55.0	–	51.4	–	61.9	–	68.2	–

For the present climatic conditions the average irrigation demand in the Warta region was estimated to be 2,250 m^3/ha, season, while for expected 2050 climate the irrigation demand slightly changed to the level of 2,180–2,360 m^3/ha, season, depending on climate scenario (Fig. 13). Future industrial water needs were evaluated according to the expected GNP growth, with regard to some rationalization of water use. It was assumed that domestic water use would increase proportionally to the population growth. In addition, a possibility of water transfer up to 15 m^3/s from Jeziorsko reservoir to the Noteć River catchment, characterized by temporal water deficits, was analyzed. A minimal reservoir outflow Q_0 = 10.3 m^3/s from Jeziorsko was set to meet hydro-biological criteria, and ecological requirements from 25.3 m^3/s in March–June to 22.8 m^3/s in July–October should be met.

Formulation of the optimization problem

The object of control is the Jeziorsko reservoir storage volume *V*, the inflow denoted by *d*, and the outflow denoted by *m*. The downstream discharge, the water withdrawal from the reservoir and water transfer to the lower part of the basin are considered to be one variable and are therefore treated jointly in the model. The objective function of the optimization problem under consideration can be written in the form:

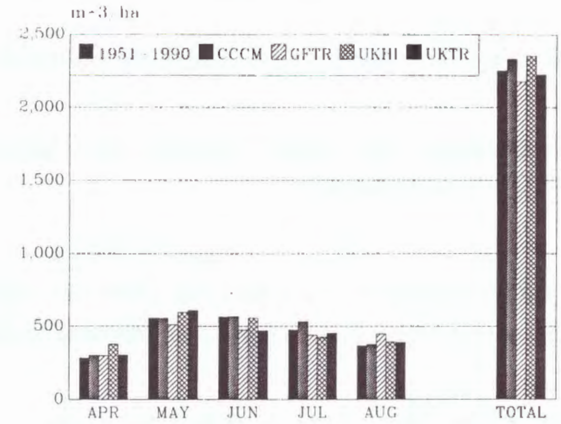

Fig. 13. Irrigation requirements: Warta river catchment

$$Q(m,V)=\sum_{j=1}^{12}\left[a^{+j}\left(m^{j}-z^{j}\right)^{2}+b^{j}\left(V^{j}-V^{*j}\right)^{2}\right]. \qquad (19)$$

The performance index $Q(m,V)$ depends explicitly on controls m^j and the state trajectory V^j (reservoir contains). Other quantities which occur in its formulation are treated as parameters.

4.5. Two-level optimization technique

Both reservoir systems have been analyzed by means of an optimization technique. In this way one can avoid the influence of the always subjective decision rule on the water distribution.

Required retention trajectory V^{*j}

It is assumed that the operation of both reservoir systems is carried out on annual bases in the following way:

* By late December, the reservoirs normally should return to low level to prepare the system for the next flood season completing the annual cycle;
* Storage reserved for flood control on January first was determined for control--ling the maximum probable flood. During the flood period, usually from January to April, the reservoirs should be filled up.

Weighting coefficients a^{+j} and b^j

According to the general objective of the control problem, which is aimed at the rational protection against water deficits and at reaching the desired state of storage level at the end of April, the following values of weighting coefficients in the optimization problem are used: $a^{+j}=1$ if demands are greater than supply and $a^{+j}=0.01$ otherwise, for k=[1,36]. As far as the second coefficient is concerned, in order to avoid a good performance in one year followed by a very poor performance in the next year b^j = .001

for j = [1,30] (May–February), b^j = .004 for j = [31,33] (March) and b^j = .01 in April, for j=[34,36].

The objective function during each month is subject to the constraints on the state of the system, controls and flows in given profiles:

$$V^j_{\min} \le V^j \le V^j_{\max}; \qquad m^j_{\min} \le m^j \le m^j_{\max}; \qquad u^j_{\min} \le u^j \le u^j_{\max}. \tag{20}$$

To solve the aforementioned problem we adjoin the inequality constraints (20) with Lagrange multiplier sequence λ (prices). The Lagrangian function has the form:

$$L(m,V,\lambda) = \sum_{j=k}^{k+T} \left[Q(m^j, V^j) + \lambda^j \left(V^{j+1} - V^j + B * m^j - C * d^j \right) \right]. \tag{21}$$

To include the state-variable and outflow constraints the above problem is solved by means of the two-level optimization method and solved in a decentralized (coordinated) fashion. At this stage we make use of the additivity of the Lagrangian function and the possibility of separation of the decision variables.

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

$$\max_{\lambda} \left[\min_{V,m} L(\lambda, V, m) \right] \tag{22}$$

with inequality constrains on state and control variables and no constrains on Lagrange multipliers. At *lower level* for given values of the Lagrange multipliers we look for the minimum of the Lagrange function. The necessary condition is zero value of the gradient with respect to m and V. The task of the *upper level* is to adjust the prices λ in such a way that the direct control of the reservoir, affected by λ, results in the desired balance of the system (the mass balance equation is then fulfilled satisfactorily). On the upper layer, in the maximization of the Lagrange function with respect to λ the standard conjugate gradient technique is used.

In the applied two-layer optimization control method (TLM) the solution of the two-level optimization problem is the essential "upper layer part". Note that this planning layer "proposes" the sequence of T control variables $\{m^k, \ldots m^{k+T}\}$ for one year long time horizon. At the current month they are taking into account by the lower layer that tries to apply them in the real conditions and eventually subject to some additional operator's interventions.

4.6. Comparison by simulation

The simulation has been carried out over the long time horizon of 40 years for the current and disturbed climate conditions. The results for any particular scenario are evaluated through many different performance indices—equivalent, in a way, to degree of realization of conflicting goals. Hence, the indices reflect only the partial, not global, effects of system performance. In our model, each performance index is represented as a function of time:

* For water users (*B, R, OD, K* and the cross-sections *H, P, DW*) this is the deficit function expressed with respective time unit (months).
* For the reservoirs this is the function of storage level (we are interested mainly in its average value in the summer period).

At the same time, each index is evaluated through many multiply scalar criteria. In order to define them precisely, let us consider the deficit in meeting the needs of a given water user, e.g., *R* (fish farms) in a period of one year. The function m_R^j, where j corresponds to month, together with z_R^j (representing the needs of fish farms), characterize this one particular index in the most complete manner. However, in order to compare in a clear, well ordered manner the results of different controls m_R^j, and furthermore with the results of the others controls, we introduced some scalar criteria depending on these functions.

