POLISH ACADEMY OF SCIENCES
INSTITUTE OF GEOGRAPHY AND SPATIAL ORGANIZATION

GEOGRAPHIA POLONICA

71

GLOBAL CHANGE:
POLISH PERSPECTIVES
5

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IGBP - GLOBAL CHANGE

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71

HYDROLOGICAL PROCESSES AND WATER RESOURCES IN THE FACE OF GLOBAL CLIMATE CHANGE

(Proceedings from the Conference in Warsaw,
22-23 October 1997)

EDITED BY
LESZEK STARKEL, MAŁGORZATA GUTRY-KORYCKA,
Guest Editor: ZDZISŁAW KACZMAREK

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FOREWORD

The years 1993–1996 saw a series of studies done in Poland with a view to determining the vulnerability of aquatic ecosystems to changing climatic conditions and considering the possible influence of these changes on decisions made in planning the development of water-management systems. Some of the studies in question were carried out in cooperation with foreign scientific centres, within the framework of the European programme entitled "Impact of Climate Change on Hydrology and Water Resources in Europe", as well as a programme financed by the US government within the "United States Country Studies Initiative". It should be added that, as a Party to the 1992 UN Framework Convention on Climate Change, Poland is obliged to support research that works towards a better understanding of the laws of physics shaping atmospheric processes, as well as to devise methods by which the economy may be adapted to climate change.

The results of the Polish studies have been published in the form of several monographs, as well as a large number of articles in Polish and foreign journals. They also allowed Polish experts to have significant input into the preparation of the 2nd Assessment Report of the UN Intergovernmental Panel on Climate Change. It seemed that the time had come for a critical summing-up of results obtained so far, as well as for consideration of the directions to be taken by future research within the National Climate Programme now being prepared by the Polish Academy of Sciences and the Ministry of Environmental Protection, Natural Resources and Forestry.

For these reasons, the National "IGBP Global Change" Committee to the Praesidium of the Polish Academy of Sciences joined the PAS's Institute of Geophysics in organizing the October 1997 Conference entitled "Hydrological Processes and Water Resources in the Face of Global Climate Change". The organizers' intention was to provide an arena for discussion of this topic among representatives of the different scientific disciplines, and various research centres, interested in it. The material collected from the Conference is presented in this volume of the "Global Change" series.

The Conference included 15 papers in three subject groups:

a) Change and Variability of Climate: Identification and Scenarios;

b) Sensitivity of Aquatic Systems to Change and Variability of Climate; and

c) Water-Resource Management in Conditions of Uncertainty.

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We present readers with the texts of the papers given, or else with abstracts in cases in which the full versions have already been published in other journals. As interesting conclusions were reached during the discussion, we also present the interventions of some of the participants in an abbreviated form.

The organizers would like to invite all those interested in the influence of climate on water resources to provide the editorial board of the "Global Change" series with their remarks and proposals regarding the issues that the papers included raise.

Zdzisław Kaczmarek
Chairman, Conference Organizing Committee

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PHYSICAL PRINCIPLES OF CLIMATE MATHEMATICAL MODELLING

BOGUMIŁ JAKUBIAK
Interdiciplines Centrum of Mathematical and Computer Modelling, University of Warsaw
ul. Pawińskiego 5a, 02-196 Warszawa, Poland

ABSTRACT: Climate is a composite system consisting of five major interactive adjoint components: the atmosphere, the hydrosphere, the oceanosphere, the cryosphere, the lithosphere and the biosphere. In the paper the nature, state and variability of the climate system are described briefly. Of particular importance in open systems such as components of the climatic system is feedback. Feedback mechanisms act as internal controls of the system and result from a special adjustment among two or more subsystems. The meteorological, oceanic and glacial records show considerable variability on all time scales. Starting from chosen elements of the observed main state of the atmosphere (air temperature, atmospheric circulation, precipitation and evaporation) interannual and interdecadal variability in the climate system is briefly described. Such natural phenomena as quasibiennial oscillations (QBO) in the stratosphere, the El Niño — Southern Oscillation (ENSO) in the tropics and regional teleconnections such as the North Atlantic Oscillation are examples of such variability. The climate of the earth has undergone large changes in the past, is changing now and will change in the future. External factors (solar radiation, absorbing gases in the atmosphere, ice cover) and the thermodynamic quantities that characterize the climate (temperature, density, velocity, moisture content, salinity) are all interrelated through a set of physical laws expressed by various equations based on the general principles of conservation of mass, momentum and energy. The set of coupled partial differential equations can be solved subject to knowledge of the solar radiation input and other specified boundary and initial conditions that define the instantaneous state of a climate system. Mathematical models provide a new way to not only understand the climate's behaviour, but also to explore the possibility of future climate developments being predicted.

KEY WORDS: climate, numerical climate models, climate variability.

A thermodynamic system can be classified as isolated (without an exchange of energy with its surroundings) or open, when transfers of matter and energy across boundaries is allowed. Most natural systems, such as the atmosphere, oceans and the biosphere are open. Open systems may attain a steady-state condition in which the properties are invariant when averaged over a given time interval and are sustained by continuous supply and

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removal of matter and energy. Open systems can be classified as: dissipative, cyclic and randomly-fluctuating. Dissipative systems consume their own mass or energy, cyclic systems follow oscillatory behaviour imposed by diurnal or annual cycles, and randomly-fluctuating systems change in an irregular and unpredictable way. Cascading systems are important in nature. They consist of a chain of open subsystems dynamically-linked with each other by a cascade of matter or energy so that the output of mass or energy from one subsystem becomes the input for the next. Such processes as the hydrological cycle or cycle of incoming solar radiation can be described in terms of cascading systems.

Climate is a composite system consisting of five major interactive components: the atmosphere, the hydrosphere, the cryosphere, the lithosphere and the biosphere. All these subsystems are open and non-isolated.

THE ATMOSPHERE

The thickness of the earth's atmosphere is small in comparison to its horizontal dimensions and more than 99% of its mass is below an altitude of 30 km. However, in spite of this small relative mass and thickness, the atmosphere is the central component of the climatic system, being kept in motion primarily through differential heating by the sun. Thus the study of atmospheric motion is a problem of convection under the influence of rotation. It is a complex process because the motion of the atmosphere is infuenced by many factors besides the rotation of the earth, such as non-homogeneous thermodynamic and mechanical surface conditions.

THE HYDROSPHERE

The most important part of the hydrosphere for climatic studies are oceans. They cover approximately two-thirds of the earth's surface. Their large mass and high specific heat make the oceans a large reservoir of energy, while their thermal inertia allows then to act as buffers and regulators of temperature. The circulation is much slower in ocean than in the atmosphere, though the two are strongly coupled. Air-sea interactions occur on many scales in space and in time through the exchange of energy, matter and momentum. The exchange of water vapour through evaporation into the atmosphere supplies the water vapour and energy to the hydrological cycle, leading to condensation, precipitation and runoff. On the other hand, precipitation strongly influences the distribution of ocean salinity.

Lakes, rivers and subterranean waters are essential elements of the terrestrial branch of the hydrological cycle and influence the climate on local, regional and global scales.

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THE CRYOSPHERE

The cryosphere comprises the large masses of snow and ice of the earth's surface. It represents the largest reservoir of fresh water on the earth and its importance to the climatic system results mainly from its high reflectivity for solar radiation and its low thermal conductivity. Continental snow cover and sea ice provide for large intra-annual variations in the energy budgets of the continental regions and of the upper mixing layer of the ocean. The snow and ice fields act at high latitudes as insulators for the underlying land and water, preventing them from losing heat to the atmosphere. The strong cooling of the atmosphere near the earth's surface stabilizes it against convection and contributes to the occurrence of a colder local climate.

The large continental ice sheets play a major role in climatic change on time scales up to the tens of thousands of years characterizing the glacial and interglacial periods that occurred during the Pleistocene.

THE LITHOSPHERE

The lithosphere includes the continents and the bottoms of oceans. There is a strong interaction of the lithosphere with the atmosphere through the transfer of mass, angular momentum, sensible heat and the dissipation of kinetic energy by friction in the atmospheric boundary layer. The transfer of mass occurs in the form of water vapour, rain, snow and dust. Volcanoes eject matter and energy from the lithosphere into the atmosphere, increasing the turbidity of the air. The added particulate matter together forming aerosols may have an important effect on the radiation balance of the atmosphere. There is also a large-scale transfer of angular momentum between the lithosphere and the oceans, presumably through the action of torques between the oceans and the continents.

THE BIOSPHERE

The biosphere comprises the terrestrial vegetation, the continental fauna, and the flora and fauna of the oceans. Vegetation alters surface roughness, surface albedo, evaporation, runoff and the field capacity of the soil. It also infuences the carbon dioxide balance in the atmosphere and oceans through photosynthesis and respiration. The biosphere is sensitive to changes in the atmospheric climate and in such human activities as agriculture, urbanization and industry.

Is assumed that the global system is as whole a non-isolated one in the case of energy, but a closed system for the exchange of matter with outer space. The atmosphere, hydrosphere, cryosphere, lithosphere and biosphere act as a cascading system linked by complex physical processes involving

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fluxes of energy, momentum and mass across the boundaries, and generating many feedback mechanisms. The behaviour of the climate system depends on two main external forces: solar energy and the action of gravity Of the two, the primary factor is solar radiation, with that reaching the top of the atmosphere being partially transferred, partially transformed into other forms of energy and partially used in chemical and biological processes.

Short-wave radiation is distributed unequally over the various parts of the climate system due to the sphericity of the earth, orbital motion, and the tilt of the earth's axis. More radiation reaches and is absorbed in tropical regions than at polar latitudes. Observations show that the earth as a whole system loses about the same amount of energy through infrared radiation as it gains from incoming solar radiation. The decrease in emitted terrestrial radiation with latitude is much less pronounced than the decrease in absorbed solar radiation, leading to a net excess of energy in the tropics and a net deficit poleward of 40° latitude. This source and sink distribution provides the basic driving force for all thermodynamics processes occurring within the climate system. The terrestrial climate has varied significantly and continuously on time scales ranging from years to glacial periods. The variability of the climate may be expressed in terms of two basic modes: the forced variations which are the response of the climatic system to changes in external forcing and the free variations due to internal instabilities and feedbacks leading to non-linear interactions among the various components of the climatic system. The external forcing could be terrestrial or astronomical in nature. The astronomical factors include changes in the intensity of solar irradiance, in orbital parameters of the earth and in its rate of rotation. Within the terrestrial forcing we should take into consideration variations in atmospheric composition (carbon dioxides, ozone, aerosol loading), variations of land surface characteristics and long-term changes in tectonic factors. The internal variations are associated with many positive and negative feedback mechanisms and other strong interactions between the atmosphere, oceans and cryosphere. Climate variability results from complex interactions of forced and free variations because the climate system is a dissipative, highly non-linear system with many sources and instabilities. The interactive and non-linear nature of the instabilities and feedback mechanisms of the climate system make it very difficult to obtain a straightforward interpretation of cause and effect.

FEEDBACK PROCESSES IN THE CLIMATE SYSTEM

Feedback is a concept used in electrical engineering. Feedback mechanisms act as internal controls of the system and result from a special coupling among two or more subsystems. Part of the output returns to serve as an input again, so the feedback mechanism may act either to amplify the final output (positive feedback) or to dampen it (negative feedback). The feedback

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concept and its application to the climate system is explained in detail by Peixoto and Oort (1992), so we present here only two simple examples. Negative internal feedback is evident in the temperature-long-wave radiation coupling in the atmosphere. If temperature increases, the atmosphere will generally lose more longwave radiation to space, thus reducing temperature and damping the initial perturbation. A positive feedback mechanism is inserted in the water vapour-greenhouse effect. An increase in surface temperature will cause evaporation at the earth's surface and the amount of water vapour in the atmosphere will increase. Since water vapour is a strong absorber of long-wave radiation, more terrestrial radiation will be trapped, heating the lower atmosphere and leading to a further increase in temperature.

VARIABILITY OF BASIC CLIMATE ELEMENTS IN THE ATMOSPHERE

AIR TEMPERATURE

The distribution of air temperature in the atmosphere is of fundamental importance to its thermodynamic state. The annual range in temperature highlights land-sea contrasts. The January minus July air temperature difference (Fig. 1) is a good measure of the annual range. In the equatorial zone, values of it are very small because solar irradiation does not change substantially during the year. The fluctuations over oceans are moderate due to the high value for specific heat and the large thermal inertia of the oceans. Extreme values occur over all the continents, which become alternately hot in summer and cold in winter. The lowest values are found in central Siberia (–50°) and northern Canada (–40°). A local extreme (–20°) exisits over the Sahara.

Following Peixoto and Oort (1992), we present in Fig. 2a zonal-mean cross sections for variability in temperature in terms of zonal-mean standard deviations for extreme sesons. The variability is of the order of 5°C in mid to high latitudes and about 3°C in the tropics. The air temperature variability is also more intense in the northern than in the southern hemisphere, mainly in the lower troposphere. The variability in the upper atmosphere is due to variations in the tropopause height. The variability of stationary eddies on Fig. 2b shows low values of the order of less than 1°C south of 20N. High values (above 2,6°C) at mid and high latitudes of the northern hemisphere are associated with the land-sea contrast.

ATMOSPHERIC CIRCULATION

The vertical and meridional distributions of the mean zonal flow show many similarities between the northern and southern hemispheres. The zonal circulation in both hemispheres (not presented here) is dominated by a westerly jet maximum of about 25 m/sec at 200 hPa. The annual-mean and

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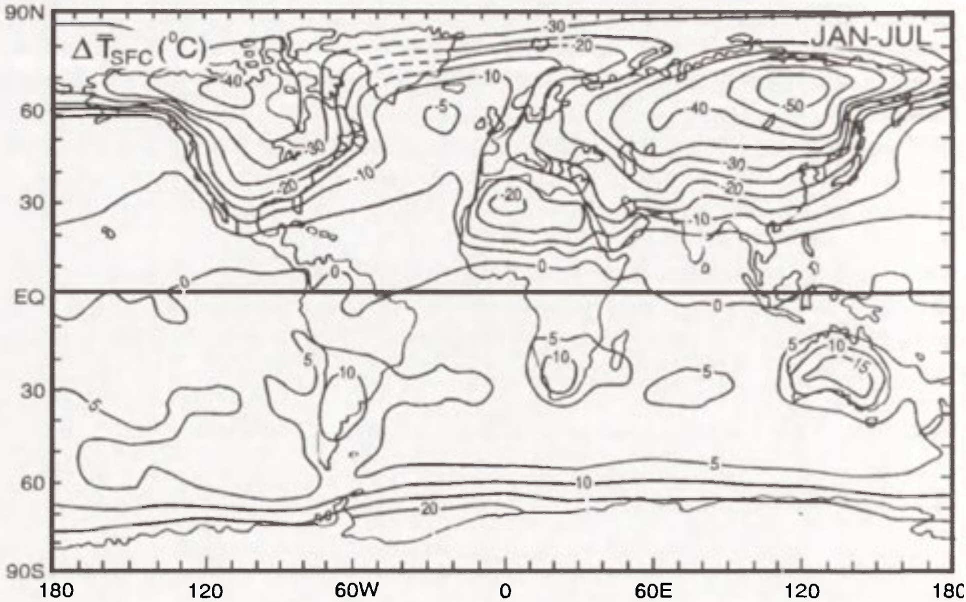

Fig. 1. Horizontal distribution of the January–July difference of surface air temperature (°C) based on the 1963–1973 analyses of Oort (1983). Source: Peixoto, Oort 1992, p. 139

seasonal streamlines computed by Oort and Peixoto are presented on Fig. 3, show mean meridional circulations with evidence of such cells as the Hadley cell in the tropics, the Ferrel cell at mid latitudes and the polar cell at high latitudes. The seasonal cross sections presented in Fig. 3 are very interesting because they show the strong predominance and intensification of the winter Hadley cell and the near-disapperance of the summer Hadley cell in each hemisphere. The direct Hadley cells in the tropics are much stronger than the indirect Ferrel cells at mid latitudes. In the Hadley cells there is a rising of warm, light and moist air in the equatorial region and a descent of colder and heavier air in the subtropics, leading to a thermally-driven direct circulation. In the Ferrel cells there is a rising of relatively cold air at high latitudes and a sinking of relatively warm air in the lower mid latitudes, leading to the thermally indirect circulation in which cold air is forced to rise. The direct Hadley circulation produces a kinetic energy, whereas the indirect Ferrel circulation consumes a kinetic energy.

PRECIPITATION

Precipitation is one of the main elements in the climate system. It is highly variable in space and in time. The most significant features of the annual and seasonally-averaged precipitation patterns are the high rainfall at equatorial latitudes associated with the strong convection in the Inter-tropical Convergence Zone (ITCZ). Subsidence and low precipitation rates

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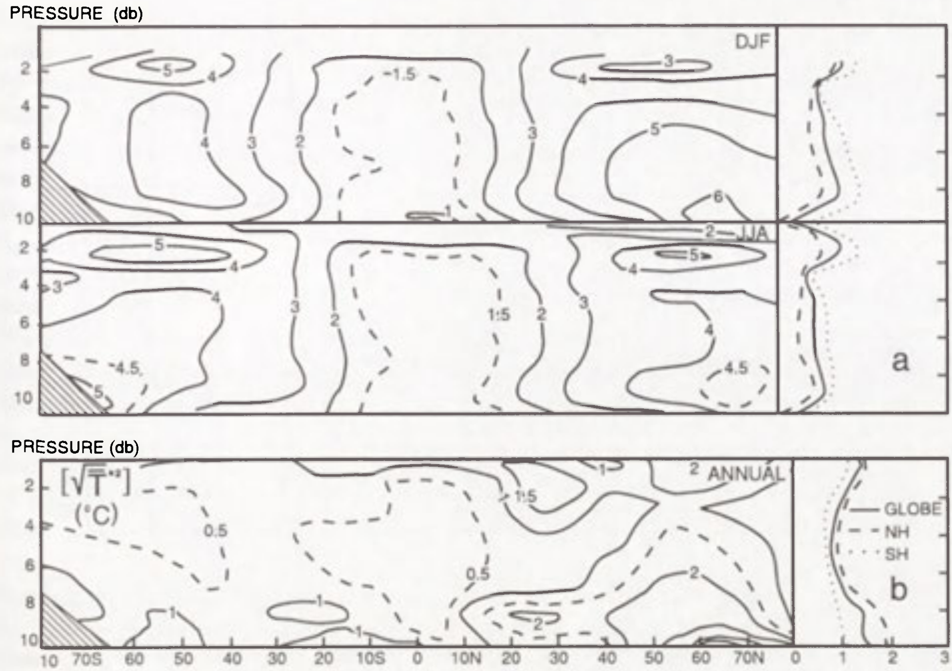

Fig. 2. (a) Zonal-mean cross sections of the day–to–day standard deviation of air temperature (°C) for winter (DJF) and summer (JJA) seasons; (b) Zonal-mean cross sections of east–west standard deviation of the annual-mean air temperature field (°C).
Source: Peixoto, Oort 1992, p. 144

often of less than 200 mm/year dominate in many of the subtropical regions which are under the influence of the large semipermanent anticyclones. There is a secondary maximum of precipitation over mid latitudes where the polar fronts and associated disturbances predominate. Over the polar regions the moisture content in the atmosphere is very low, and amounts of precipitation are of less than 200 mm/year during all seasons.

EVAPORATION

The evaporation rate depends on many factors, of which the most important are incoming radiation, temperature, wind speed, humidity, stability of the air and the availability of water. Estimations of evaporation with different methods differ substantially, reflecting the uncertainties involved in estimating the evaporation fields. Maps show that the highest values for evaporation occur over the subtropical oceans with an evident influence of warm and cold ocean currents and land-sea differences. Over the continents, maximum evaporation occurs in the equatorial belt, mainly due to greater precipitation and higher temperatures observed there.

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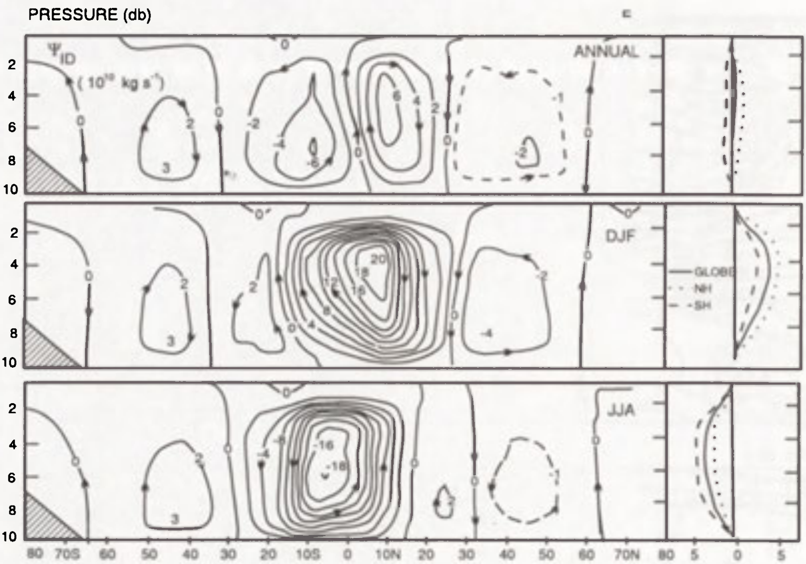

Fig. 3. Zonal-mean cross sections of the mass stream function in 10^{10} kg/sec for annual, DJF and JJA conditions. Vertical profiles of the hemispheric and global mean values are shown on the right. Source: Peixoto, Oorte 1992, p. 159

INTERANNUAL AND INTERDECADAL VARIABILITY IN THE CLIMATE SYSTEM

In addition to the expected annual and semiannual cycles existing in most of the atmosphere Reed et al. (1961) and Veryard, Ebdon (1961) found a peculiar oscillation in zonal winds in the tropical stratosphere with an irregular period generally of slighty longer than two years. This is the so-called quasi-biennial oscillation (QBO). Most of the suggested explanations for the QBO are given in terms of a zonally asymmetric wave forcing. The momentum source for the downward-propagating QBO is probably the absorption of the upward-propagating equatorial waves from the troposphere (Lindzen, Holton 1968). Wave absorption would take place below a critical level where the group velocity of the waves would go to zero. The rate of downward-propagation and the amplitude of the QBO seem to be determined by the intensity and phase speed of the upward-travelling waves. Thus the QBO is a good example of a large-scale internal oscillation that results from wave-mean flow interactions in the atmosphere itself.

The most spectacular example of the internal variation is the ENSO phenomenon that may be regarded as a free oscillation of the ocean-atmosphere system. It is the only true global-scale oscillation that has been identified so far. ENSO consists of two components. The first, mainly oceanic component, El Niño, is a large-scale phenomenon that occurs every three to seven years. In it, the normally cold waters over the entire eastern equatorial

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Pacific Ocean show a dramatic warming of several °C. The second, mainly atmospheric component of ENSO, the Southern Oscillation, was first described by Walker in 1924. This oscillation is associated with large east–west shifts of mass in the tropical atmosphere between the Indian and West Pacific Oceans and the East Pacific Ocean. The atmosphere infuences the oceans mainly through anomalies in the stress exerted by surface winds, whereas the ocean influences the atmosphere mainly through anomalies in sea-surface temperatures and upward fluxes of sensible and latent heat. During ENSO conditions, the waters in the central and eastern equatorial Pacific warm up, the western waters cool down slightly, and convection is enhanced over the central and eastern equatorial Pacific Ocean but is reduced over the Indonesian area. Under normal conditions, the westward trade winds maintain a difference in sea level of about 40 cm between the east and west coasts as well as strong slope in the thermocline in the ocean. When for some reason the western atmospheric pressure gradient decreases and the trade winds weaken, warm waters replace the cold waters of the eastern equatorial Pacific and the ENSO event starts. The index of the Southern Oscillation is given by the difference in surface pressure between two stations: Darwin, Australia (12S, 131E), where the maximum correlation between annual mean sea level pressure over the globe and surface pressure is observed and Easter Island (27S, 109W), where these values are close to the minimum. The ENSO event is characterized by a reduced westward pressure gradient over the equatorial Pacific (a low negative Southern Oscillation Index), weaker-than-normal trade winds over the central Pacific, and warmer-than-normal sea surface temperatures in the eastern equatorial Pacific. The most important aspect of an ENSO event is the change in precipitation patterns over the globe. Observations show strong increases in precipitation over the central Pacific, in the narrow coastal zone of Ecuador and Peru, over the region just south of India and over eastern equatorial Africa. At the same time relative drought conditions are found in the tropics over the western tropical Pacific, Indonesia, Australia, India, south–eastern Africa and north–eastern South America. At mid latitudes only a weak trend for regional increases in rainfall over North America during ENSO is observed (Ropelewski, Halpert 1987).

Beside ENSO, several other, weaker and more regional oscillations have been discovered. At the surface we can identify the North Atlantic Oscillation (NAO), the Pacific — North American Oscillation (PNA), and the North Pacific Oscillation (NPO). These oscillation patterns are associated with regional anomalies in both temperature and precipitation. All seem to be typical modes of the atmospheric system and affect the regional predictability of weather and climate anomalies.

ANTHROPOGENIC INFLUENCES

Human activities can interfere in the climate through changes in the composition and structure of the atmosphere, the release of heat into the

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atmosphere and changes in albedo and other properties of the earth's surface. The composition of the atmosphere is altered by the emission of gases, smoke and particulate matter from industry, from urban centers and from agricultural practices (deforestation, burning of trees, fertilize). These processes use produce substantial changes in the surface albedo then affecting the radiation and moisture balances near the surface. The gases emitted to the atmosphere may affect the climate because they alter the radiation balance of the atmosphere, leading to modifications in the thermal and dynamic structure. They also interfere in the photochemical equilibrium of the stratosphere and especially in the ozone balance. They can also form acids which lead to acid precipitation.

MATHEMATICAL SIMULATION OF CLIMATE

If we had a general theory of climate and climate change it would be possible to explain the causes of climate variability, to obtain a better understanding of the observed changes, and finally to predict their occurrence in the future. Unfortunately there is no such comprehensive theory at present. However, we know that the external factors and thermo-hydrodynamic quantities that characterize the climate are all interrelated through a set of physical laws expressed by various equations. These equations are based on general principles of the conservation of mass, momentum and energy. Taken together with the physical and chemical laws that govern the composition of the components of the climate system, they constitue the fundamental theoretical basis for studying the climate and its evolution. These three-dimensional equations are non-linear and each variable is related to the others. The set of coupled partial differential equations can, in principle, be solved subject to a knowledge of the solar radiation input and other specified boundary and initial conditions that define instantaneous state of the climate system. This mathematically-closed set of equations constitutes a well-posed mathematical problem and forms the core of all mathematical model simulations of climate.

A climate model is a set of specialized thermo-hydrodynamic equations with usually prescribed boundary and initial conditions, certain given values for physical constants and specified schemes of parameterization of the subgrid-scale fluxes of water vapour, momentum and energy. The physical constants include planetary data, such as the radius of the earth, acceleration due to gravity, the angular velocity of rotation, and internal constants such as total mass, chemical composition of the air and oceans, specific heats, latent heats and phase transitions of water and radiative transfer parameters. The boundary conditions include the solar energy input as influenced by the orbital parameters, surface topography, surface roughness, heat capacity of the underlying surface, albedo, soil moisture capacity and vegetation. In order to understand the climate system as a whole, we should consider the behaviour of each of its individual components and the interactions between

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these components. However, in practice, it seems impossible to do this because of the wide range of temporal and spatial scales involved. The time scales for the atmosphere have been found to be 10^{-3} to 10^{-1} years, for the oceans 10^{-1} to 10^{3} years and for the cryosphere 10^{0} to 10^{5} years. So, to simplify the problem, we can take the atmosphere as the main system, with continental surface topography, surface roughness, and sea-surface temperatures as the boundary conditions, and thermo-hydrodynamic equations confined to the atmosphere.

A climate model has three main components: the dynamics, physics and other factors. The dynamics deal with the numerical schemes of the equations of motion and the large-scale transports of mass, water vapour and energy. The physics comprise specialized schemes by which the input of solar radiation and the emission and absorption of terrestrial radiation are treated within the climate system, by which the water in the atmosphere is dealt with during cloud formation, cloud distribution, precipitation, and the release of latent heat. The other factors include surface processes which link the atmosphere with the oceans, and with the continental surface through the transfer of mass, momentum, sensible and latent heat, land-sea ice contrasts and the resulting variations in albedo, soil moisture and vegetation cover.

The governing equations of the atmospheric models are given essentially by the equation of motion, the first law of thermodynamics, the balance equation for water vapour, and the equation of state (Trenberth 1992). They form a closed system of equations with specified boundary conditions. The set of so called primitive equations widely used in climate and NWP investigations and applications is presented below. They are:

a) the horizontal equations of motion

$$\frac{du}{dt} = \left(f + u\,\frac{\tan\varphi}{R}\right)v - \frac{1}{\rho}\,\frac{\partial p}{R\cos\varphi\partial\lambda} + F_{\lambda} \tag{1}$$

$$\frac{dv}{dt} = -\left(f + u\,\frac{1}{\rho}\,\frac{\partial p}{R\partial\varphi}\right) + F_{\varphi} \tag{2}$$

where

$$\frac{d}{dt} = \frac{\partial}{\partial t} + u\,\frac{\partial}{R\cos\varphi\partial\lambda} + v\,\frac{\delta}{R\partial\varphi} + w\,\frac{\partial}{\partial t}$$

b) the hydrostatic law

$$\frac{\partial p}{\partial z} = -\,\rho g \tag{3}$$

c) the continuity equation

$$\frac{\partial\rho}{\partial t} = -\,\frac{1}{R\cos\varphi}\left[\frac{\partial}{\partial\lambda}(\rho u) + \frac{\partial}{\partial\varphi}(\rho v\cos\varphi)\right] - \frac{\partial}{\partial z}(\rho w) \tag{4}$$

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d) the first law of thermodynamics

$$c_p \frac{d\ln T}{dt} - R_d \frac{d\ln p}{dt} = \frac{Q}{T} \tag{5}$$

e) the equation of state for air

$$p = \rho R_d T(1 + 0.6lq) \tag{6}$$

f) the balance equation for water vapour

$$\frac{dq}{dt} = (e - c) + D \tag{7}$$

The basic predicted variables are the wind components u and v, temperature T, specific humidity q, and surface presure p_0. The climate equations are highly non-linear in nature and no general analytical methods are available to solve them. Thus, the partial differential equations have either to be replaced by equivalent finite difference equations or solved by spectral techniques. To solve the model equations 1–7 we have to treat the system at discrete number of instants in time and at discrete number of points in space, substituting the continuum by a spatial grid of isolated points. The dimensions of the basic grid determine the minimum scale of phenomena that can be resolved by the equations. Scales smaller than the basic grid are known as subgrid scales. For example, clouds, sharp fronts gravity waves and turbulence are not usually resolved explicitly and therefore represent subgrid scale phenomena. However, they are thought to be very important in the various budgets, and especially in the vertical transports of momentum, heat and water vapour. Through parameterization techniques it is possible to describe the effects of all subgrid-scale phenomena on large-scale processes.

In summary, mathematical models provide a new way to not only understand climatic behaviour but also to explore the possibility of predicting future climate developments. In recent years the main effort of the scientific meteorological community has concentrated on the problem of simulations of the global climate change. At least of equal importance are problems of regional climate change, and we observe an increasing amount of work concerned with this subject.

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FLOOD FREQUENCY ANALYSIS UNDER NON-STATIONARITY

WITOLD G. STRUPCZEWSKI

Institute of Geophysics, Polish Academy of Sciences
ul. Księcia Janusza 64, 01-452 Warszawa, Poland

WOJCIECH FELUCH

Institute of Meteorology and Water Management
ul. Podleśna 61, 01-673 Warszawa, Poland

ABSTRACT: The assumption of stationarity made in flood frequency analysis has been relaxed by introducing the possibility of the existence of a tread in the first two moments of a probability distribution function. The problem of the estimation of the time-variable moments and probability distribution function has been analysed. The basic assumptions and structure of the IDT (Identification of Distribution and Trend) soft package as well as a plan for its further development have been presented and discussed. The maximum likelihood method is used to estimate model parameters from a time series and the Akaike Information Criterion goodness-of-fit test to identify an optimum model, i.e. of distribution and trend functions. Preliminary results of a flood frequency analysis for Polish rivers obtained with the IDT package are described briefly.

KEY WORDS: Time series, trends, annual flood peaks, probability distribution, time variable parameters, time-dependent moments, likelihood function, Akaike Information Criterion.

INTRODUCTION

The objective of flood frequency analysis is to relate the magnitude of annual peak flow discharges to their frequency of occurrence through the use of probability distributions. The hydrological data employed are assumed to be distributed identically and independent. Then the problem amounts to:

a. the choice of a probability density function (PDF) which fits the sample;
b. estimation of PDF parameters;
c. assessment of the accuracy of parameters and quantile estimates.