The following criteria have been proposed for the functions which represent the water users performance (*i, j, k* are included in a given period of one year, i.e. of 12 months):

the global deficit time *TD*

$$TD = Card\left(\left\{i : m_R^j < z_R^j\right\}\right), \tag{23}$$

maximal continuous deficit time *TDc*

$$TDc = \max\left(\left\{\left|k \le l\right| : k \le l \wedge \left[\forall k \le j \le l; \quad m_R^j < z_R^j\right]\right\}\right) \tag{24}$$

average relative deficit *AvD*

$$AvD = \sum_{j=k}^{k+T} \frac{100\left(z_R^j - m_R^j\right)}{T \times z_R^j}, \tag{25}$$

maximal average relative continuous deficit *AvDc*

$$AvDc = \max\left(\left\{\sum_{j=k}^{l} \frac{100\left(z_R^j - m_R^j\right)}{T \times z_R^j} : \ \forall k \le j \le l; \ m_R^j < z_R^j\right\}\right), \tag{26}$$

maximum relative deficit *MxD*

$$MxD = \max\left(\left\{\frac{100(z_R^j - m_R^j)_+}{T \times z_R^j} : \; k \le j \le (k+T)\right\}\right). \tag{27}$$

Any function defining particular water user supply (m_B, m_R, m_{OD}, m_K), as well as the flow in the cross-section (*H, P, DW*) is characterized for a given one year period by 5 numbers as defined above. At the same time the trajectories V_T^j, V_G^j are described by two criteria. For example, the average water content in the summer period for Goczałkowice reservoir is:

$$AvV_G = \sum_{j=1}^{12} \frac{V_G^j}{12}. \tag{28}$$

In result, we obtain for each user/goal the sequence of 5 numbers, characterizimg a given performance index function in a synthetic way. It could be sufficient to evaluate and compare the different functions for one, fixed index, e.g., with the aid of any multi-objective optimization method. However, this is more complicated, because we have to compare the control effects for 9 "users" and not for a particular year, but for 40-year long historical record. To solve such a problem it was necessary to use a specific approach, which is arbitral to some extent and makes use of intuition. To obtain the final comparison results we analyze the diagrams of the so-called *frequency (reliability) criteria*, calculated on the basis of simulation for each of nine "users" and for each of 5 or 2 scalar criteria.

Those frequency criteria are functions defined over the set of values of respective scalar criteria *TD,..., MxD,* etc. These values represent the number of years for which the respective scalar criterion has its values in a given range. Formally, e.g. for *MxD* we have:

$$f_{MxD}(x) = Card(\{I : \; x - \Delta \le MxD^I \le x\}), \tag{29}$$

$$F_{MxD}(x) = Card(\{I : \; MxD^I \le x\}), \tag{30}$$

where MxD^I denotes the value of criterion *MxD* (15) for the year *I*, and Δ is the step of discretization of values of *MxD* (e.g., 2 per cent). It can be seen that *f(*)* corresponds to the notion of density function and *F(*)* – of cumulative distribution function of the "random variable" MxD^I, when *I* is treated as representing the elementary events.

4.7. Optimization results and conclusions

Upper Vistula river system

Figures 14 to 24 present results of statistical evaluation of the control results for different system users and for different criteria for the Upper Vistula river system. All the scalar criteria described above (*TD, MxD, AvD,* V_A, V_F) and all system users have been taken into account, that is, each criterion and each user is at least once presented. One can see some regularities which characterize the effects of control for the selected scenarios, namely CCCM, GFTR, UKHI, and UKTR.

One can observe that:

1. For the criterion *TD* (the global time, i.e. number of months with deficit in the year), and for users which take the water directly from the Soła River, or from both reservoirs (e.g., Katowice, Fig. 14), the best results are achieved with the UKTR scenario. For the H cross-section on the Soła River (Fig. 19) and for *TD* criterion, the plots are much closer one to another, only the diagram for the CCCM variant represents clearly the worst effect.
2. Similar results are observed in the case of *AvD* criterion (Fig. 16 for Katowice, Fig. 24 for Oświęcim-Dziećkowice). Note, that the succession of the obtained effects, from the worst case to the best, is as follows:

   $$\text{GFTR} < \text{CCCM} < \text{UKHI} < \text{UKTR}$$
3. The same succession as for *AvD* is observed for *MxD* criterion in the case of Katowice (Fig. 15), Bielsko (Fig. 17) and fish farms in Kęty (Fig. 23). The same results have been obtained also for both cross-sections at the Vistula river, the Pustynia cross-section (Fig. 18) and the Dwory cross-section (Fig. 20).
4. In contrary, the results for V_{GAv} criterion (average water content of Goczałkowice Reservoir in summer, Fig. 21) are ordered inversely; we have in this case

   $$\text{UKTR} < \text{UKHI} < \text{CCCM} < \text{GFTR}$$
5. The results obtained for V_{Ty} (average water content of Tresna reservoir at the end of the year, Fig. 22) are again very similar to those for *AvD*; we have

   $$\text{GFTR} < \text{CCCM} < \text{UKHI} < \text{UKTR}$$

The results obtained can be explained by comparison of the average values of total yearly inflows for the scenarios under consideration. The following succession of these values:

$$\text{CCCM} < \text{GFTR} < \text{UKHI} < \text{UKTR}$$

is valid for inflows, both to Tresna and Goczałkowice reservoirs. One can see that this succession is similar to that described in conclusions 1–3, and 5, the bigger the average inflow the better results can be achieved while managing the system in order to satisfy the needs of the users taking the water from rivers and reservoirs. It is worthy to notice that different criteria of system performance react in a similar manner for different scenarios.

A comment is needed to explain the result described in point 4 (for the V_{GAv} criterion), where the sequence of effects is almost inverse to the sequence average values of total yearly inflows of scenarios. This results from the character of the criterion V_{Av}, which evaluates the system performance (water content in Goczałkowice reservoir) only for the period of four months in summer. The order of the total average inflow in summer is quite different when compared with the annual averages for the scenarios discussed, namely:

CCCM < UKHI < UKTR < GFTR.

This particular result reflects the influence of various, opposite phenomena in the system.

Jeziorsko reservoir

For the Jeziorsko reservoir all water needs were fulfilled 100% of the time for the five cases discussed. The question arises whether the surplus water could be transferred to the catchment of the Noteć river through the existing channel (see Fig. 12), because some earlier studies had shown that the irrigation water deficit in that catchment may be as high as 30 m^3/s in some years. It seems (Figs. 25–26) that during summer months about 15 m^3/s can be relocated without causing any problems for Warta river itself.

Similarly to the Upper Vistula system, the results obtained can be easily interpreted by comparison of the average values of annual flows for the chosen scenarios. The following succession of these values:

CCCM < GFTR < UKHI < UKTR

results with the same succession of the system performance.

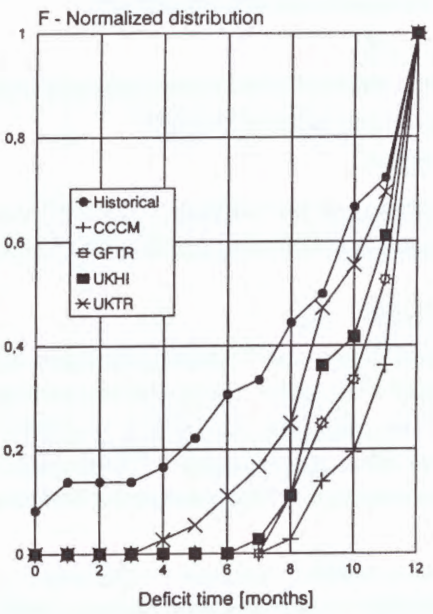

Fig. 14. *TD* reliability criterion for Katowice.