The crucial assumption made in the hydrological design of high-flow structures is stationarity of the annual peaks process, i.e. that the probabilistic model derived from a period of records remains valid in respect to the future.

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The upper tail of the PDF in use in the hydrological design has neither a sound empirical basis nor a theoretical one in view of available stream flow records and of the unknown "true" PDF. Chi-square and similar tests of goodness-of-fit are used to choose the distribution which best describes the sample data. Unfortunately, in spite of commonly-shared criticism of such an approach there are no constructive counterproposals.

Observed changes in landscape, catchment characteristics and composition of the atmosphere suggest continuous change in the hydrological regime. In consequence any assumption of stationarity in hydrological time-series must be questioned. The possibility of relaxing it is the object of the paper. It seems realistic to reject the assumption of stationarity in regard to the PDF parameters but not to their type. Since every year of flow records is represented in a time series by a single value of annual peak flow, in order to have the problem well posed a form of time-trend must be assumed. Then the only differences between the stationary and non-stationary approach would be time variable values of PDF parameters and consequently an extension of the selection of the best-fitting model for a time-trend (Strupczewski, Mitosek 1991). Investigations of a trend in a hydrological time series are mainly focused on the detection of a trend for the mean value. To do it, standard statistical techniques are used, based essentially on the hypothesis testing theory. A trend in the variance or in the autocorrelation function is rarely analysed. In fact the statistical moments are simpler to interpret than the original parameters of the PDF. For this reasons the original parameters of the PDF will be expressed in the present study by the moments and replaced by them. This unifies various PDFs in respect to the meaning of their parameters. In an application of flood frequency analysis it is a trend in the variance which may be even more important than a trend in the Mean. This comes from a practical interest in the upper tail of the PDF. Therefore the possibility of a trend existing in both first moments of a time-series shall be included into flood frequency analysis. In the present study a time trend is investigated in the first two moments, i.e. in the Mean value and the Standard Deviation (SD), and it is assumed to be a continuous function of time.

REVIEW OF METHODS

There are three parameter estimation techniques in current use where flood frequency analysis with stationarity is concerned:

1. the method of moments (MOM),
2. the method of maximum likelihood (ML),
3. the method of L moments.

It is easy to show that the method of moments is equivalent to the least squares method (LS) applied to the first, second,... separately. The ML method is the most theoretically-correct method of fitting probability distributions to data, in the sense that it produces-asymptotically effective and unbiased

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parameter estimates — those which estimate the population parameters with the least average error. In spite of this the method of moments is considered more suitable for practical hydrological analysis as it is easier to apply than the ML method. For the majority of PDFs there is no analytical solution of the ML method for all the parameters in terms of sample statistics, and the log-likelihood function must then be maximised numerically, a process not practical until the advent of computers. Despite advances in global optimisation methods permitting searches for global maxima for functions with an enormous number of local maxima, and the availability of high-speed computers, the ML method is still considered quite difficult in application by hydrologists. Without easy access to macrocomputers, practitioners are left with computer programs based on gradient methods (e.g. Kite 1988) which may not give solutions for datasets having multiple roots. In general, it is not possible for any automatic gradient procedure to guarantee finding the global maximum of the likelihood function. It calls for careful selection of the starting vector for an iterative solution. The replacement of the original parameters of the PDF by a set consisting of statistical moments, as done in this paper, may simplify the numerical search for the global maximum of the log-likelihood function. The L-moments method is the newest of the above mentioned parameter estimation techniques (e.g. Hosking 1990, Stedinger et al. 1993). Sample estimators of L moments are linear combinations (hence the name L moments) of the ranked observations, and as a result L moments estimators of the coefficient of variation and skew are almost unbiased and very nearly have a normal distribution. Because we do not see any possibility of L moments extension for time-varying L moments the technique is outside of our interest.

In dealing with non-stationary time-series, it is the least squares (LS) method which is in common use for trend estimation. Applied separately for the first moment about the origin, i.e. Mean, for the second central moment and so on, it can serve to estimate the time-dependent moments. It is therefore a straight extension of the method of moments for the conditional moments. To test whether or not the data do indeed fit the assumed distribution it is convenient to transform the time series to a stationary series and then to apply goodness-of-fit procedures. This can be done through the probability of each element of the series of exceedance which depends on its value, time-trends and the assumed distribution. Any year can be taken as the reference year to reduce the series to stationary conditions.

However, in order that the LS method be an efficient estimator: (1) the errors of estimation shall be normally or at least symmetrically distributed and (2) the population variance of the deviations along the LS curve shall be constant (e.g. Kite 1988). Due to the typically positively skewed flood-peak distributions the first condition is not satisfied even in respect to estimation of the Mean or the time-dependent Mean. Transformation of the annual peaks into variables of the normal distribution is not a solution to the problem as the goal is trend estimation in the statistical moments of the original

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series. Dealing with the first moment, the second condition means that the variance shall be time constant if the Mean is free of a trend, and the same is true of the residual variance if the Mean is time-variable. Concluding, the second condition is satisfied when there is no trend in any moments other than the first one and therefore an attempt should be made to adjust the LS method to cover the case of time-variable standard deviation.

The only way to obtain estimates of the time-dependent moments which are asymptotically effective and unbiased is the use of the maximum likelihood (ML) method (Strupczewski, Mitosek 1995). Unfortunately, this has some practical and technical shortcomings if compared with the LS method. In the ML method, the estimators of the time-dependent moments depend on an assumed PDF. They therefore vary with the probability distribution, which can cause confusion. Readers who have used Kite's algorithms and programs of ML estimation for various distribution functions (Kite 1988) are well acquainted with differences in the moment estimators for a given sample. This can happen when the distribution being fit deviates significantly from the distribution of observations, and as a rule the discrepancies are growing with the order of the moment, being for the Mean negligible small[1]. Furthermore the likelihood function must be maximised for every alternative type of distribution and class and form of trend separately, which requires uphill numerical procedures. Numerical difficulties are enhanced with the growing number of model parameters. Although the LS estimation also requires a numerical solution, with the exception of when it is a Mean affected by a trend of simple form only, the number of problems to be solved is limited to the product of the number of classes and forms of trend.

THE IDT SOFT PACKAGE

The Identification of Distribution and Trend (IDT) soft package is being developed to serve in the identification of an optimum flood frequency model with time dependent parameters from a class of competing models, and then to design high-flow structures in a changing environment. The model here means a type of probability distribution together with a class and form of trend. For every model, the IDT program estimates model parameters from the time series using ML method, derives the variance/covariance matrix and estimates the probability distribution of exceedance with confidence intervals for any given year.

In all, six PDFs are included, namely:

(1) Normal (N),
(2) Two-parameter Lognormal (LN2),
(3) Three-parameter Lognormal (LN3),

[1] If the chosen functional form of the probability distribution is not short of the "true" one, the ML-estimator of the design flow discharge may be less accurate than the MOM-estimator.

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(4) Two-parameter Pearson Type III (P2), i.e. Gamma distribution,
(5) Three-parameter Pearson Type III (P3),
(6) General Extreme Value Type I, i.e. Fisher-Tippett Type I distribution (FT).

None of these has an upper limit which reflects our view of flood physics, and two, i.e. N and FT, are unbounded. Although the normal distribution is rarely used as an alternative in flood frequency analysis, it is included here not only because of its leading place in statistics but because of the connection of LS and ML trend estimates for a normally-distributed variable. For all of these distributions there are analytical relationships between parameters and statistical moments which is convenient from the computational point of view. All the distribution's parameters are allowed to vary in time except the lower bound. In the present version, the value of the lower bound parameter is subject to estimation as the constant. Obviously, a better fit of a model to a time series can be obtained by allowing the lower bound to vary in time. For the computation of the confidence interval the lower bound is considered here as a given value.

A time trend is investigated in the first two moments, i.e. in the Mean value and in the SD and it is assumed to be a continuous function of time. The three classes of time-trend are included in the present version, while work on the fourth class (D) is in progress:
(1) trend in the Mean (A);
(2) trend in the Standard Deviation (B);
(3) trend in both the Mean value and the SD, keeping the variation coefficient constant in time (C);
(4) unrelated trend in the Mean and the SD (D).

Each one of the first three classes increases the number of parameters of the stationary PDF by the same number defined by the form of a time-trend function. The basic option is the time-invariable parameter, called the stationary option (S).

Due to the limited lengths of hydrological time-series, the trend investigation comprises the two first moments only. Their trend propagates to the higher-order moments as shown for the two parameter distributions in the Appendix. For distributions with the lower bound, i.e. for the LN2 and P2 distributions, the trend in the higher moments is related both to the Mean and to the SD, while for the unbounded distributions, i.e. for N and FT, it is a function of SD only.

As far as forms of trends are concerned, there are two options included:

(1) the linear form of the trend (L), which adds one parameter to the stationary model's option (S) in the case of the classes A, B and C, and two parameters in class D;

(2) the square trinomial (parabolic) form (P) for classes A, B, C only, which increases the number of parameters of the stationary case by two.

According to the above notation, the FTBP denotes the Fisher-Tippett type I distribution with parabolic trend in the SD, while the NAL is the Normal distribution with a linear trend in the Mean. Presently, the total number of

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models is: No of Stationary models + No of PDFs · No of classes · No of time-trend functions = 6 + 6 · 3 · 2 = 42, and 6 others will be added soon.

To estimate the parameters of the time-dependent PDF its original parameters are expressed in terms of time-dependent moments and then the ML is applied as for a series consisting of independent observations, i.e. it is assumed that the only reason for dependency is a trend incorporated already into a time series' model. It should be noted that the use of the ML method ties up the trend estimators with the type of PDF. It recalls the importance of proper choice of a PDF[2]. The ML method can be used for a time series with random observation gaps without the necessity of filling them. This is a convenient property of the ML method, and of the Akaike Information Criterion (AIC) built on it, which contrast with statistical tests of time-series homogeneity, which demand continuity of observations. To take advantage of this property, allowance has been made for interrupted time series in the computer programs of the IDT package.

In dealing with a three-parameter distribution like LN3 or P3, the trend is investigated in the two first moments only, which means that one of the three parameters of the distribution is considered time-invariable. In this respect, four possibilities have been analysed:

(1) the third central moment (μ_3);
(2) the skewn coefficient (c_s);
(3) the lower bound (ε) with value estimated for every class and form of trend;
(4) the lower bound (ε) with value estimated from the stationary option.

The first possibility arises directly from replacement of the original parameters of the PDF by the moments. However with a constant value of the third central moment and a trend in SD, the coefficient of skewness can vary from zero to plus or minus infinity while the sign of its time-trend is opposite to that of SD. In the traditional flood frequency analysis a regional value of c_s is frequently in use, due to a growing sampling error with the moment order increase. Proceeding in a similar way in respect to time we have adopted a time-invariable skewness coefficient for the version of the IDT package which is being worked on. The c_s value will be estimated for every class and form of trend of LN3 and P3 separately. In the present version, it is the third possibility which has been implemented. This was accepted for a numerical reason. The search for the optimum value of the lower bound (ε) has been reduced to multiple solutions of the estimation problem of a two-parameter distribution. While testing the above approach on real data its deficiency emerged. As the value of ε is optimised in respect to the whole time series, the estimator of ε obtains a lower value for the AL model than for the S model, increasing in that way the estimated range of variability in annual peaks in comparison to that for the S option. As a result, the estimator of the SD of the AL option may happen to have a

[2] For the hydrological design, it is the necessary condition of priority of the ML-estimator of the design flow discharge over the estimator based on LS-method.

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greater value than that for the S option. The common lower-bound value for all options, e.g. determined from the S option, resolves the above paradox formally but this is not a proper use of the lower bound parameter. There is neither best use of the above parameter for fitting the non-stationary models nor any rational justification but simplification of parameter optimisation. It is easy to show that if the lower bound varies in time, the c_s is constant and the A class of trend is assumed then the lower bound will follow the trend for the Mean. The performance of non-stationary models built on the lower-bounded distributions will be improved if the assumption of the constant lower bound is relaxed. Since the lower bound is to be determined by means of moments, the dimension of the optimisation problem will not change if the lower bound is time variable and the coefficient of skewness considered constant in time.

As was already mentioned, estimated model parameters allow one to derive the PDF for any year, including years preceding or following the observation period. From the mathematical point of view, if the Mean or the SD vary in time, an extrapolation in time is constrained by the conditions that the Mean shall be greater than the lower bound and the SD positive. However, from the practical point of view, it is the breadth of the confidence interval which can serve as a lead of a reasonable range of time extrapolation. The width of the confidence interval for moments or quantiles increases with the time distance from the centre of the observation period. It should be remembered that the standard error of estimation expresses parameter uncertainty only, but not model uncertainty.

Since there is no *a priori* information concerning the model itself the only possibility is to obtain it from the time series. The time series will therefore serve not only to estimate model parameters but also to select the optimum model as well. The Akaike Information Criterion (AIC) goodness-of fit test (e.g. Akaike, 1974) is used here in the identification of an optimum model in a class of competing models (Strupczewski, Feluch 1996, 1997). Based upon information theory, Akaike developed the AIC formula is given as

$$AIC = -2 \ln ML + 2k \tag{1}$$

where ML denotes the maximum likelihood and k the number of fitted parameters. The first term on the right-hand side of equation (1) accounts for the criterion of good statistical fit, while the second incorporates the doctrine of parameter parsimony into AIC. When there are several available models for modelling a given time-series, the model that possesses the minimum value for AIC should be selected. Its estimators of time-dependent moments are considered the most reliable for hydrological design. If the stationary option results in the minimum AIC value for a given time-series then the series is considered stationary and the PDF of the AIC minimum optimal While working with annual-peak time-series, it was found that the distribution function has a greater effect on the AIC value than a trend model, and the PDF choice has little influence on the identified optimum

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model of a trend. One of the great advantages of the AIC test in comparison to nonparametric statistical tests of homogeneity (e.g. Mitosek, Strupczewski 1996) is complete freedom in hypothesis choice.

The IDT soft package includes hydrological design under hydrological non-stationary conditions. Having regard to non-stationarity, the probability of exceedance will refer to the whole period of life of a hydraulic structure, but not to a single year as has been agreed in the stationary case. The IDT package contains a procedure for the estimation of a probability distribution together with standard error not only in respect to one year but to a period of any length (T), optionally located along the time axis:

$$P_T\,(X > X_c) = 1 - \prod_{t=t_1}^{t_1+T-1} \left[1 - p(x_c\,,\,t)\right] = 1 - \prod_{t=t_1}^{t_1+T-1} \int_{-\infty}^{x_c} f(x\,,\,t)\,dx \qquad (2)$$

Therefore the design task is, for a given time dependent probability density function $f(x,t)$, to find the design flow discharge x_c with probability of exceedance P_T during a service life of T-years which begins in year t_1, and then to determine its confidence interval.

CASE STUDY

Available historic time series for annual peak flow discharges of Polish rivers have been taken as the subject of an IDT application. A total of 37 uninterrupted seventy-element series have been collected (Table 1) covering the period 1921–1990. They come from rivers not much affected by artificial water storage. All but five are from the Vistula river or its tributaries and the majority originate from southern Poland. The Odra basin is represented by four series from hydrological stations located along its main tributary — the Warta river. The stations marked on Table 1 by numbers 1, 2, 12, 13, 16, 18, 19 and 21–27 represent mountain river regimes, where the annual peaks usually result from rainfall events, while the numbers 8–11 and 33–37 refer to lowland course of rivers.

TABLE 1. Trend in the Mean estimated from NAL and the best fitting model with its estimate

Basin (river) Station		Area 10^3km^2	Trend m^3/s / year	Mean 10^2m^3/s	Trend/ Mean %/year	Best Model	$p^{1990}(Q_{1\%}{}^{1921})$ % for B.M.
1	2	3	4	5	6	7	8
	Vistula						
1.	Jawiszowice	.971	–.110	1.49	–.073	LN2S	1.0
2.	Tyniec	7.52	–.333	7.19	–.046	P3S	1.0
3.	Jagodniki	12.06	–5.79*	11.3	–.5.14	LN2CL	.09

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1	2	3	4	5	6	7	8
4.	Szczucin	23.90	–4.94	19.0	–.259	LN2S	1.0
5.	Sandomierz	31.85	–2.07	24.9	–.083	P3BL	6.8
6.	Zawichost	50.73	+5.96	32.8	+.182	P3BL	8.1
7.	Puławy	57.26	–3.37	30.0	–.112	P3BL	8.1
8.	Warsaw	84.54	–19.2*	30.0	–.639*	P3AL	.55
9.	Kępa	169.0	–14.9*	39.5	–.377*	LN2CL	.09
10.	Toruń	181.0	–15.0*	39.2	–.382*	LN2CL	.07
11.	Tczew	194.4	–12.0	39.6	–.303	LN2CL	.16
			Vistula\Soła				
12.	Żywiec	.785	+.011	3.01	+.004	LN2BL	.05
			Vistula\Skawa				
13.	Sucha	.468	–1.04*	1.53	–.679*	LN2S	1.0
			Vistula\Skawa\Wieprzówka				
15.	Rudze	.154	+.219	.530	+.414	P2S	1.0
			Vistula\Raba				
16.	Stróża	.644	–.795	2.19	–.363	P3S	1.0
17.	Proszówki	1.47	–2.04	4.60	–.444	P3S	1.0
			Vistula\Dunajec				
18.	Nowy Targ	.681	–.646	2.51	–.257	LN2S	1.0
19.	Krościenko	1.58	+.648	4.59	+.141	LN2S	1.0
20.	Żabno	6.74	–6.87	11.6	–.592	P3CL	.04
			Vistula\Dunajec\Cz.Dunajec				
21.	Nowy Targ	.432	–.196	1.72	–.114	LN2S	1.0
			Vistula\Dunajec\B.Dunajec				
22.	Zakopane	.058	+.312*	.379	+.823*	LN2CL	5.8
			Vistula\Dunajec\Poprad				
23.	Muszyna	1.51	+.106	2.28	+.047	LN2BL	.06
24.	Stary Sącz	2.07	+.223	3.19	+.070	P3BL	.06
25.	Nowy Sącz	4.34	+.200	9.34	+.021	P3S	1.0
			Vistula\Dunajec\Biała				
26.	Koszyce W.	.957	–.228	2.67	–.085	LN2BL	5.0
			Vistula\San				
27.	Jarosław	7.04	–8.56*	7.94	–1.08*	P2CL	.01
28.	Radomyśl	16.8	–9.30*	9.85	–.944	FTCL	.01
			Vistula\San\Wisłok				
29.	Tryńcza	3.52	–1.94*	2.40	–.805*	LN3CL	.06
			Vistula\Wisłoka				
30.	Żółków	.581	+4.99	1.67	+.298	P3S	1.0
31.	Mielec	3.89	–2.55	5.45	–.467	LN3AL	.89

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1	2	3	4	5	6	7	8
			Vistula\Wisłoka\Ropa				
32.	Klęczany	.482	+.573	1.15	+.499	P3S	1.0
			Vistula\Bug				
33.	Wyszków	39.1	–.156	6.67	–.023	P3S	1.0
			Odra\Warta				
34.	Konin	13.4	–.889*	2.55	–.348*	LN2S	1.0
35.	Poznań	25.9	–2.12*	3.78	–.562*	LN2S	1.0
36.	Skwierzyna	32.1	–1.99	4.16	–.479	LN2S	1.0
37	Gorzów	52.4	–1.45	5.45	–.267	P3S	1.0

TREND

First of all, the linear trend in the mean for each of the 37 time series was calculated assuming the NAL model, which gives as estimator identical to one for the least squares method. The results are displayed in Columns 3 and 5 of Table 1. If the AIC value of the NAL model is lower than that of the NS model, the trend is considered significant and the case indicated on Table 1 with an asterisk. A negative slope appears in 27 of the 37, being significant in ten cases, while an upward trend occurs in 10 series, being significant in one only. One difference between the results for lowland and mountainous rivers is noteworthly. While all nine series from lowland river courses show a negative trend in the Mean and five are significant, there are six series with negative slope for mountainous rivers (two significant) and six with a positive slope (one significant). In general, the summer floods do not show clear symptoms of non-stationarity in the Mean, while the winter floods show a downward trend in the Mean. The conclusion will be verified after data for summer and winter peaks, are obtained.

Using the AIC, the best-fitting model was identified for each time-series and the results comprising linear trend models displayed in Column 7 of Table 1. The stationary option (S) appears to be the best in 19 of the 37 cases, which represent mostly the mountainous region, i.e. that in which the annual peak is usually formed from rainstorms. The results for Konin (No. 34) and Poznań (No. 35) require a comment. Previously, a significant negative trend in the Mean was reported in these two series (Table 1, Columns 3 and 5), when the Normal distribution was assumed. However, both series appear stationary if a better-fitting distribution is chosen (Table 1, Column 7). The last column of Table 1 contains the probability of exceedance related to the end of the observation period of the annual flow peak of the probability 1% at the beginning of the period. Thirteen series show a decrease in the probability of exceedance during the observation period, five show the opposite trend and nineteen no change. Note the decrease of flood risk on the Vistula river downstream of Warsaw.

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Model C of the trend is most often chosen as the optimal one. It has been identified as the best of the linear models in nine of the eighteen non-stationary series while a negative trend has appeared in eight cases. In turn, the second is model B which was the best for seven series. However, there is no prevailing trend in respect to the sign of the B trend. The parabolic form of the trend was best in six cases (not shown in Table 1), namely for series 1, 3, 9, 10, 23 and 28.

There is the opposite sign for the trend in the two first moments observed in the middle course of the Vistula (series 5 and 7), i.e. applying the AL model, a downward trend for the Mean has been identified, while from the BL, model a positive trend for SD has been obtained. According to the AIC test, the trend for SD dominates over the trend for the Mean. To explain this, the time-property of winter-season peaks needs to be recalled. Snow melting floods give annual peaks in the years of a lack of heavy rainfall-fed floods and they shape the lower tail of the PDF in the middle course of the Vistula. The downward trend for the Mean of winter-season peaks causes a similar trend for the annual-peak Mean and an increase in the range of annual peaks at the same time, i.e. a positive trend for SD. Obviously, neither of the presented models of trends is appropriate in the case of the opposite signs of trends in the Mean and SD, and it is model D which will be best for series 5 and 7.

DISTRIBUTION

LN2 is the best-fitting distribution for 18 of the 37 series in the class of six PDFs (Table 1), for 36 of the series in the class of two-parameter PDFs and for 23 series if all series are considered stationary It is worth noting that, while P2 has rarely been chosen as the best-fitting distribution, P3 is the second, best-fitting distribution after LN2. It was identified as best for 14 series (Table 1) and for 12, if all series are treated as stationary. The N distribution shows the worst fit of all distributions for every series and every trend option. This is quite understandable as all the analysed time series show distinct positive asymmetry. The FT distribution is the second worst-fitting. It was chosen only once (Table 1) for linear trends and stationarity alternatives and it was never best under the stationary assumption. The performance of the non-stationary models based on the LN3 and P3 distributions can be improved if a time-dependent lower bound is considered in the ML method of estimation. From the results of the case study one can learn that the assumed model for the trend has little influence on the optimal PDF identified. Furthermore, the results do not show any distinct regional differentiation in respect to the best fitting PDF.

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CONCLUDING REMARKS

The idea of a relaxation of the stationarity assumption in flood frequency analysis is implemented by the IDT soft tool, which enables an optimum non-stationary flood frequency model to be identified, i.e. a probability distribution function (PDF) and a time trend in the first two statistical moments, from a class of competing models through consideration of the model that gives the overall minimum to the Akaike Information Criterion statistic. A difference in the standard error of estimation of the stationary and non-stationary cases reveals the informative value of the stationary assumption, which is not in fact the only arbitrary assumption made in flood frequency analysis. Moreover, one can wonder whether the trend model selected by the AIC is really the "true" one, and the same doubts concern the probability distribution function. Experience from the use of the IDT on real data helps realise uncertainty of the hydrological base of water-resources planning. To the authors' best knowledge, the IDT package is a unique one combining a trend with distribution in analysis. For this reason, it can likely find wide application in research and hydrological design covering both stationary and non-stationary flood frequency analysis[3].

The flood regime of Polish rivers shows symptoms of non-stationarity. However, the directions of the detected changes can not be interpreted by reference to changes in land use or river regulation. Therefore it may have been caused either by natural fluctuations of climate or by anthropogenic climate change. There is no certainly as to whether the detected trends would last for a period of the kind considered in water-resource development plans.

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[3] If the ultimate goal of research is investigation of trend in the two first moments, the ML-estimators of time-dependent moments got under normality assumption may be accepted as final results. It is out of the scope of the study to show that they are equivalent to those got from the generalised LS-method.

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LIST OF SYMBOLS

A — trend in the Mean
AIC — Akaike Information Criterion
B — trend in the Standard Deviation
C — trend both in the Mean and in the Standard Deviation keeping the variation coefficient constant in time
C_k — coefficient of kurtosis
C_s — coefficient of skewness
C_v — coefficient of variation
D — unrelated trend in both Mean and Standard Deviation
FT — Fisher-Tippett Type I distribution
IDT — Identification of Distribution and Trend
L — Linear trend
LN2 — Two-parameter Lognormal distribution
LN3 — Three-parameter Lognormal distribution
LS — Least Squares
m — First moment about the origin, i.e. Mean value
ML — Maximum Likelihood
MOM — method of moments
μ_R — Central moment of R-th order
N — Normal distribution
P — Parabolic trend
PDF — Probability Density (or Distribution) Function
P2 — Two-parameter Pearson Type III distribution, i.e. Gamma distribution
P3 — Three-parameter Pearson Type III distribution
S — Stationary model
SD — Standard Deviation

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APPENDIX

TREND IN HIGHER MOMENTS OF TWO-PARAMETER PROBABILITY DISTRIBUTION FUNCTIONS

Because any order moments of any two parameter probability distribution function can be expressed in terms of distribution function parameters, the trend detected in the first two moments, i.e. in Mean and Variance, shall be transferred to the higher moments according to the probability distribution function.

I. Unbounded distributions

Normal distribution. The central moments (e.g. Fisz 1963) are:

$$\mu_{2R+1} = 0 \quad \text{for} \quad R = 1, 2, \ldots \tag{A.1}$$

$$\mu_{2R} = 1 \cdot 3 \cdot 5 .. (2R - 1) \cdot \mu_2^R \quad \text{for} \quad R = 1,2,.. \tag{A.2}$$

Since there is no Mean (m) in the LHS of both equations, a trend in the Mean is not transferred to the higher order central moments. If the variance is time-variant, all even central moments will be time-variant, while all odd moments remain equal to zero.

Fisher-Tippett Type I distribution. Using relationships between moments about the origin and the central moments (Kendall, Stuart 1958), and deriving the moments about the origin by Laplace transform of the density function, we obtain the higher-order central moments in terms of the variance:

$$\mu_R = B_R \cdot \mu_2^{R/2} \quad \text{for} \quad R = 2,3,.. \tag{A.3}$$

where B_R = numerical values given in the Table:

R	3	4	5	6	7	8
B_R	1.13955	5.40000	18.5666	91.4143	493.151	3091.03

As in the normal distribution, a trend in the Mean does not cause a trend in the central moments. However a trend in the Variance is transferred to all higher central moments leaving time-invariant the coefficients of skewness and kurtosis equal to 1.13955 and 5.4 respectively.

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II. Lower-bounded distributions

Gamma distribution. Using the formula for the R-th order cumulant (e.g. Dooge 1973), and relationships between moments and cumulants (Kendall, Stuart 1958) one can express the R-th central moment in terms of lower order moments as:

$$\mu_R = \left(\frac{\mu_2}{m}\right)^R \cdot f_R\left(\frac{m^2}{\mu_2}\right) = (m \cdot c_v^2)^R \cdot f_R\left(\frac{1}{c_v^2}\right) \tag{A.4}$$

where $f_R(\cdot)$denotes the polynomial of degree [R/2], [·] denotes the Entier function and c_v is the coefficient of variation. In particular for R = 3

$$\mu_3 = 2m^3c_v^4 \tag{A.5}$$

and for R = 4

$$\mu_4 = 3m^4c_v^4(1 + 2c_v^2) \tag{A.6}$$

That is the time-variant Mean or Variance or both cause all time-variant central moments of an order higher than the second, while the form of the trend is determined by the form of trend in the two first moments and the relationship (A.4). From eq.(A.5) we get

$$c_s = 2c_v \tag{A.7}$$

and from eq (A.6)

$$c_k = 6c_v^2 \tag{A.8}$$

i.e. the time-invariant coefficient embraced in trend model C results in constant skewness and kurtosis coefficients.

Lognormal distribution

Since the expression for the R-th central moment does not have a simple form (Aitchison, Brown 1957), the expressions for the third and fourth moments will be given here:

$$\mu_3 = m^3c_v^4(c_v^2 + 3) \tag{A.9}$$

$$\mu_4 = m^4c_v^4(c_v^8 + 6c_v^6 + 15c_v^4 + 16c_v^2 + 3) \tag{A.10}$$

or in a simpler form

$$\mu_4 = m^4c_v^4(A^4 + 2A^3 + 3A^2 - 3). \tag{A.10a}$$

where $A = 1 + c_v^2$.

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Therefore the coefficients of skewness and kurtosis are:

$$c_s = c_v(c_v^2 + 3) \tag{A.11}$$

$$c_k = A^4 + 2A^3 + 3A^2 - 6 \tag{A.12}$$

As one can see, all previous remarks concerning the Gamma distribution remain in force here.

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SOME REMARKS ON DETECTING NON-STATIONARITY IN NATURAL PROCESSES

HENRYK T. MITOSEK
Institute of Geophysics, Polish Academy of Sciences
ul. Księcia Janusza 64, 01-452 Warszawa, Poland

ABSTRACT: The paper contains some remarks on detecting climate variability or climate change in river discharge processes. The selection of adequate non-parametric statistical tests is discussed as well as the conditions which should be fulfilled by data records of the considered processes. After statistical analysis had been carried out on the basis of more than 150 long-term river-discharge time series, using non-parametric tests at the 5% significance level, it was found that the stationary hypothesis could not be rejected in most cases. Moreover, no conclusion could be drawn as to an regional pattern of trends in runoff characteristics: in some cases, neighboring river catchments show trends in the opposite direction.

KEY WORDS: climate, non-parametric tests, non-stationarity.

INTRODUCTION

Climate variability and climate change can be identified with two different ideas of climatic processes, namely those of the climate represented by a stationary process or a non-stationary one. According to such an approach, climate is analyzed as a non-stationary process that can be approximated by a stationary one on a shorter time scale of a few decades. This stationary approximation is connected with the idea of climate normals considered as measures of the central tendency around which the climate fluctuates. The problem of climate variability versus climate change provokes a question as to whether it is possible to detect non-stationarity of hydrological and meteorological processes by applying statistical tests to existing data.

In considering the problem, we should be aware of the fact that the relation between the signal, in the form of a possible trend, and the noise, is very disadvantageous. In other words, any possible trend can be masked by the high natural variability of the considered processes (compare Fig. 1).

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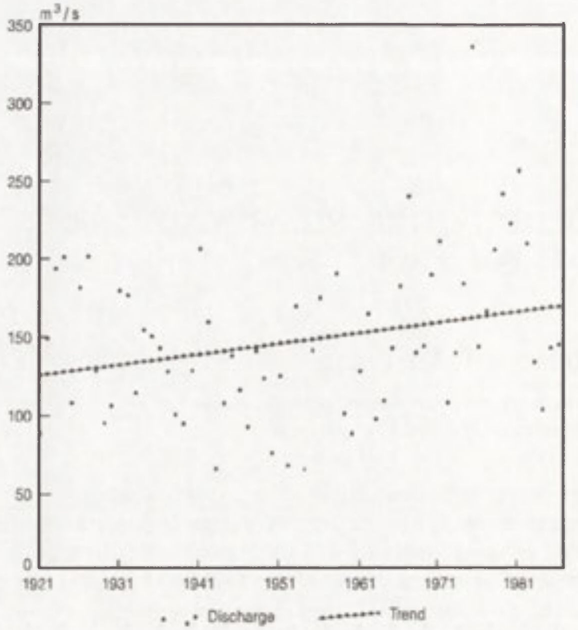

Fig. 1. Mean annual discharge of the Bug river at Wyszkow and a possible trend

DATA

A 30-year period is the minimum length of a discharge time series. It is assumed that the data should be consistent and homogeneous. They are consistent when it can be acknowledged that they have been acquired by the same measurement technique. In turn, homogeneity is connected with constancy of the measurement site and environmental conditions. In practice, a long time series is almost never absolutely consistent and homogeneous, so we have to accept tacitly that the conclusions of the climatic studies will not be influenced too much by any such heterogeneities, if present. As a result of the assumptions, it has to be accepted that the existing time series can be considered random, as well as that the elements of the time series are independent and have identical probability distributions.