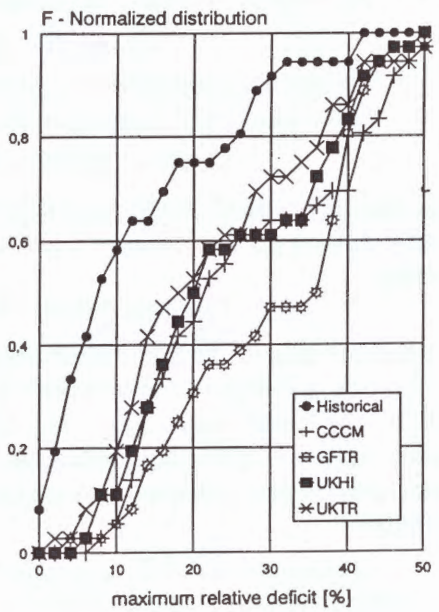

Fig. 15. *MxD* reliability criterion for Katowice.

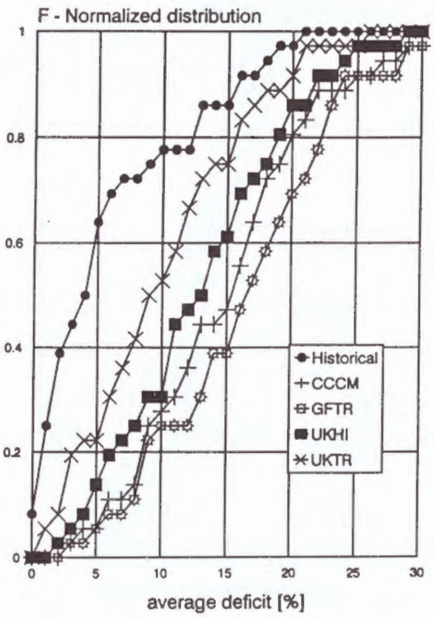

Fig. 16. *AvD* reliability criterion for Katowice.

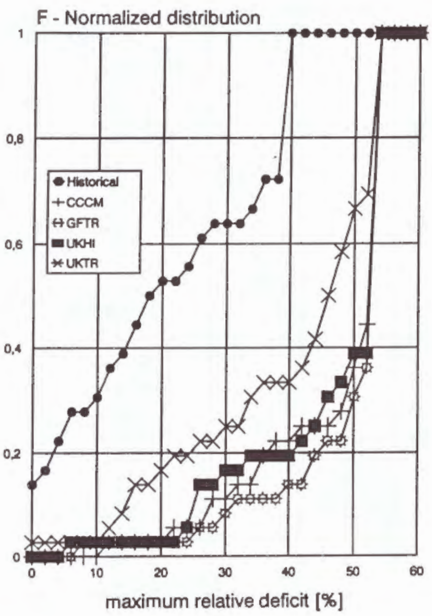

Fig. 17. *MxD* reliability criterion for Bielsko.

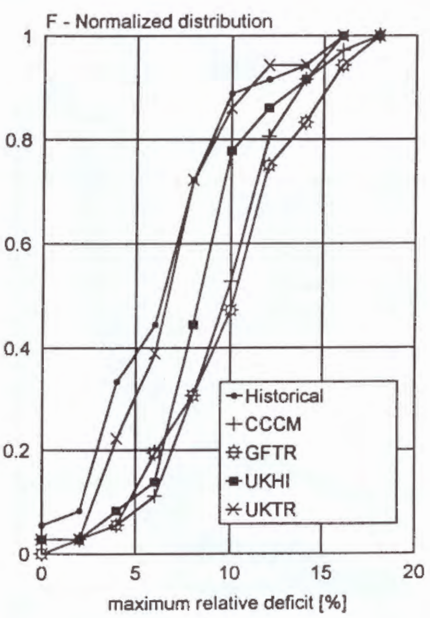

Fig. 18. *Mxd* reliability criterion for *P* cross-section (Vistula river).

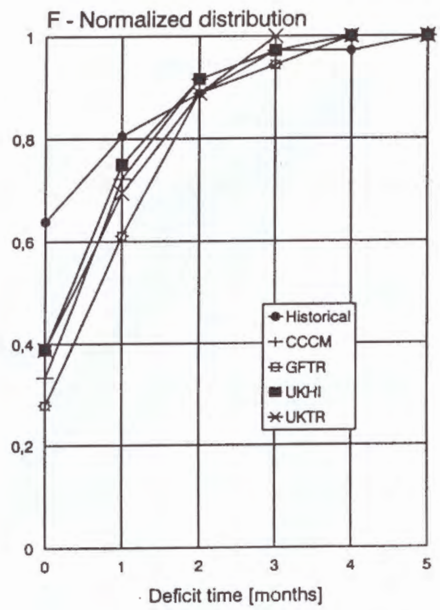

Fig. 19. *TD* reliability criterion for *H* cross-section

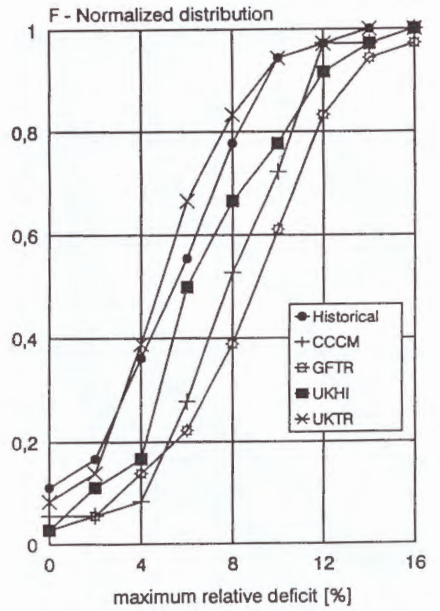

Fig. 20. AvD reliability criterion for DW cross-section.

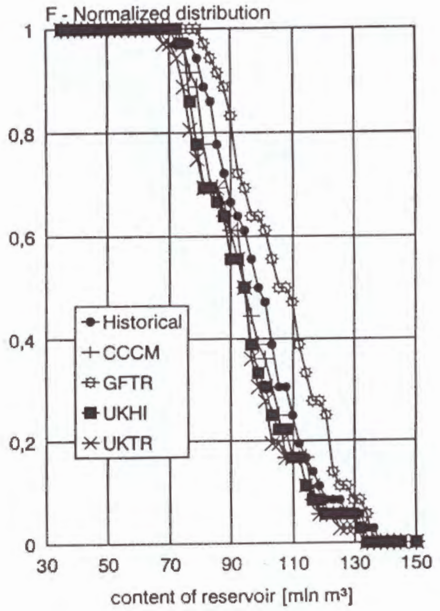

Fig. 21. Reliability criterion of average water content of Goczałkowice reservoir in summer.