TESTS

The selection of adequate statistical tests is always a key problem of a study as that is where the decision is made as to the possibility and form of the answer to questions concerning the way in which climate variability and change are reflected in hydrological data.

Moreover, the stage of creating and veryfying statistical hypotheses is a critical one in the research procedure. The methods of verification of hypotheses, both parametric and non-parametric tests, have an "inborn defect" in their structure that reveals itself in the exclusive capacity of rejecting advanced hypotheses. The statement that a test does not — at the assumed level of significance — give grounds for rejecting the tested hypothesis is never equivalent to an authorization of its complete acceptance.

We have hypothesised that climatic processes of monthly values are periodical stochastic processes with a one-year cycle, i.e. that the 12-dimensional random variables for months of the same name have two identical moments, mean value and variance. We have adopted the same assumption for annual climatic

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values, i.e. for the one-dimensional random variable. In every case, this assumption refers to the identity of the appropriate mean values and variances.

The adopted hypothesis has been subject to the falsification procedure of the following non-parametric tests: the runs test, the Kruskal-Wallis test of equality of means and variances, and the Mann-Kendall test of trends in the mean and variance. The non-parametric tests are distribution-free, i.e. these criteria are robust. Sneyers (1975) showed that the most appropriate test of a trend is the Mann-Kendall test, in the absence of any knowledge of the distribution of elements in a time series.

The runs test (Fisz 1963) allows one to consider a hypothesis concerning the origin of an analyzed realization from a process with independent elements. It is a non-parametric competitor of the parametric test built on the basis of autocorrelation coefficients (Sneyers 1975). Results of these tests can also be used as indicators of the possible existence of trends. However, the test constructed on the basis of autocorrelation coefficients is limited to a linear trend only.

The results of studies on the interdependence of successive elements of the analyzed processes, carried out using the runs test, have no influence on considerations of climate variability and climate change. The rejection of the hypothesis that there is no interdependence between successive elements of the process creates additional problems because the time series can no longer be considered independent random variables.

The Kruskal-Wallis test (Sneyers 1975) of the identify of mean values or variances is applied for a complete period of observation of N-years divided into 6 sub-intervals of identical length [N/6]-years where [.] denotes the 'integer part of'. The first year of observation constitutes the beginning of the first sub-interval. The test enables us to draw a conclusion as to the possible heterogeneity of the mean value or variance of the analyzed process. Moreover, one should be aware that the postulated independence of samples remains unfullfilled because every sub-interval represents a certain part of the observation period.

The sequential form of the Mann-Kendall test based on Kendall's range correlation statistic enables us to assess the overall trend in the quantities of the mean values or variances.

It is necessary to be aware of the consequences of detecting an unstable mean value (trend) in the considered time series. If this time series is treated as a realization of a stationary process, then the trend is an effect of low-frequency harmonic variabilities. However, if the time series is perceived as a realization of a non-stationary process, the trend is a deterministic continuous time function. Unfortunately, the available realizations give no chance to discern the influence of low frequencies from trend in the mean value.

To verify the hypotheses, it is proposed that successive use be made of the following non-parametric statistical tests (the procedure is a modification of the proposal presented by Vannitsen, Demarée (1991):

(i) The runs test (Fisz 1963) permits consideration of the hypothesis

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concerning the origin of the time series from a process with consecutively independent-elements.

(ii) The Mann-Kendall test (Mann 1945) enables us to assess the overall trend in the mean-value run of the time series.

(iii) In a case where there are no grounds for the rejection of the hypothesis concerning homogeneity in the mean value, one goes on to consider possible changes in the variance by way of the Mann-Kendall test (Snyder 1975). This ends the test analysis of the time series.

(iv) If the Mann-Kendall test reveals an overall trend in the mean value questions should be asked about the existence of abrupt changes in the series. The Lombard test (Lombard 1988) allows us to assess a number of the change-points.

(v) Finally, the Pettitt test (Pettitt 1979) enables us to estimate the change-point.

Frequently, one cannot ascribe to the statistically significant number of the change-point the same number of the statistically significant change-points.

Tests (i)-(v) should be used in the above-mentioned succession. The verification of the assumed hypotheses is conducted at the 5% significance level.

CONCLUSIONS

Statistical analysis was carried out on the basis of more than 150 long-term hydrological time series of monthly river discharges (Mitosek 1992, 1995). Applying non-parametric tests at the significance level of 5% give found that the stationary hypothesis could not be rejected in most cases. Moreover, no conclusion could be drawn about the regional pattern of trends in runoff characteristics: in some cases, neighboring river catchments show trends in the opposite direction.

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REGIONAL CLIMATE SCENARIOS AND THEIR APPLICATIONS

MAŁGORZATA LISZEWSKA, MARZENA OSUCH

Institute of Geophysics, Polish Academy of Sciences
ul. Księcia Janusza 64, 01-452 Warszawa, Poland

ABSTRACT: In the first part of the paper various approaches to the formulation of regional climate scenarios are described. In the second part an example of a climate scenario for Poland based on results from the ECHAM1/LSG general circulation transient model is presented. Two perturbed runs of the model are considered: A — "business as usual" and D — "accelerated policies". The hydrological regime of Polish catchments in changed climate conditions is evaluated using the CLIRUN 31 watershed model. Some of the results are discussed.

KEY WORDS: regional climate scenarios, general circulation models, global climate change, downscaling, water balance model, hydrological impact assessment.

INTRODUCTION

Rapid industrial development this century raised the question of its possible influences on global climate, and the especially important problem of whether its likely regional consequences could be assessed. Impact studies use models with high resolution of the order of several metres to several kilometres, and climatologists are expected to produce results from their simulations at similar resolution. The first part of our paper presents a review of methods used in the formulation of regional climate scenarios, while the next two parts contain an example of a regional climate scenario for Poland based on the output of the ECHAM1/LSG model and some results of our hydrological assessments of the responses of Polish catchments to climate change.

REGIONAL CLIMATE SCENARIOS

The various approaches to constructing regional scenarios for changes in climate variables being developed, can, in general, be classed as: empirical

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analyses of historical datasets, or as semi-empirical or dynamic downscaling of the results of general circulation models (Giorgi, Mearns 1991).

Empirical methods use information derived from historical series of observations. Research is being carried out in two directions on the basis of data from recent decades and paleoclimatic analogues. Regional scenarios obtained in such a way may depend strongly on the periods selected to construct them (Jones, Kelly 1983). The approach is used in the qualitative evaluation of the directions and ranges of possible changes in climate parameters, rather than in quantitative assessments.

The tools used most widely to investigate climate evolution are general circulation models comprising full three-dimensional descriptions of the atmosphere-ocean-earth system, integrated over time. Various experiments corresponding to different scenarios for emissions of greenhouse gases are carried out, and the results of such integrations compared against control runs of the models. The spatial horizontal resolution of general circulation models is of the order of $2.5^o \times 3.75^o$, longitude x latitude, while impact models require their input variables to be resolved on a much finer grid. It is for this reason that many kinds of statistical and dynamic downscaling methods are being developed.

A simple, often-used way, to include regional information on climate change into impact models is to add the interpolated differences between perturbed and control runs of a model to the observed series. In the case of parameters like precipitation, the adding of differences is substituted by the multiplication of observed values by respective ratios. Other modifications have also been developed (e.g. Mearns et al. 1984), and the same technique was applied in preparing the Polish Country Study Project (Polish Country Study to address climate change 1996).

In a more advanced strategy introduced by Kim et al. (1984), the correlation between observed values for climate variables at meteorological stations, and spatial averages for the same variables, was determined, giving regression equations for the most probable mesoscale distributions of meteorological parameters. The approach was applied to monthly means for temperature and precipitation in Poland (Jakubiak, Liszewska 1990; Liszewska, Olecka 1994), results attesting to the great complexity of the Polish climate and the impossibility of explaining it by reference to only one mode of expansion on the basis of empirical orthogonal functions.

The next approach employs the principles of the Perfect Prog (PP) and Model Output Statistics (MOS) Methods, which were elaborated for the purposes of interpretating numerical weather forecasts (Klein 1982). The empirical relations derived are between observed values for mesoscale climate parameters and observed (PP) or simulated (MOS) large-scale general circulation fields. The main justification for such a strategy is a conviction that global models can simulate general circulation features much better than the parameters at the earth's surface. These kinds of relationships were found by within the framework of the Climate Scenarios for Poland project (Liszewska, Olecka 1994).

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It is very helpful for these studies to embrace empirical orthogonal function analysis, which allows for a reduction in the number of predictors through the selection of only the most significant modes, and helps filter noise from the input fields. However, this strategy can also result in the abandonment of some potentially useful information. Canonical correlation analysis is used to find spatial patterns of climate variables with optimally-correlated time coefficients (Zorita et al. 1992; von Storch et al. 1993).

The main assumption of the semi-empirical approach is that the relations derived for an observed climate can be used for the changed conditions. It depends on the physical nature of the parameter considered. Very often, if not always, values for climatic parameters are influenced by local forcings at the surface which can also be modified in a new climatic state. An important task is to select the appropriate predictors representative of the processes affecting the projected variable. Predictors are computed, usually in a region including the area of interest, but teleconnections may sometimes play an important role.

Despite all its limitations, the semi-empirical approach is very effective. Being computationally less demanding it allows for multiple assessments and provides better evaluations than direct use of the output of general circulation model.

The most advanced tools for constructing regional climate scenarios are the limited area models embedded into general circulation models (e.g. Giorgi 1990). They are based on a deterministic description of physical atmospheric processes. The important issue is the selection of the domain and resolution of the regional model. On the one hand, this should allow for the encapsulation of significant mesoscale features, e.g. topography, but on the other it should be large enough for domination of boundary conditions to be avoided. Of course, a compromise between the demands of the model and the costs of computation must be found. Nested models are very expensive and require computers with great computational power. It is not possible to perform entire long-term simulations of regional climate evolution using limited-area models, so computations are only carried out for selected time periods.

The alternative dynamic approach, again very expensive, is to apply a variable horizontal grid in global climate models. This allows for an increase in resolution in the considered regions. This stretching technique is used very successfully in the ARPEGE/IFS model implemented by Météo-France (Déqué et al. 1993; Déqué and Piedelievre 1994). The horizontal resolution of the model decreases monotonically in both directions when moving from one pole of the sphere to the other, while the choice of the pole, and of the highest and lowest resolutions depends on the application.

This review of methods used in the formulation of regional scenarios is not comprehensive. There are a variety of studies on this subject undertaken at climate centres (see Giorgi, Mearns 1991) and many have not been mentioned above. We aimed merely to approach the problem and to indicate some Polish attempts to create climate scenarios for our region.

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CLIMATE SCENARIO FOR POLAND DERIVED FROM THE ECHAM1/LSG MODEL

The coupled ocean-atmosphere general circulation model ECHAM1/LSG was developed at the Max-Planck Institute in Hamburg (Cubasch et al. 1992; Deutsches Klimaterechenzentrum 1994). It consists of a low-resolution version of the spectral model of the European Centre for Medium Range Weather Forecasts, extensively modified for climatological applications by the Hamburg group of climate modellers. The prognostic variables are: vorticity, divergence, temperature, surface pressure, water vapour and cloud water. The model is spectral with triangular truncation T21, corresponding to a Gaussian grid resolution of 5.6°. In Fig. 1 we present the land–sea mask used for T21 model truncation to show how less detailed results are available for further impact investigations. Vertically, the model has 19 levels. The integration scheme is semi-implicit, with a 40-minutes' time step. The atmospheric module is coupled to the Hamburg Large Scale Geostrophic Ocean General Circulation Model (Maier-Reimer, Mikolajewicz 1992), based on primitive equations, with 11 vertical levels.

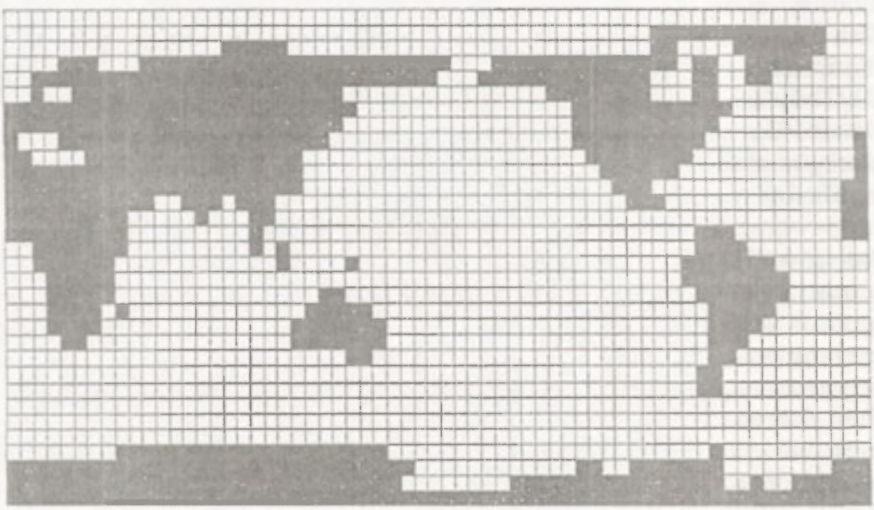

Fig. 1. The land–sea mask used for T21 model truncation acc. (Deutsches Klimaterechenzentrum 1994).

Our analyses concern three 100-year simulations of the model: a control run and two perturbed ones corresponding to the A and D emission scenarios accepted by the Intergovernmental Panel on Climate Change (IPCC). Scenario A ("business as usual") allows an unrestricted increase in greenhouse gases emissions, while scenario D ("accelerated policies") represents the situation with the severest reduction in emissions (IPCC 1992).

Statistical downscaling based on empirical orthogonal function analysis (EOFA) and canonical correlation analysis (CCA) (Liszewska, Osuch 1997)

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was applied to the results of the three experiments with the ECHAM1/LSG model. Monthly means for temperature and precipitation at the Polish meteorological stations were downscaled from the model's output fields of 500 hPa geopotential height.

Fig. 2 presents the maps of observed temperature, precipitation, runoff and evapotranspiration in Poland averaged for the period 1951–1990, which are our reference-point in further considerations. Fig. 3 contains patterns of relative (%) differences of T defined as $(T_A - T_{ct})/T_{ct}$ and $(T_D - T_{ct})/T_{ct}$, where T_A, T_D and T_{ct} denote annual mean temperature derived from experiments A and D and the control respectively, for the two decades 2035–2044 and 2075–2084. The next Figures present the same relative changes for precipitation and two selected hydrological parameters: runoff and evapotranspiration. We discuss only some results here, with the aim being to indicate some problems connected with the assessment of regional climate scenarios and to show certain possibilities for the interpretation of the results of general circulation models for Poland.

Both experiments give an increase in air temperature. Our analyses show that the changes in air temperature projected are greater in experiment A than in experiment D. While at the beginning of the integration, air temperature in experiment A is only slightly higher (below 1°C in the decade 1995–2004), by the end of the simulation, in 2075–2084, differences between annual values for air temperature in the scenarios range from 3°C on the Baltic Sea coast to over 4°C in Central Poland. In the case of A, relative changes in air temperature with respect to the control run are from 20% to 50% in the decade 2035–2045 and from 50% to 80% in the decade 2075–2085, whereas in the case of D the respective differences range from 10% to 20% in 2035–2045, and from 20% to 30% in 2075–2085%. The spatial patterns for the relative changes in temperature are very similar in both experiments and for both decades, in general with the greatest increases in the eastern part of Poland.

The ECHAM1/LSG model projects a decrease in rainfall in Poland. If we compare scenarios D and A, differences between them range annually from 70 to 150 mm in 2035–2044 and from 35 to 270 mm in 2075–2084, generally with maximum values in southern Poland. Maps of relative decreases for experiments A and D with respect to the control run (Fig. 4) are very similar, but the changes are more marked in case A than case D. Minimum relative decreases in precipitation occur in the southern regions characterised by the highest annual precipitation (compare Fig. 2).