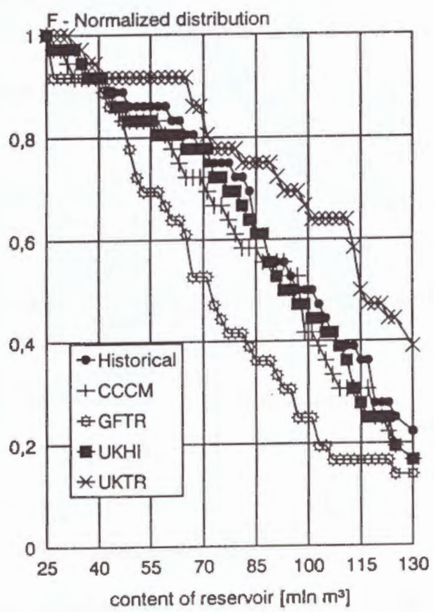

Fig. 22. Reliability criterion of average water content of Tresna reservoir at the end of year

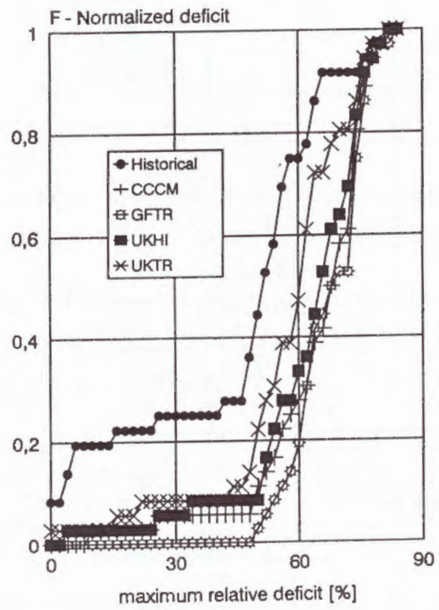

Fig. 23. *MxD* reliability criterion for fish farms around the town of Kęty

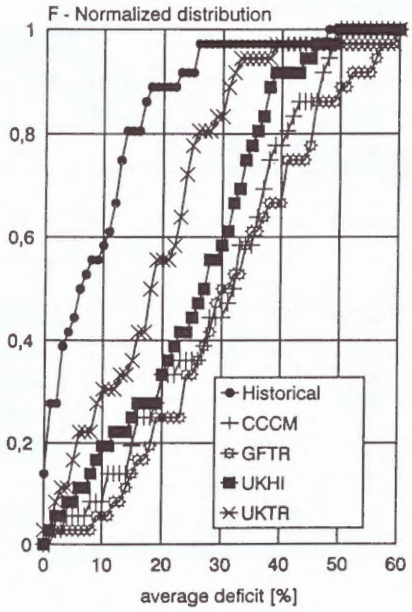

Fig. 24. *AvD* reliability criterion for Oświęcim-Dziećkowice

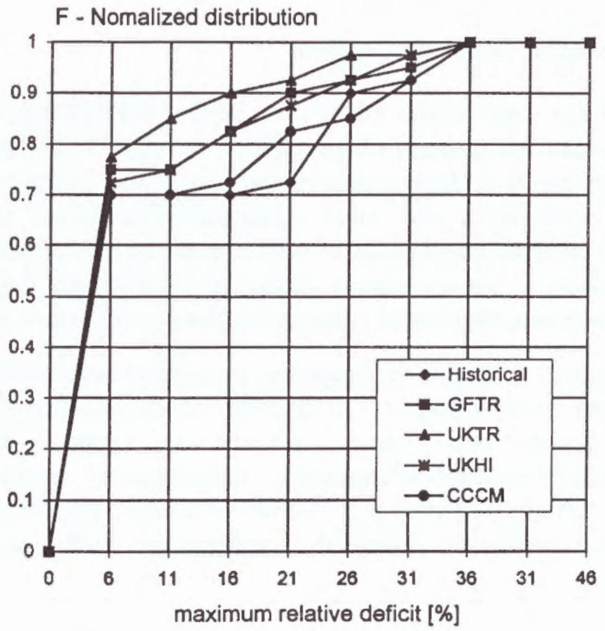

Fig. 25. *MxD* reliability criterion in the case of water transfer of 10 m^3/s to Noteć catchment: Jeziorsko reservoir

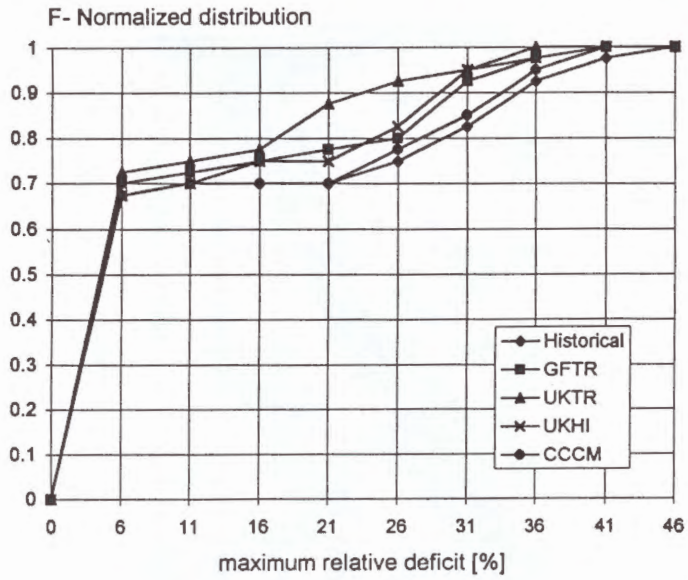

Fig. 26. *MxD* reliability criterion in the case of water transfer of 15 m^3/s to Noteć catchment: Jeziorsko reservoir

4.8. Remarks on possible adaptation options[1]

There are still large uncertainties that are propagated through the numerous levels of analysis as one moves from multiply CO_2 scenarios: through the comparison of different GCM outputs; transference of climatic data to runoff and other hydrologic characteristics; impacts on each water sector and water management decisions; and finally on the socioeconomic and incremental impacts of response measures. In addition, incremental impacts due exclusively to climate change should be differentiated from changes (sometimes also highly uncertain) that would occur in the absence of climate change.

Water management at present is frequently concerned with reconciling competing demands for limited water resource. At present, these conflicts are solved through legislation, prices, customs or a system of priority water rights. A change in both the amount of water available and water demanded is likely in many cases to lead to increased competition for resources. Conflicts may arise between users, regions, and countries, and the resolution of such conflicts will depend on political and institutional arrangements in

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[1] This section is based on 1995 IPCC Report (Kaczmarek *et al.*, 1996a)

force. Management of water resources inherently deals with mitigating the effects of hydrologic extremes and providing a greater degree of reliability in the delivery of water related services. Because different uses have different priorities and risk tolerances, the balance point among them after climate change may be quite different from now (e.g., hydropower and instream uses may be lost disproportionately compared to water supply). The marginal costs of reducing each additional increment of risk of water scarcity typically rises rapidly as reliability approaches 100 percent. Hence, water managers usually deal with 90%, 95% and 99% levels of reliability as useful performance measures of the available quality and quantity of water.

The 1990 and 1992 IPCC reports (Shiklomanov *et al.*, 1990; Stakhiv *et al.*, 1992) contained a discussion on the philosophy of adaptation and a list of adaptation options suited to the range of water management problems that are expected under climate change. Based on the review of most recent literature, no additional water management actions or strategies that are unique to climate change have been proposed to be added to the list, other than to note that many nations have pledged to implement action plans for sustainable water resources management as part of their obligation towards AGENDA 21. In that respect, the principles laid out in that document would serve as a useful guide for developing a strategy that would enable nations, river basin authorities and water utilities to prepare for and partially accommodate the uncertain hydrologic effects that might accompany global warming.

There are many possibilities for individual adaptation measures or actions. An overview of water supply and demand management options was presented by Frederick (1994) as part of an attempt to develop approaches to dealing with increasing water scarcity. A long-term strategy requires that a series of plausible development scenarios be formulated based on different combinations of population growth assumptions along with economic, social and environmental objectives (Carter, *et al.*, 1994). After these scenarios are established, taking into account the possibility of climate change, a set of alternative long-term strategies for water management must be formulated that consist of different combinations of water management measures, policy instruments or institutional changes, which are designed to meet best the objectives of a particular growth and development scenario and its consequent CO_2 emissions rate. The range of response strategies must be compared and appraised, each with different levels of service reliability, costs, environmental and socioeconomic impacts. Some will be better suited to dealing with climate change uncertainty — i.e., more robust and resilient, others will focus on environmental sustainability. Some are likely to emphasize reliability of supply. The reality is that, after application of engineering design criteria to various alternatives, the selection of an "optimal" path is a decision based on social preferences and political realities. Engineering design criteria, however, also evolve over time, and are updated as new meteorological and hydrological records are extended and the performance of water management systems is tested under varying conditions.

The nature of contemporary water resources management is such that countless numbers of principal factors, economic criteria, and design standards are incorporated simply because of the complexity of integrated water management and objectives (reliability, costs, safety). The key problem in responding to possible consequences of man-induced global warming is to decide *when* and *what kind* of adaptive measures should be undertaken to assure reliability of water supply. Policy decisions depend on local hydrologic conditions, economic situation, and national priorities. There is no reason to apply sophisticated decision making techniques for river systems abundant of water, when the results of any climate impact assessment will be trivial. On the other hand, even limited climatic disturbances may lead to serious worsening of water situation in arid and semi-arid regions requiring necessary adaptation actions.

Three approaches are possible in dealing with adaptation of water systems to changed climatic conditions. Firstly, a *"wait and see"* or *"business as usual"* strategy, which means to postpone decisions on adaptation measures until more reliable information on global atmospheric processes will become available. Existing water schemes remain unchanged, and the new ones will be planned and implemented according to standard analytical procedures. Because in case of large hydraulic schemes the time needed for planning and implementation is usually very long, this approach may cause undesirable delays in taking necessary decisions. Secondly, a *"minimum regret"* approach, when decisions will be taken to solve current problems in the best possible way, and at the same time to prepare water systems to possible changes and shocks by making them more robust, resilient and flexible for any future. Finally, the third approach assumes that optimality rules should be applied to a range of climatic scenarios.

Different strategies apply to different circumstances. Watersheds that have little or no control of natural flows, and are largely dependent on precipitation, must implement a different set of water management strategies than river basins with a high degree of control in the form of reservoirs, canals, levees, etc. Similarly, rapidly urbanizing areas will require different responses than agricultural regions. There is no standard, prescribed approach. However, if a rational management strategy is undertaken to deal with reasonably foreseeable needs of a region in the absence of climate change, according to the principles espoused in AGENDA 21, that strategy will also serve to offset much of the range of possible adverse consequences of climate change.

Though our Project focused on three river basins only, some general conclusions may be drawn on future Poland's water policy:

* Although Poland is scarce in water resources, the present (1990) in-stream and off-stream water requirements may be generally met, with possible local deficits in some years;
* It is doubtful whether future water needs, rising due a number of non-climatic factors, can be easily satisfied by existing structural, economic, and legal policy tools;

* Independent of the climate change issue new structural and non-structural measures will have to be implemented to assure reliable water supply for sustainable development of the country;
* The possible impact of climate change on water supply and demand in Poland is uncertain; in the worst-case "dry" scenario, one should expect enhanced drought conditions in summer, particularly in central regions of the country.
* It is difficult to formulate a definite list of possible adaptation options, unless more reliable information on future climate will be available.

Possible actions that might be undertaken in Poland to cope with negative consequences of climate change include: (a) new legal and economic measures aimed on conservation of water by population and various sectors of economy; (b) temporary limitation of water use in industry and for irrigation in drought periods; (c) efficient operation of existing water resources infrastructure; (d) water systems development, e.g. through constructing new storage reservoirs, transferring water among river basins, etc.

Role of water resources investments in coping with expected water deficits must be carefully investigated by water resources authorities. There is a strong opposition in Poland against new large-scale hydraulic investments. The reasons are the relatively high density of population, lack of lands which could be eventually used for additional storage, environmental concerns, and insufficient investment funds. This leads to a conclusion that the most probable approach in adapting to hypothetical climate change would be water conservation and improved management. One possible option is to reduce the acreage of irrigated lands, and to solve the food supply problem by introducing drought-resistant crops or by importing food. The key recommendation resulting from the Country Study is to undertake an intensive research program on the vulnerability of national agriculture to climate change, with particular emphasis on irrigation strategies. The experience of several European countries shows that in the domestic and industrial sectors, water conservation may be an efficient and economically justified tool to cope with water deficits.

5. Impact of climate change on Poland's aquatic ecosystems

5.1. Climate change and water quality management

Water resource systems in Poland are increasingly being managed to maintain and improve the quality of aquatic ecosystems. Expected changes in water temperature and flow regime may create new problems related to oxygen balance, thermal pollution, nutrient balance and eutrophication, nitrate contamination, toxicity, salinization and acidification. Water quality depends on a number of non-climatic factors such as point source emissions (municipal and industrial), non-point sources and land use management in a broader sense. The pollution problems may be, however, further complicated by a potential change of climate. Most of the climate-induced water quality impacts depend on changes in a large number of counterbalancing processes and thus it is difficult to assess general trends.

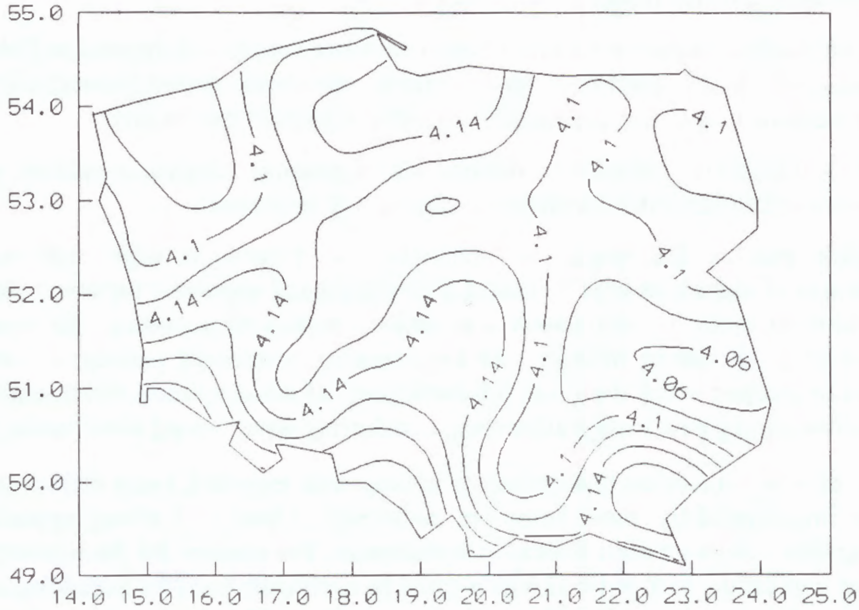

Fig. 27. Water temperature change [°C] in summer months in Poland, for the GFDL climate scenario