HYDROLOGICAL APPLICATION

Poland is a country in which water deficit can cause problems in certain catchments. Potential climate changes can influence water balance elements and some investigations show that this impact can be rather undesirable. The problem of evaluating eventual changes in water supplies is therefore

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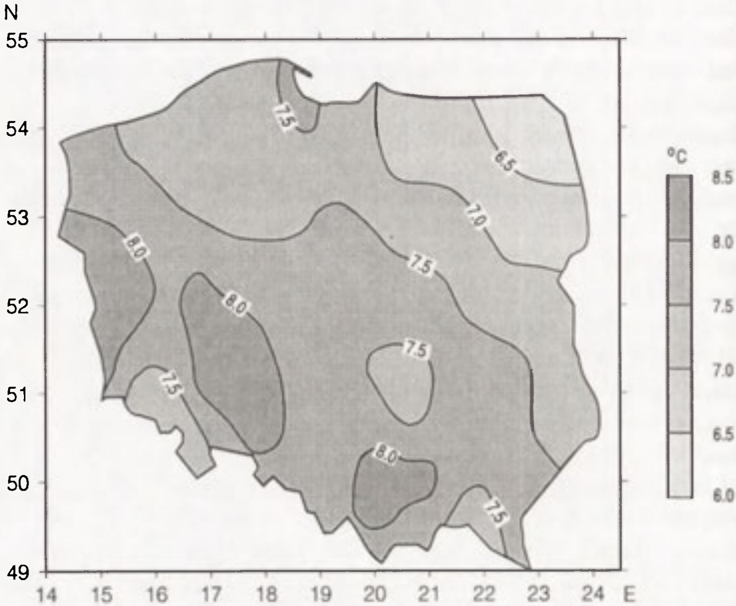
A



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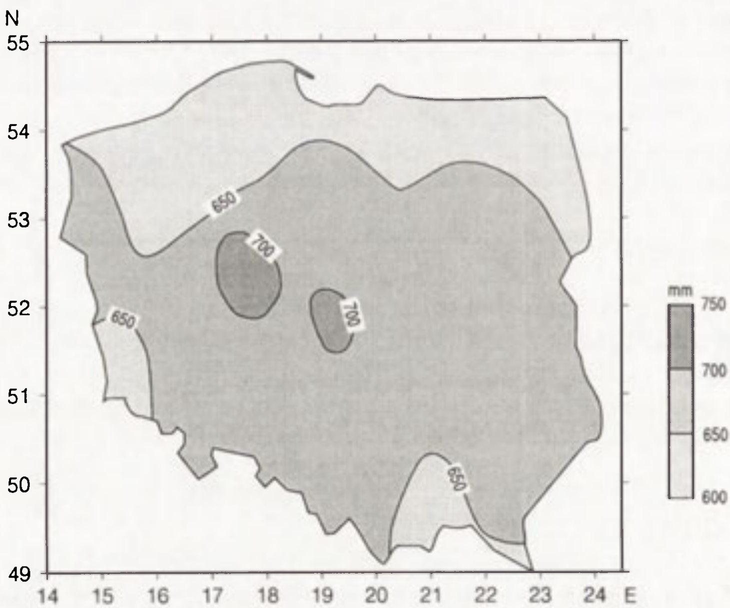

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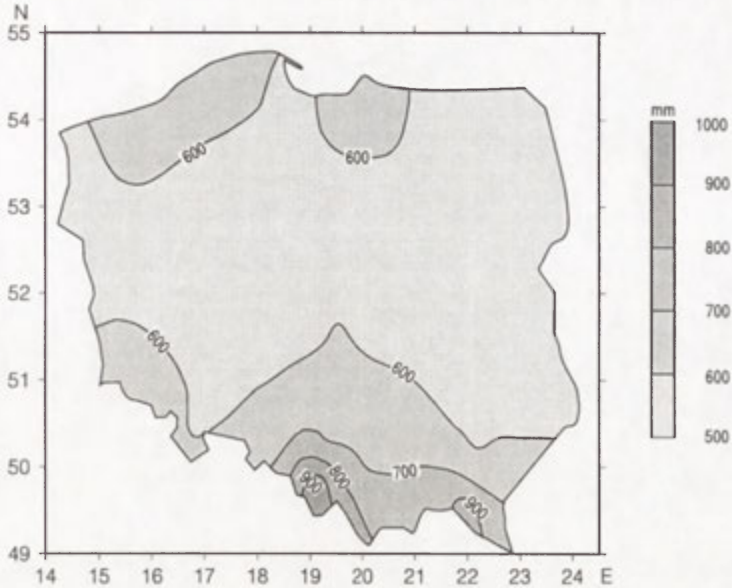
B



D

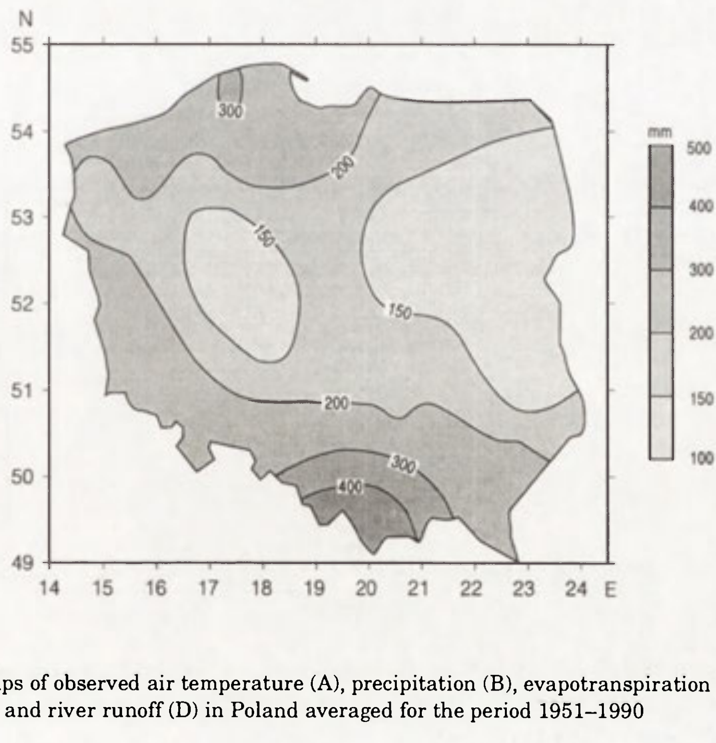


Fig. 2. Maps of observed air temperature (A), precipitation (B), evapotranspiration (C) and river runoff (D) in Poland averaged for the period 1951–1990

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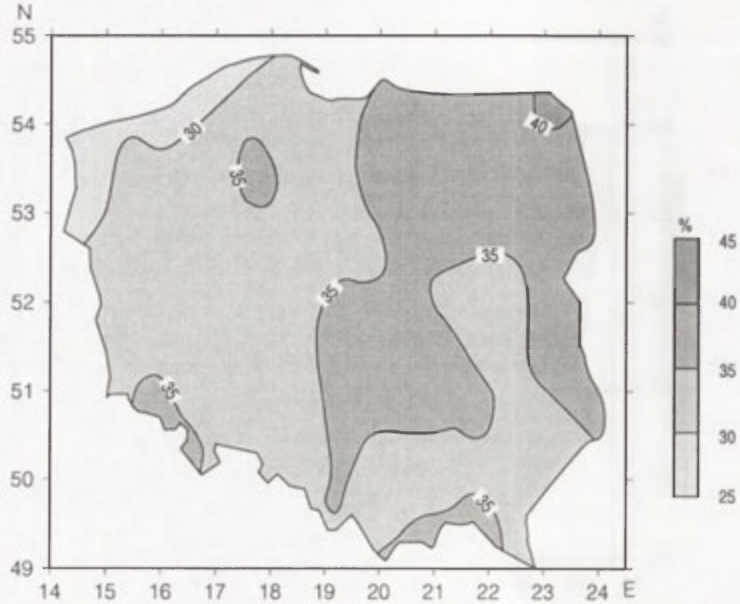
A



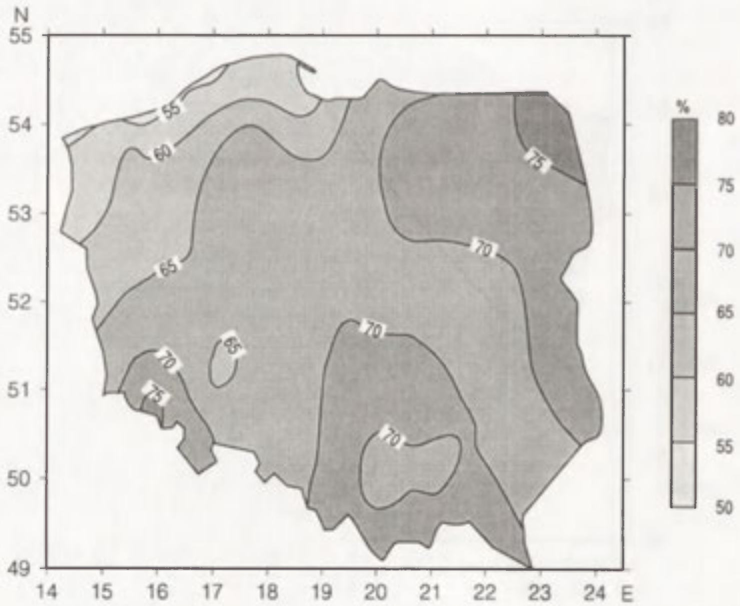


Fig. 3. Maps of relative differences of air temperature defined as $(T_A - T_{ct})/T_{ct}$ and $(T_D - T_{ct})/T_{ct}$, expressed in %. T_A, T_D and T_{ct} denote annual mean air temperature derived from experiments

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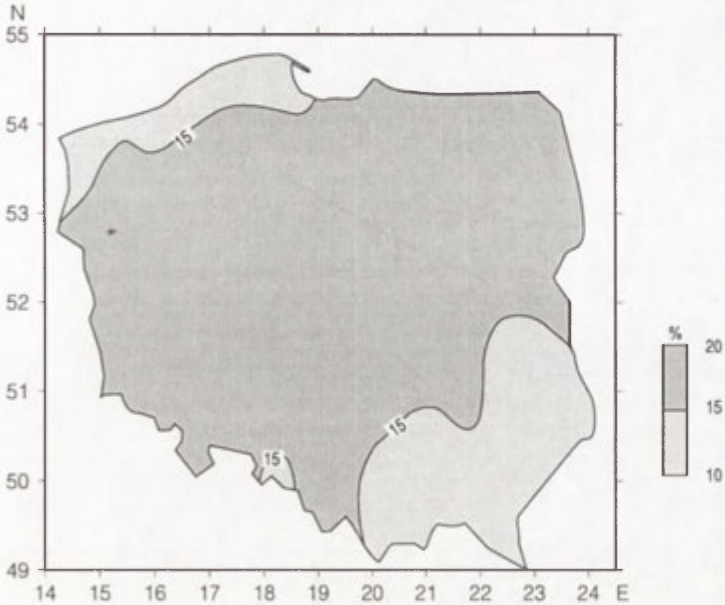
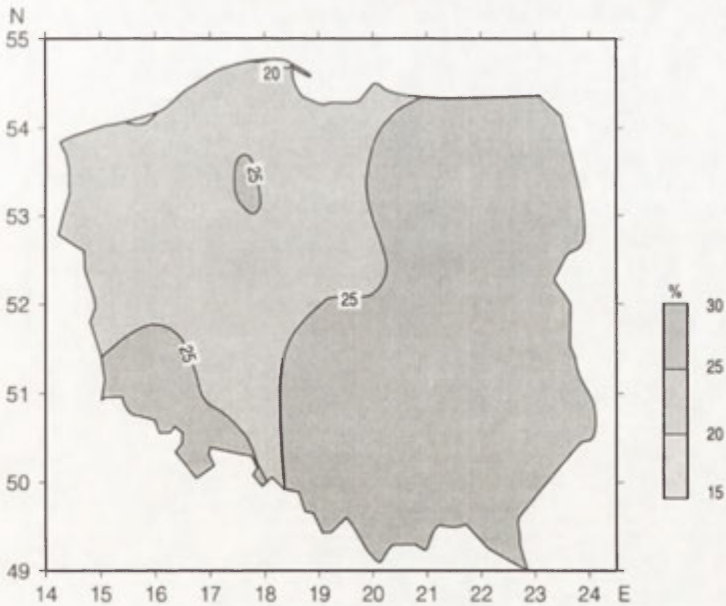
D





A (lef) and D (right) and the control, respectively, for the two decades 2035–2044 (top) and 2075–2084 (bottom)

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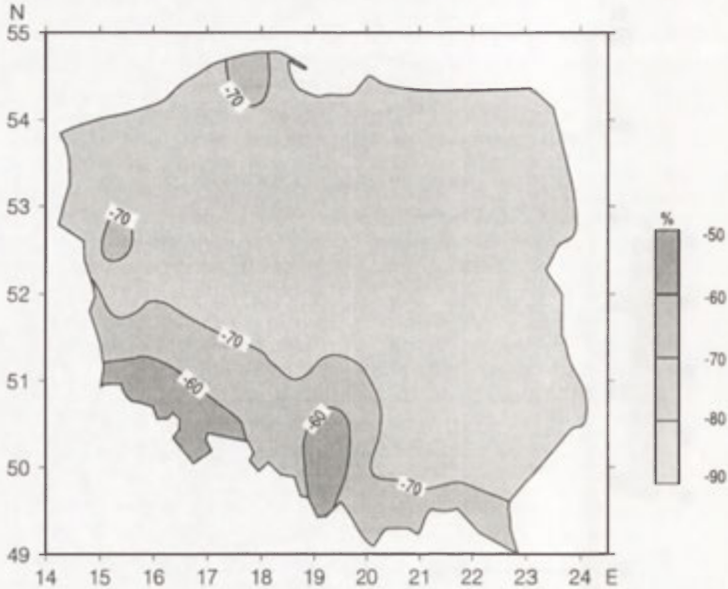
A



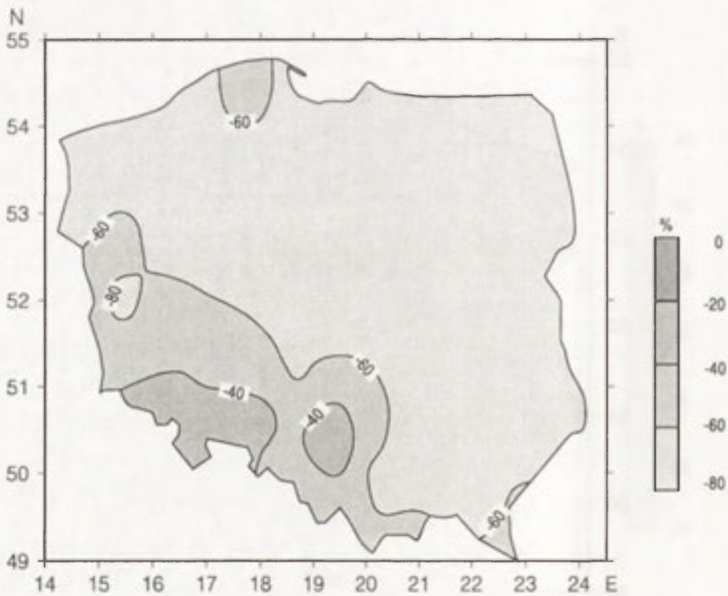


Fig. 4. Maps of relative differences of precipitation defined as $(P_A - P_{ct})/P_{ct}$ and $(P_D - P_{ct})/P_{ct}$ expressed in %. P_A, P_D and P_{ct} denote annual mean precipitation derived from the experiments

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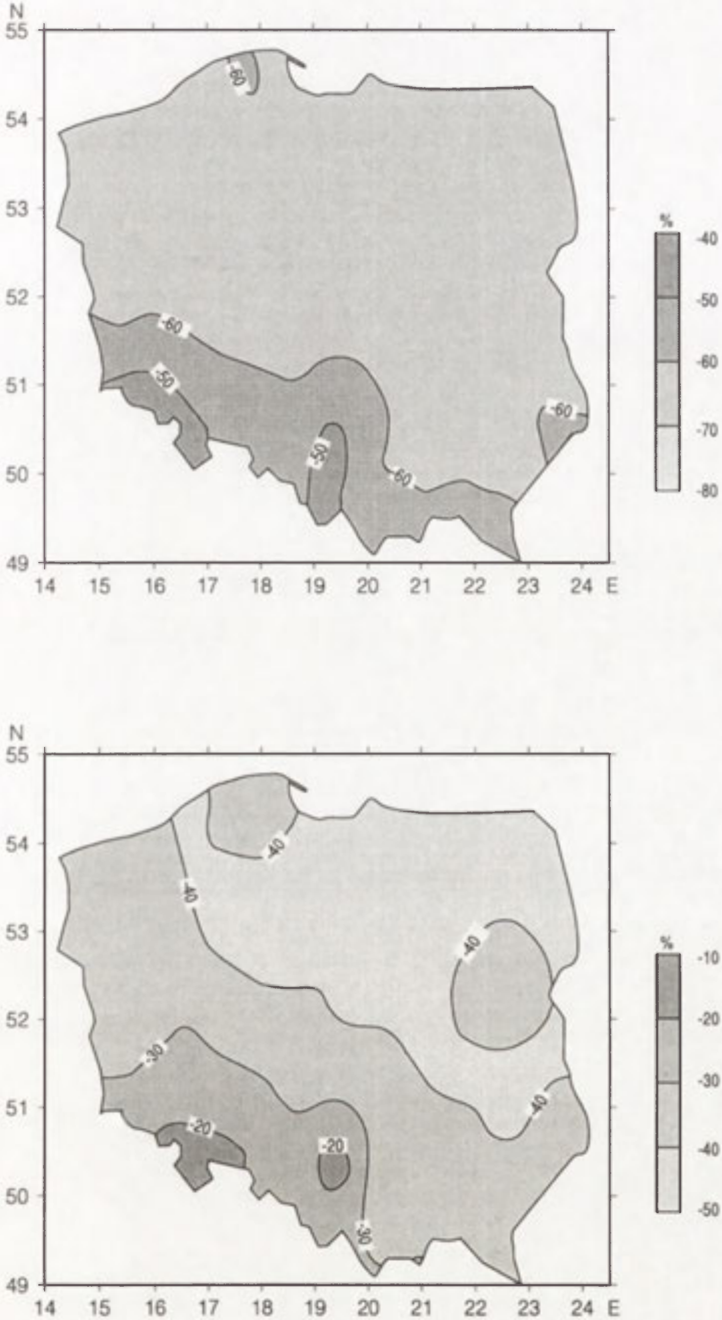

A (left) and D (right) and the control respectively, for the two decades 2035–2044 (top) and 2075–2084 (bottom)

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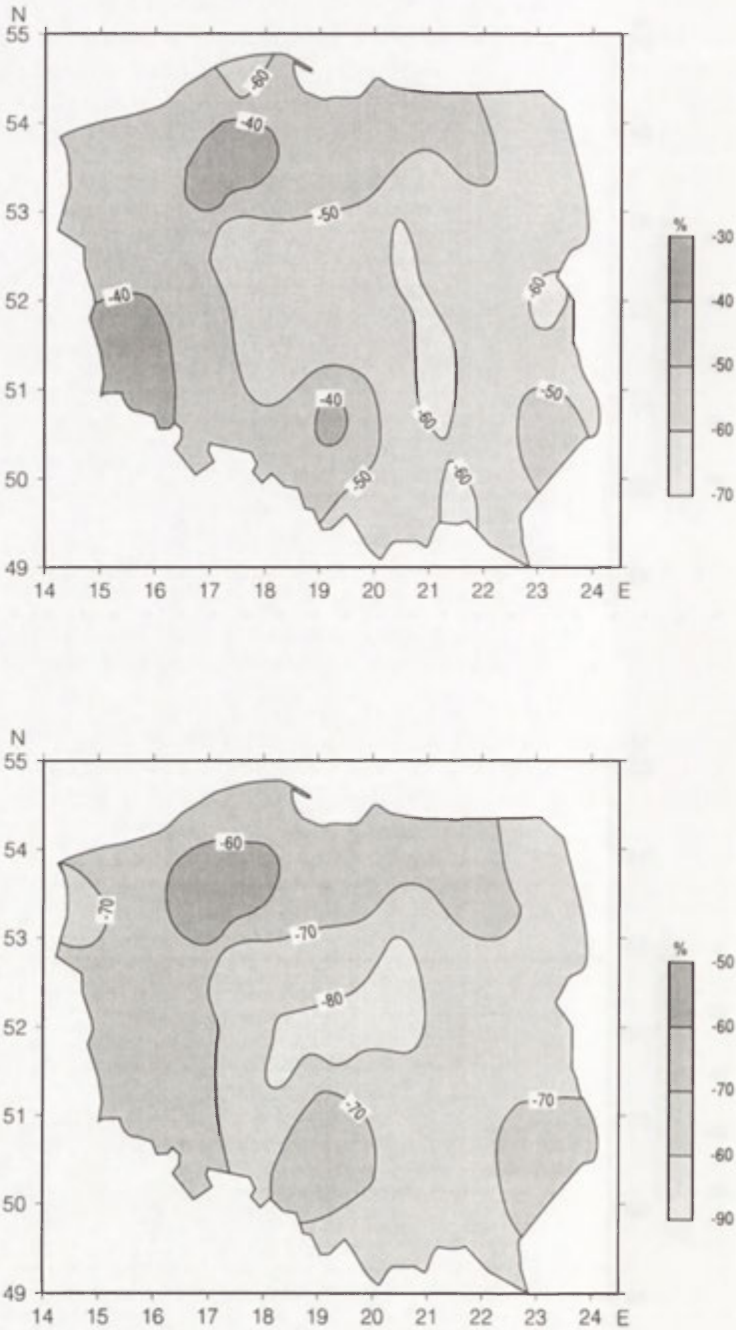

Fig. 5. Maps of relative differences of runoff defined as $(R_A - R_{ct})/R_{ct}$ and $(R_D - R_{ct})/R_{ct}$, expressed in %. R_A, R_D and R_{ct} denote annual mean runoff derived from experiments

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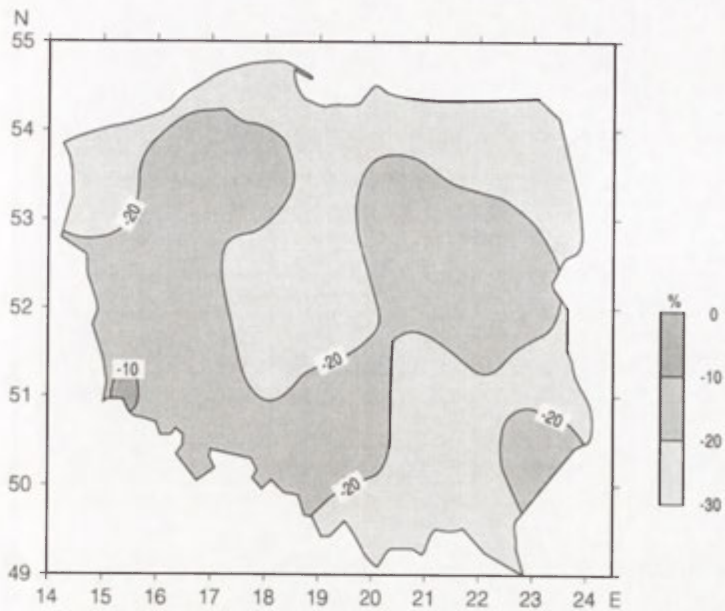

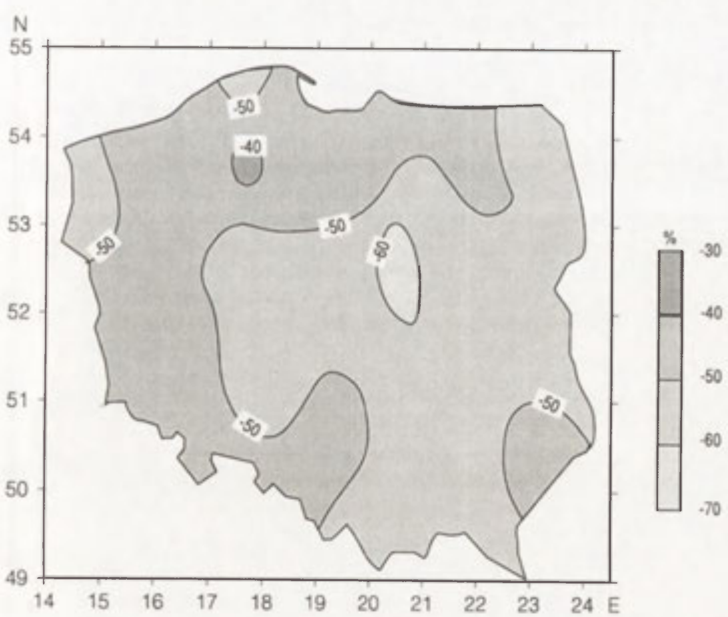

A (left) and D (right) and the control respectively, for the two decades 2035–2044 (top) and 2075–2084 (bottom)

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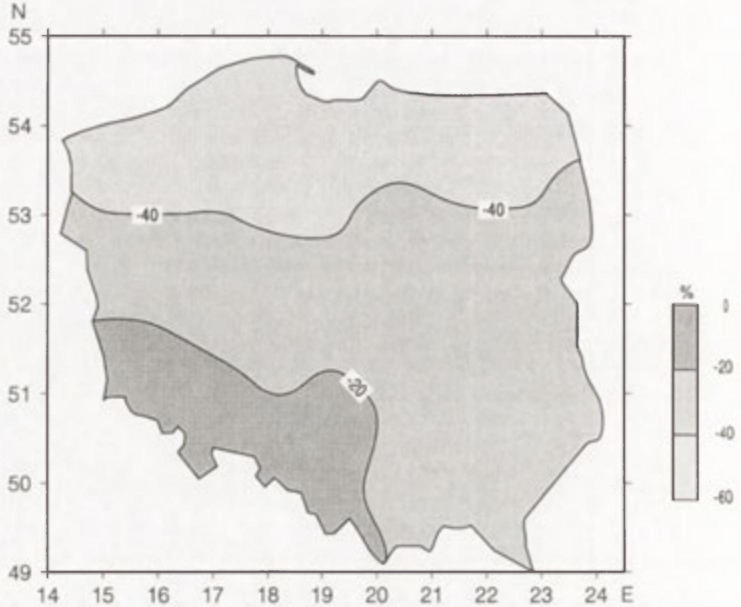

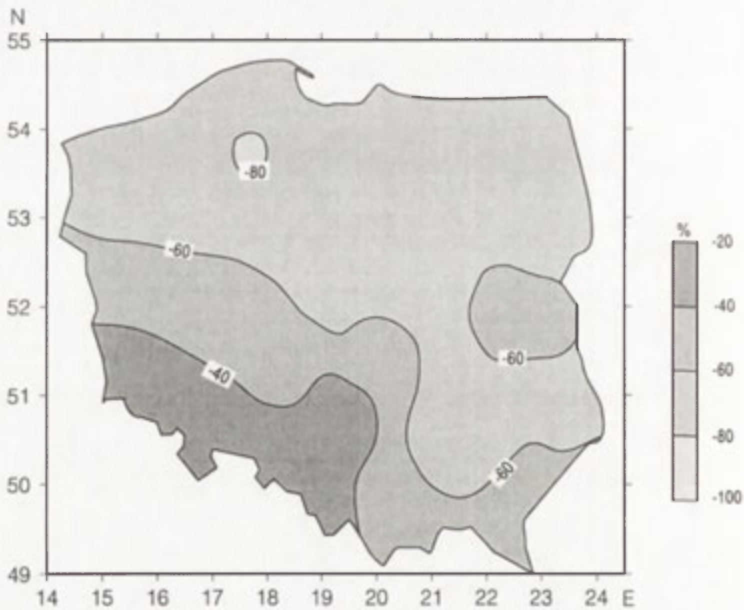

Fig. 6. Maps of relative differences of evapotranspiration defined as $(E_A - E_{ct})/E_{ct}$ and $(E_D - E_{ct})/E_{ct}$, expressed in %. E_A, E_D and E_{ct} denote annual mean evapotranspiration derived

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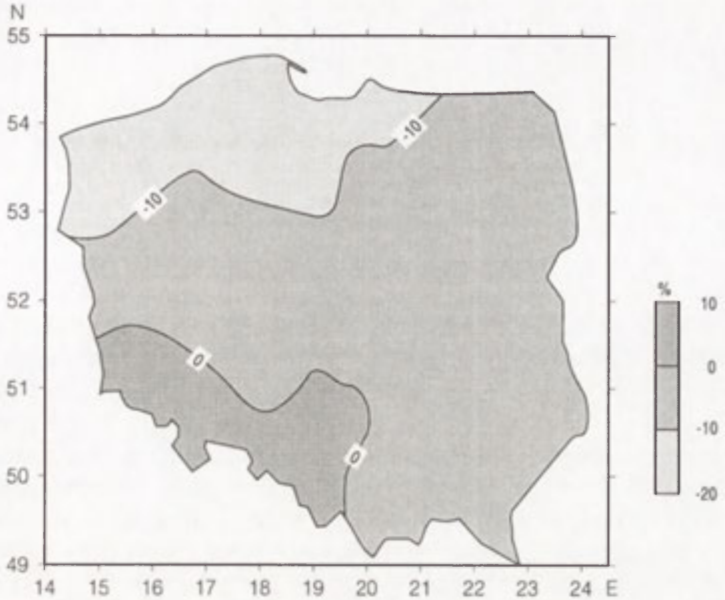
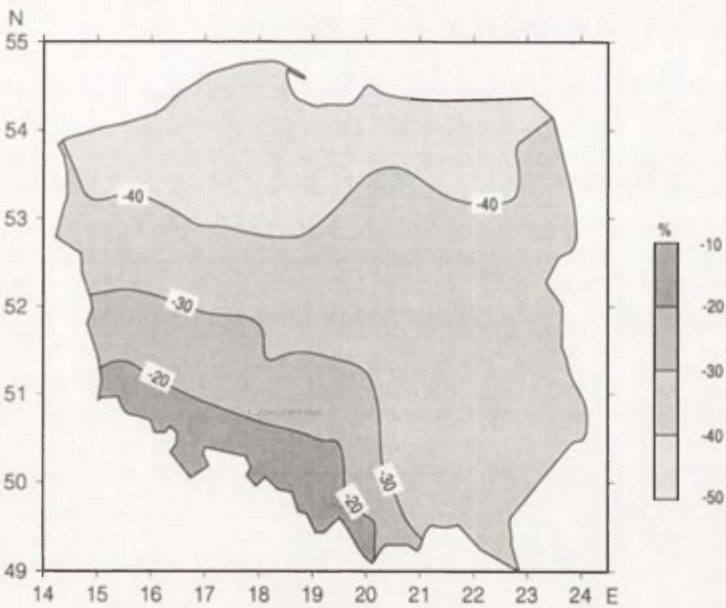
D





from experiments A (left) and D (right) and the control respectively, for the two decades 2035–2044 (top) and 2075–2084 (bottom)

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crucial in our region and this study is our attempt to approach the issue. In order to assess the hydrological response of 45 Polish catchments to climate change simulated by the ECHAM1/LSG model, the CLIRUN 31 water balance model was applied (Kaczmarek 1993a, Kaczmarek 1993b). The water-balance variables runoff and actual evapotranspiration were computed for the three downscaled climate scenarios of the control, A and D, as was described in Liszewska, Osuch (1997).

Fig. 5 presents relative changes in runoff with respect to the control run. A downward trend was found. Maximum changes for both scenarios were obtained in the regions in Central Poland with lowest observed values for runoff (compare to Fig. 2), what can indicate problems connected with greater water deficit there. In general, the patterns for runoff changes are similar but the ranges different, e.g. absolute values for the decade 2075–2084 are 50–90% in case A and 30–70% in case D. The presented spatial distributions attest to the high dependence of runoff changes on precipitation changes.

In the case of evapotranspiration there is again a downward trend (Fig. 6). Projected changes for scenario D are more limited than those for scenario A. While changes in potential evapotranspiration depend strongly on changes in temperature, actual evapotranspiration is also sensitive to precipitation. The greatest decreases in evapotranspiration coincide with regions with the greatest decreases in rainfall.

CONCLUSIONS

Ocean-and-atmosphere general circulation models simulate global climate quite well in terms of large-scale means. On the one hand there is fairly good accord between the results of diverse models on the global scale while on the other, there are great discrepancies between regional assessments based on the same models (Liszewska, Olecka 1996).

We presented here an example of a regional scenario downscaled from the ECHAM1/LSG model. A semi-empirical approach based on EOFA and CCA was employed to derive spatial distributions of surface air temperature and precipitation from the global climate model. The obtained scenario has then entered as input to the CLIRUN 31 hydrological model, in order to assess possible changes in runoff and evapotranspiration in Polish catchments due to the potential climate changes projected by the ECHAM1/LSG model. The overall purpose was to follow the complete path from a general circulation model to the catchment scale. Although the applied strategy appeared effective, the interpretation of our results should be very cautious. First, the analysed climate model can only be regarded as a certain idealisation of the atmosphere-ocean-earth system, and second, the downscaling procedures themselves cause errors. Finally, the impact hydrological model has its own deficiencies. In consequence, our evaluations can only be considered a possible projection of changes in climatic and hydrological parameters, not a forecast.