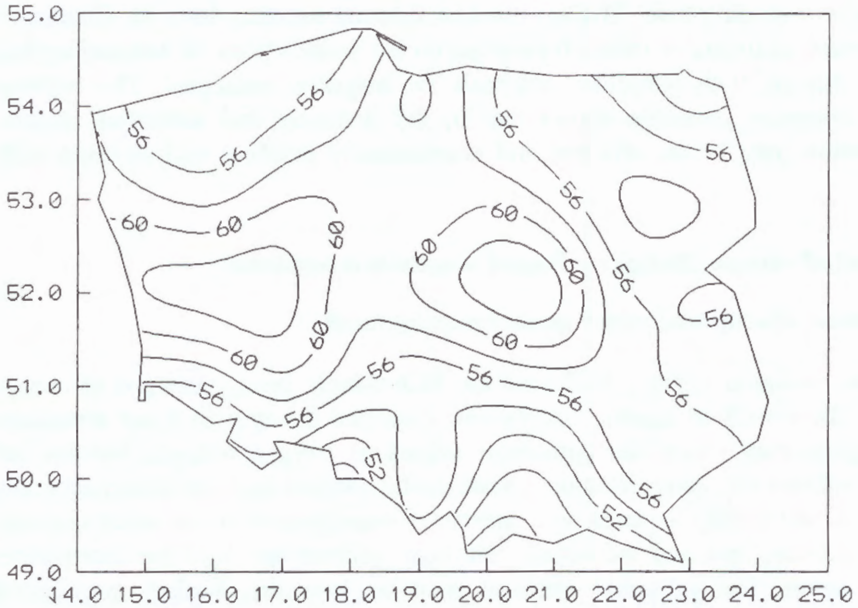

Fig. 28. Change in summer free surface evaporation [mm/season], for the GFDL climate scenario

A potential impact of climate change on temperature of rivers and lakes in Poland, for $2*CO_2$ equilibrium GFDL and GISS scenarios, was investigated by Jurak (1992). The author concluded (Fig. 27) that the highest possible water temperature increase in summer months, predicted for the GFDL scenario, may be equal to 4.0°C. This creates a possibility of exceeding the ambient standard temperature which in Poland is set to be equal to 26°C. Also the frequency of freezing conditions would fall in most of Poland's rivers. For relatively clean lakes and rivers no drastic water quality changes are anticipated in Poland due to climate alteration. On lowland river stretches with large emission of pollutants the impact can be high. Changes in seasonal lake evaporation for the same scenario are shown in Fig. 28.

For contaminated waters, characterized by complex interactions of many different pollution problems, climate change adds an incremental impact which can be estimated only with significant uncertainty at present. Because the rate of chemical reaction and biochemical processes in living organisms are controlled by the temperature, the reaction of biotic communities will be amplified, as far in some temperature ranges some species may double their metabolism only by 4°C ambient temperature increase. For instance, blue-green algae and sediment phosphorus load are favoured by a higher water temperature.

Cycling of inorganic chemical compounds to biochemical active components in freshwater ecosystems is possible due to the processes of organic matter decomposition, which at least partly are controlled by thermal conditions. Calculations done for a river in Poland allow to conclude that for the $2*CO_2$ conditions the length of period of water temperature appropriate for high decomposition rate may increase by about 40% for both GFDL and GISS scenarios. This may result in higher nutrients concentration in river and consequently in lowering of water quality. Nutrients are also transported into reservoirs contributing to intensifying symptoms of eutrophication. Increase of temperature may be articularly dangerous for shallow non-stratified lakes and reservoirs. Experimental studies done recently for the Sulejów reservoir, supplying water to the Łódź agglomeration in Central Poland, have shown high dependence of intensity of cyanobacterial blooms on water temperature (Zalewski and Wagner, 1995).

5.2. Impact of climate change on temperature and evaporation of shallow lakes

Four shallow lakes were selected in the Masurian lake district (North-East Poland) in order to assess the impact of climate scenarios on water temperature and lake evaporation. The main lake attributes are shown in Table 15. Baseline climatic data, i.e. monthly values of air temperature, relative humidity, wind speed and sunshine duration, from stations Olsztyn (ϕ = 53.8 N, λ = 20.4 E) and Suwałki (ϕ = 54.1 N, λ = 23.0 E), as well as incremental air temperature values from CCCM, HCTR, UKHI and UKTR scenarios were used in our analysis. To calculate water temperature for time period $<0, t_k>$, the following relation was developed (Jurak, 1992):

$$\overline{T}_w = -\frac{\beta}{2\gamma} - \frac{\rho_w c_w h}{2\gamma t_k}\left[\ln\frac{\left[1-\phi(t_k)^2\right]}{\phi(t_k)} - \ln\frac{\left[1-\phi(0)^2\right]}{\phi(0)}\right] \tag{31}$$

where:

$$\Phi(t) = \frac{\beta + 2\gamma T_{wo} - \sqrt{\beta^2 - 4(\alpha + G)\gamma}}{\beta + 2\gamma T_{wo} + \sqrt{\beta^2 - 4(\alpha + G)\gamma}} * \exp\left[\frac{t}{\rho_w c_w h}\sqrt{\beta^2 - 4(\alpha + G)\gamma}\right] \tag{32}$$

h [m] is the mean depth of lake, T_{wo} denotes water temperature in moment $t = 0$; coefficients α, β and γ depend on meteorological data, and G is the energy flux between the lake and its bottom. Model (31)–(32) is based on physical laws of the lake heat balance, with no calibration, and may be used for the climate change impact assessment.

Table 15

Shallow lakes in Masurian district selected for climate impact assessment

Name of lake	Długie	Kolno	Luterskie	Wydmińskie
Latitude	54.1 N	53.8 N	54.0 N	53.0 N
Longitude	23.2 E	23.0 E	20.8 E	22.0 E
Surface area [m^2]	1,024,000	2,644,000	6,914,000	3,366,000
Volume [m^3]	7,669,000	3,303,000	49,824,000	11,738,000
Average depth [m]	7.5	1.2	7.2	3.4
Altitude above sea level [m]	138.7	118.9	140.0	130.5

Water temperature and lake evaporation were calculated for mean monthly meteorological data for two relatively "cold" years 1978 and 1987, and two "warm" years 1975 and 1983. Than calculations were repeated with added temperature increments for year 2050, based on four climate scenarios. Results on ΔT_w [°C] are shown in Tables 16–19 for two lakes and data of the years 1978 and 1983.

Table 16

Water temperature in Kolno lake in "cold" year and for four scenarios

Scenario	April	May	June	July	Aug	Sept	Oct	Nov
1978	6.6	13.6	17.2	19.0	17.7	11.0	7.4	4.8
CCCM	7.7	14.1	17.7	19.7	18.3	11.9	8.3	5.9
GFTR	9.2	14.1	17.1	19.5	18.9	13.5	9.5	6.2
UKHI	10.4	15.8	18.6	20.1	19.2	12.6	9.6	7.3
UKTR	10.6	16.2	18.6	20.9	19.3	12.9	9.8	9.5

Table 17

Water temperature in Kolno lake in "warm" year and for four scenarios

Scenario	April	May	June	July	Aug	Sept	Oct	Nov
1983	9.4	17.4	18.3	20.9	20.7	14.1	7.6	.9
CCCM	10.4	17.9	18.9	21.5	21.3	15.0	8.4	2.0
GFTR	12.0	17.9	18.3	21.4	21.8	16.5	9.7	2.2
UKHI	13.2	19.7	19.7	22.0	22.0	15.6	9.8	3.4
UKTR	13.3	20.1	19.8	22.7	22.1	15.9	10.0	5.6

Table 18

Water temperature in Luterskie lake in "cold" year and for four scenarios

Scenario	April	May	June	July	Aug	Sept	Oct	Nov
1978	5.1	11.9	18.1	19.6	19.1	15.6	12.0	7.9
CCCM	6.4	12.6	18.7	20.2	19.7	16.3	12.8	8.8
GFTR	6.9	13.1	18.3	19.9	20.0	17.4	14.1	9.4
UKHI	8.4	14.7	19.9	20.8	20.4	17.0	13.8	10.0
UKTR	9.2	15.1	20.1	21.4	20.8	17.2	14.0	11.3

Table 19

Water temperature in Luterskie lake in "warm" year and for four scenarios

Scenario	April	May	June	July	Aug	Sept	Oct	Nov
1983	5.0	10.8	17.3	21.5	22.6	19.0	13.0	8.7
CCCM	6.2	11.8	17.9	22.0	23.2	19.7	13.7	9.5
GFTR	6.5	12.4	17.8	21.8	23.4	20.7	14.9	10.2
UKHI	8.3	14.2	19.5	22.7	23.8	20.4	14.7	10.7
UKTR	9.2	14.7	19.7	23.2	24.2	20.6	14.9	11.6

In conclusion one can observe that the sensitivity of lake temperature to possible climate change in the Masurian district is modest. The highest water temperature increase in the case of the four selected climate scenarios was obtained for months April, May and November, while in summer months in most cases it does not exceed 1.0 to 2.0 °C.

Based on estimated water temperature, monthly lake evaporation was calculated by means of the formula:

$$E = 30{,}4B(\mu)(u+u_0)^{0.8}\left[e_0(T_w)-e\right]. \qquad (33)$$

where $B(\mu)$ depends on lake geometry, surface roughness and atmospheric stability, u is the wind speed, $e_o(T_w)$ the saturated vapour pressure by water temperature, and e is the actual air vapour pressure. Simulated seasonal evaporations (in mm) for summer period (April–September) for the two lakes and four scenarios are given in Table 20. The results evidently show a low sensitivity of free water surface evaporation to climate change.

5.3. Thermal regime of a stratified Masurian lake

A relatively deep lake Wigry (ϕ = 54.1 N, λ = 23.1 E) in the Masurian district was selected to investigate the possible impact of climate change predicted by the four scenarios on lake stratification. Basic lake's characteristics are given in Table 21.

Table 20

Evaporation in summer months [mm] estimated for four scenarios

	Scenario	Kolno lake	Luterskie lake
"cold" year	1978	481	402
	CCCM	485	406
	GFTR	489	401
	UKHI	505	429
	UKTR	512	441
"warm" year	1983	569	434
	CCCM	573	454
	GFTR	580	438
	UKHI	596	459
	UKTR	603	466

Table 21

Characteristics of Wigry lake

Lake characteristic	
Surface area [m^2]	21,311,000
Volume [m^3]	336,726,000
Average depth [m]	15.8
Maximum depth [m]	73.0
Altitude above sea level [m]	132.0

A model of thermal regime for stratified lakes (Jurak and Kaczmarek, 1996) has been applied. The Wigry lake was divided into m horizontal layers of an equal depth $h = H/m$. An energy balance of the water surface for the n-th period is:

$$QC_n = R_{sn}(1-alb) + QLR_n - QE_n - QH_n \, , \tag{34}$$

where R_{sn} is the short-wave radiation balance, QLR_n the long-wave radiation balance, QE_n the latent heat flux, and QH_n the sensible heat flux. According to Edinger and Geyer (1968), equation (32) may be approximated by a linear relation:

$$QC_n \approx \alpha_l + \beta_l T_w \tag{35}$$

in which coefficients α_l and β_l depend on a number of meteorological elements. In a vicinity of water temperature $T_w = T_a$ one can get (Jurak, 1978):

$$\begin{aligned}\alpha_l &= R_s(1-alb) + QLR(T_a)^{0.8} \\ &\quad - 28.83 B_\mu (u+u_0)^{0.8} \times \left[e_0(T_a)\left\{1 - \frac{4250 T_a}{(242+T_a)^2}\right\} - 0.61 T_p - e \right] \\ &\quad + 4.4\times10^{-8}(T_a + 273.2)^3 (1+4n_s) T_a \, ,\end{aligned} \tag{36}$$

$$\begin{aligned}\beta_l &= -28.83 B_\mu (u+u_0)^{0.8} \left[\frac{4252}{(242+T_a)^2} \times e_0(T_a) + 0.61 \right] \\ &\quad - 4.4\times10^{-8}(T_a + 273.2)^3 (1+4n_s) \, .\end{aligned} \tag{37}$$

The energy flux entering water body at z meters below the surface is presented in the model by the equation (after Zaneveld and Spinrad, 1980):

$$Q(z) = R_{sn}(1-alb_n) \times \exp(-k_1 z) \times [1 - k_2 \arctan(k_3 z)] \, , \tag{38}$$

where coefficients depend on the chemical composition of lake's water. For average conditions one can use (see, e.g., Henderson-Sellers (1984)): $k_1 = 0.354$, $k_2 = 0.463$ and $k_3 = 3.681$. Transfer of heat due to diffusion processes may be approximated by the following equation:

$$A(z)\frac{\partial T(z)}{\partial t} = \frac{\partial}{\partial z}\left[A(z)(K_m + K_t)\frac{\partial T(z)}{\partial z} \right] + \frac{1}{\rho_w c_w} \times \frac{\partial Q(z)}{\partial z} \, , \tag{39}$$

where $K_m = 1.4*10^{-7}$ m^2/s is the coefficient of molecular diffusion, K_t the coefficient of turbulent diffusion, $c_w = 4187$ [J kg^{-1} °C] is a specific heat of water. Hondzo and Stefan (1992) applied the following empirical relation for calculating the coefficient of turbulent diffusion:

$$K_t = a_k \left(N^2\right)^{b_k}, \tag{40}$$

where a_k and b_k are empirical parameters, and N^2 is:

$$N^2 \approx \frac{9.03 \times 10^{-5}}{h}\left[\left(T_{w(i+1)} - 4.03\right)^{1.895} - \left(T_{wi} - 4.03\right)^{1.895}\right], \tag{41}$$

where $T_{w(i+1)}$ and T_{wi} are temperature values in neighbouring water layers.

The model allows to calculate the vector of water temperatures at the beginning of period $(n+1)$:

$$\mathbf{T}_{n+1} = \langle T_{w1,(n+1)}, T_{w2,(n+1)}, \ldots, T_{wm,(n+1)} \rangle$$

based on known temperature vector at the beginning of period n, and meteorological data in this period. The discretization scheme was also used after Hondzo and Stefan (1992). A system of linear equations for calculating water temperature vector $\mathbf{T}_{n+1}$ may be presented in a matrix form:

$$\mathbf{A}_n \times \mathbf{T}'_{n+1} = \mathbf{C}'_n \tag{42}$$

where $\mathbf{A}_n$ = $<<a_{ij,n}>>$ is a $<m * m>$ matrix of coefficients depending on the lake's geometry and coefficients of turbulent diffusion; $\mathbf{T}_{n+1}$' is a transposed temperature matrix, and $\mathbf{C}_n$' = $<c_{i,n}>$ is a vector of parameters depending on diffusion coefficients and on energy fluxes on the boundaries of neighbouring water layers.

After calculating water temperature for all layers and time periods one can estimate evaporation values expressed in mm/day:

$$E_n = B(\mu)(u + u_0)^{0.8}\left[e_0\left(\overline{T_{w,n}}\right) - e\right] \times \frac{\Delta t}{86400} \tag{43}$$

where:

$$\overline{T_{w,n}} = 0.5\left(T_{w1,n} + T_{w1,(n+1)}\right). \tag{44}$$

Calculations were implemented for monthly values of observed air temperature, vapour pressure, wind speed, and sunshine duration. Meteorological data for two "warm" years (1975 and 1983) and two "cold" years (1978 and 1987) were used to calculate the baseline characteristics of energy balance and thermal regime. Next the temperature increments provided by the four scenarios were added to observed values and calculations repeated for disturbed climatic conditions (relative humidity, wind speed, and sunshine duration were assumed constant). An example of the vertical temperature profiles for the "current" climate observed in year 1983 is demonstrated in Table 22, and in Fig. 29.

Table 22

Vertical profiles of water temperature in Wigry lake – summer 1983

z [m]	May	June	July	Aug	Sept	Oct	Nov
3.0	11.5	18.0	19.2	21.7	19.9	13.2	6.7
6.0	11.1	18.1	19.3	21.7	20.2	13.4	7.0
9.0	5.6	7.2	8.9	10.5	12.0	12.5	12.0
12.0	4.4	4.9	5.6	6.3	7.0	7.4	7.8
15.0	4.1	4.4	4.6	4.9	5.2	5.4	5.6
18.0	4.0	4.1	4.3	4.4	4.5	4.6	4.7
21.0	4.0	4.0	4.1	4.2	4.3	4.3	4.4
24.0	4.0	4.0	4.0	4.1	4.1	4.2	4.2
27.0	4.0	4.0	4.0	4.0	4.0	4.1	4.1
30.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0

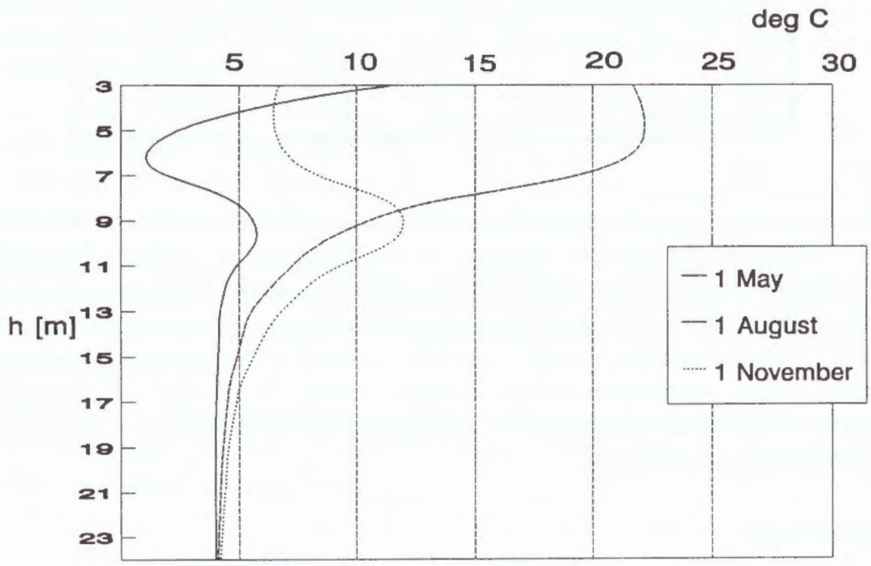

Fig. 29. Thermal stratification in the Wigry lake in the summer of 1983 year

Water temperature changes for two (extreme) scenarios are then shown in Tables 23 and 24. Similar values of the lake Wigry temperature increments were received for climatic data of other years under investigation. It was further observed that the estimated impact of climate change on summer evaporation from the Wigry lake is negligible, i.e. less than three percent.

Table 23

Water temperature increase in Wigry lake for CCCM scenario

z [m]	May	June	July	Aug	Sept	Oct	Nov
3.0	1.1	.5	.7	.7	.7	.8	.8
6.0	1.0	.5	.5	.7	.6	.9	.7
9.0	.1	.1	.2	.2	.2	.1	.3
15.0	.0	.1	.1	.0	.0	.1	.0
18.0	.0	.0	.0	.0	.0	.0	.0

Table 24

Water temperature increase in Wigry lake for UKTR scenario

z [m]	May	June	July	Aug	Sept	Oct	Nov
3.0	4.4	2.4	1.2	2.1	1.4	1.6	2.4
6.0	4.1	2.7	.9	2.2	1.3	1.7	2.3
9.0	.8	.6	.7	.7	.7	.6	.8
12.0	.1	.2	.2	.1	.2	.3	.2
15.0	.0	.0	.0	.0	.0	.0	.1

The above study provides a preliminary step in a systematic analysis of the impact of climatic conditions on thermal structure in stratified lakes. Further theoretical and experimental investigations are necessary to clarify a number of still open questions. For example, in deep lakes vertical mixing may be relatively intense in the upper layers because of wind action and possible role of convective circulation. Consequently, in addition to testing sensitivities of lake thermal regime to changes in air temperature, investigation of the effects of changes in additional climatic variables, e.g. wind speed and relative humidity, is required.

6. Final remarks

The report summarizes results obtained in a frame of the European Study on impact of hypothetical climate change on hydrology and water management in three selected catchments at the territory of Poland. Water management means a conscious interrelation of the society and nature aimed on converting natural resources into the property useful for the Man and his activities. There is historical evidence testifying, on the one hand, the importance of water to the development of nations and, on the other hand, a need to treat water management as public activity. The consciousness of the importance of water management to the proper functioning of societies increases as the difficulties in providing

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