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More examples in regard to regional climate scenarios and their hydrological application to Poland can be found at our WWW site: Climate Change and Water in Poland *(http://www/igf.edu.pl/water).*

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A STOCHASTIC WEATHER GENERATOR AS A TOOL FOR THE CONSTRUCTION OF CLIMATE CHANGE SCENARIOS

ANNA OLECKA
Climate Protection Centre, Institute of Environmental Protection
ul. Kolektorska 4, 01-692 Warszawa, Poland

KEY WORDS: weather generator, general circulation model (GCM), climate change scenario, climate variability.

ABSTRACT

General Circulation Models (GCMs) are now the tools most widely applied in the generation of scenarios for climatic change on the global scale. However, research on the modification of climatic conditions in a given region requires the drawing-up of appropriate scenarios on the local scale. One of the methods by which to move down from the global to regional scales is application of the LARS-WG weather model, a stochastic weather generator simulating daily values for elements of the climate. Results simulated by the generator should be statistically-similar to observed series, so an attempt to verify the model was made on the basis of data for the Zamość weather station. The results obtained were generally positive, so two types of scenario for climate change were then constructed assuming a doubling in the atmospheric concentration of carbon dioxide. The first scenario was of changes in monthly means, while the second took account of variability in weather from day to day. To estimate potential changes in elements of the climate at the Zamość station, use was made of results from the UKTR GCM characterizing maximum and minimum temperature, precipitation and solar radiation. In accordance with the results obtained, the following changes in climatic conditions at the station studied are anticipated: an increase in precipitation (especially in the summer months), enhanced solar radiation (mainly in spring and autumn) and an elevation of both mean maximum and minimum air tempera-

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tures. The obtainment of such scenarios allows for their further use in research on the influence of potential climatic changes on, for example, the growth and development of crops under conditions of doubled atmospheric CO_2 concentration, as well as for the devising of means by which to adapt agriculture to changed climatic conditions with the aid of vegetation models.

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POLAND'S WATER RESOURCES IN THE FACE OF CLIMATIC CHANGE

ZDZISŁAW KACZMAREK
Institute of Geophysics, Polish Academy of Sciences
ul. Księcia Janusza 64, 01-452 Warszawa, Poland

KEY WORDS: hydrology, climate change, water resources.

ABSTRACT

The issue of the influence of climatic change on water management is a source of controversy, as the opinions presented range from those anticipating catastrophic consequences in many regions of the world through to assessments stating that: "the problem of climatic change has been exaggerated out of all proportion, both in relation to the present level of scientific knowledge and with regard to the potential consequences for the planning of water-management systems" (Klemes 1993). The provision of balanced assessments is the task of science and it is possible to mention at least 5 areas of research, on: the identification of changes in the properties of random hydrological processes; improvement of the parametrization of hydrological processes in climate models; assessment of the vulnerability of the water balance to changes in meteorological characteristics; analysis of the influence of changes and variability in climate on regional resources of, and demand for, water — and hence on water management; and assessment of the influence of climate change on the physical, chemical and biological processes ongoing in aquatic ecosystems.

Changes in Poland's water resources calculated with the aid of the CLIRUN-3 model differ in relation to the given climate scenario in terms of both magnitude and direction. However, the changes in question are within

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the limits of natural variability in flows observed in the 20th century. The results point to a possible limited increase in the mean flows of Polish rivers in the first half of the 21st century, as well as to a limited shift in spring high water from March/April to February/March, brought about by changes in the accumulation and melting of snow. The influence of weather conditions on mean flows in the summer-autumn period is not great, but attention should be paid to increasing variability in flows in the spring and summer months. This may indicate an increased threat of flooding in Poland and the more frequent occurrence of extreme low-water. Drainage basins of low flow coefficients are more vulnerable to climate change than those in which coefficients are high.

The possibility of climatic change, and the accompanying greater uncertainty as regards future resources and demand in Poland, should be taken account of as long-term plans for the development of water management are drawn up. There is thus a need for revision of the practice of planning future management on the basis of "historical" data, without appropriate consideration of the non-stationarity of the natural processes.

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THE HYDROLOGICAL REGIME OF RIVERS IN THE LIGHT OF SCENARIOS OF GLOBAL CLIMATIC CHANGE

MAŁGORZATA GUTRY-KORYCKA

Faculty of Geography and Regional Studies, University of Warsaw
Krakowskie Przedmieście 30, 00-927 Warszawa, Poland

JADWIGA ROTNICKA

Institute of Physical Geography, Adam Mickiewicz University
ul. Fredry 10, 60-701 Poznań, Poland

ABSTRACT: Will the hydrological regime of rivers be transformed as a result of global climatic change, assuming physico-geographical properties of catchments to be permanent? An answer to this question was sought by way of comparison of the behaviour patterns of a river (its discharge structure in the normal yearly cycle) in real conditions defined on the basis of an observation series from the years 1961–1990 (scenario 0), and in the conditions of the assumed climatic change (GFDL and GISS scenarios). The assessment of changes in the regime was made in quantitative and qualitative terms.

The Rega, the Utrata and the Soła, three rivers, whose catchments lie in different physico-geographical regions of Poland were chosen for the analysis, in order to gain an insight into the direction and intensity of changes at a regional scale also.

The results obtained corroborate the impact of global climatic change on the rivers, both at the meso-scale of Poland and the regional scale. The total annual discharge may change significantly, either by going up, according to the GISS scenario, or going down, according to the GFDL scenario. The transformation of the discharge rhythm may manifest itself in a shift in the stages of discharge while seasonality is maintained, and in a change in its magnitude in particular seasons (e.g., the lowering of the level of base flows and their lengthening, mainly in mountain and lowland streams, as well as restricted and greatly reduced meltwater floods).

KEY WORDS: hydrological regime of rivers, effect of global climatic change.

INTRODUCTION

The hydrological regime of a river is its behaviour pattern over the year, and in particular years, in relation to the climate and the catchment's physico-geographical characteristics.

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The methodology of defining the type of hydrological regime of a river entails working out the complexity of the temporal structure of its discharge series over the normal annual cycle, and distinguishing the stages to it, called hydrological seasons. To establish the temporal structure of a river's discharge, it is necessary to have at least a 30-year discharge series with five-day intervals (pentads).

The article seeks to achieve two aims:

— to classify the hydrological regimes of the rivers Rega, Utrata and Sola, representing different climatic and physico-geographical regions of Poland, and

— to assess changes in their regimes following the adopted scenarios of global climatic change.

METHODOLOGY OF RESEARCH INTO THE RIVER'S HYDROLOGICAL REGIME

Defining the type of hydrological regime of a river in the conditions of scenario 0 requires a recognition of its component parts:

— the distinction of the characteristic hydrological seasons of the river resulting from the temporal structure of its discharge in the yearly cycle,

— the identification of the most salient properties of the seasons determining their typology, and

— the typology of the hydrological regime on the basis of the number, kind and temporal sequence of the discharge seasons.

The distinguishing of such seasons follows from the assumption that a specific characteristic or set of characteristics occurs and 'behaves', if not identically, then at least similarly in the time period under study. Simultaneously, this characteristic differentiates the season from the neighbouring time intervals, preceding and following, thus allowing its delimitation. The distinction of hydrological seasons is part of the classification procedure employing the grouping of elementary time units of the (hydrological or calendar) year on the basis of the similarity of one of their features. The elementary time unit adopted in this work is a five-day period of time (a pentad), and the grouping criterion, the river discharge. Thus, the calendar year consists of 73 pentads, each represented by five consecutive diurnal discharge figures. If we study a 30-year period, we get a 150-element set of discharge values for each of the pentads. Hence, the grouping characteristic is variable X, which can be pictured in a number of ways. For instance, in Fig. 5, variable X is given the form of a pentad coefficient of discharge (K). It can also be presented as a mean. When carrying out studies to determine types of river regime, Rotnicka (1977, 1980, 1988) proposed presenting variable X in the form of a probability distribution or a frequency distribution.

The similarity between pentads as defined by variable X can be established with the help of a variety of statistical tests. The one always tested is the null hypothesis H_0 assuming the identity of variable X in two time units

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(pentads). As a result of testing H_0, a quadratic similarity matrix of the yearly set of pentads is constructed, in which the rows and columns are designated by the numbers of the pentads in chronological order. The matrix is pictured as a diagram presenting the relations (links) holding among the pentads of the set from the point of view of the similarity of their feature.

Presented as an example are the results of five tests (Student's t-test, u-mean test, Snedecor's F-test, Kolmogorov-Smirnov's λ-test, and chi-square test) used in the search for the similarity structure in the discharge of the Rega river over the three decades of 1961–1990 (Fig. 1).

An analysis of any diagram of the similarity matrix reveals distinct groups of pentads along its diagonal. It is those groups that form the so-called hydrological seasons.

The diagrams are similar. However, the test chosen for further studies was the non-parametric Kolmogorov-Smirnov test (λ), which is presented by the matrices in Fig. 2. The choice was prompted by the analysis of diagrams in Fig. 1 and the earlier results obtained by Rotnicka (1988) during her research on the regimes of other rivers.

A significant element in determining a river's regime is the number of hydrological seasons resulting from temporal variations in its discharge in the yearly cycle, their characteristics, and the distinctness of the boundaries between them.

The classification proposed by Rotnicka (1988) distinguishes 12 types of hydrological season on the basis of such characteristics as the parameters of the frequency distribution of variable *Z* (the water stage), the coefficient of discharge, and the duration of a hydrological season from the starting to the closing date.

Hierarchical grouping carried out in accordance with Ward's (1963) criterion allowed six types of river hydrological regime to be distinguished:

Type I — a regime of five contrasting seasons, with deep summer-autumn low water and a high spring rise;

Type II — a four-season regime, with average summer- autumn low water and a high early-spring rise;

Type III — a three-season lowland regime, with average summer–autumn low water and a low late-winter or early-spring rise;

Type IV — a three-season mountain and piedmont regime, with shallow summer–autumn–winter low water and a high spring rise;

Type V — a two-season regime, with shallow summer low water and a low winter–spring rise; and

Type VI — a one-season regime.

TYPES OF HYDROLOGICAL REGIME OF THE RIVERS (SCENARIO 0)

The classification of Rotnicka's (1988) is used to present the temporal variability of the discharge of the rivers under study, shown graphically as

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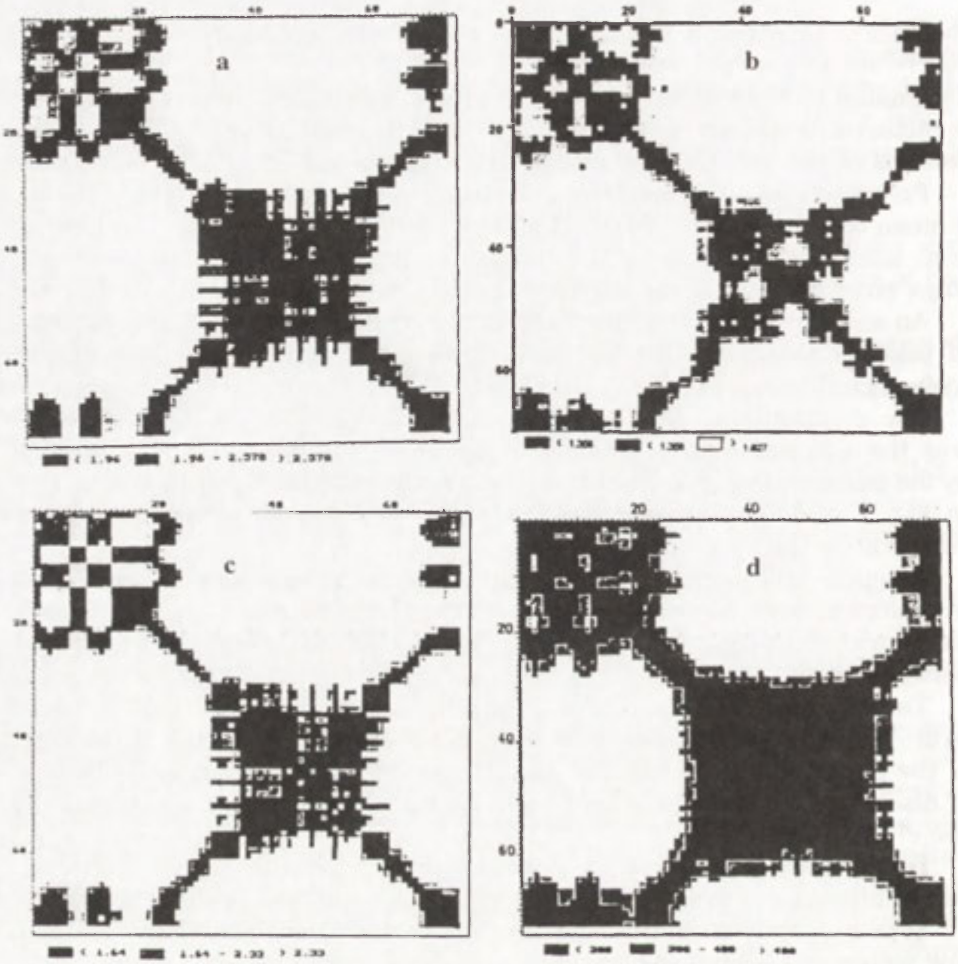

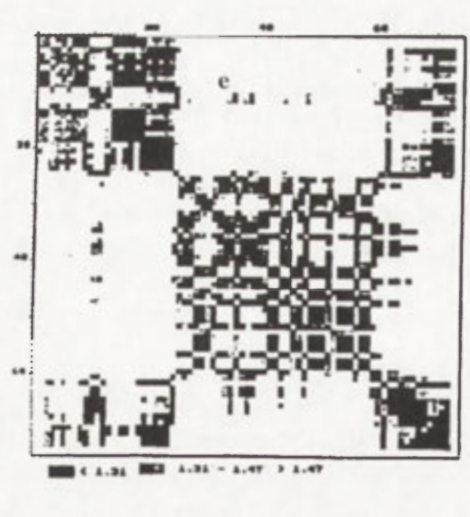

Fig. 1. Similarity matrices of the Rega's discharge in the years 1961–1990 by various statistical tests on level of confidence 5% and 1% (black nad gray colours)
a — Student's t-test, b — u–mean test, c — Snedecor F-test, d — Kolmogorov-Smirnov λ test, e — chi–square test

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similarity matrices of pentad discharge (Fig. 2). These provide not only a theoretical, but also an empirical, basis for distinguishing specific types of hydrological season, given the same value of the λ statistic. When comparing the matrices, we find that both the structure of hydrological seasons and the boundaries between them are more distinct in the Rega and Utrata rivers (Fig. 2a, b). The Sola's discharge is characterised by hydrological seasons with a structure of relations farther from the ideal, as the boundaries between seasons are fuzzy and often feature transition zones.

Two basic seasons to the Rega's discharge structure can be distinguished: one with low, unstable rises starting at the end of November and lasting almost until the end of April, and the other with shallow, moderately-unstable low water embracing a period from June to mid-October. Between them are two transition periods of the normal type (tending to a rise and tending to low water, Fig. 2a).

It follows from the similarity diagram that the Utrata's hydrological regime is characterised by four basic seasons. The high rise of the unstable type starts in the first third of March and continues until mid-April. The long season of deep, unstable low water embraces the summer and early-autumn months. The two remaining seasons were classified as normal (Fig. 2b). An analysis of the discharge similarity matrix shows that the Utrata's hydrological regime is characterised by considerable contrasts.

The structure of the Sola's hydrological regime displays the highest complexity, and its discharge similarity matrix is the hardest to read (Fig. 2c). It is, however, possible to distinguish three basic hydrological seasons in it: a season of a stable snowmelt rise occurring in the spring months, an immediately-following season of unstable rain-induced rises lasting from mid-May to the end of July, and a tripartite low-water season entered with no clear-cut boundary lasting from the beginning of August until the end of February. In its first stage it consists of shallow, unstable summer–autumn low water, in the second, of deep low water, and in the third, of shallow, moderately-unstable low water.

An analysis of the hydrological regimes of the rivers under study allows them to be included among the appropriate types distinguished by Rotnicka (1988).

The Rega — a coastal river with a catchment displaying features of post-glacial relief can be included in the two-season type of regime, with shallow summer low water and a low storm-induced winter-spring rise (type V).

The Utrata river — a typical lowland river draining post-glacial areas, belongs to the regime of five contrasting seasons, with deep summer–autumn low water and a high, well developed spring rise (type I).

The mountain Soła river — typical of the Carpathian flysch, has a discharge regime closest to the three-season mountain and piedmont type, with shallow summer–autumn–winter low water and a high, steep spring rise (type III).

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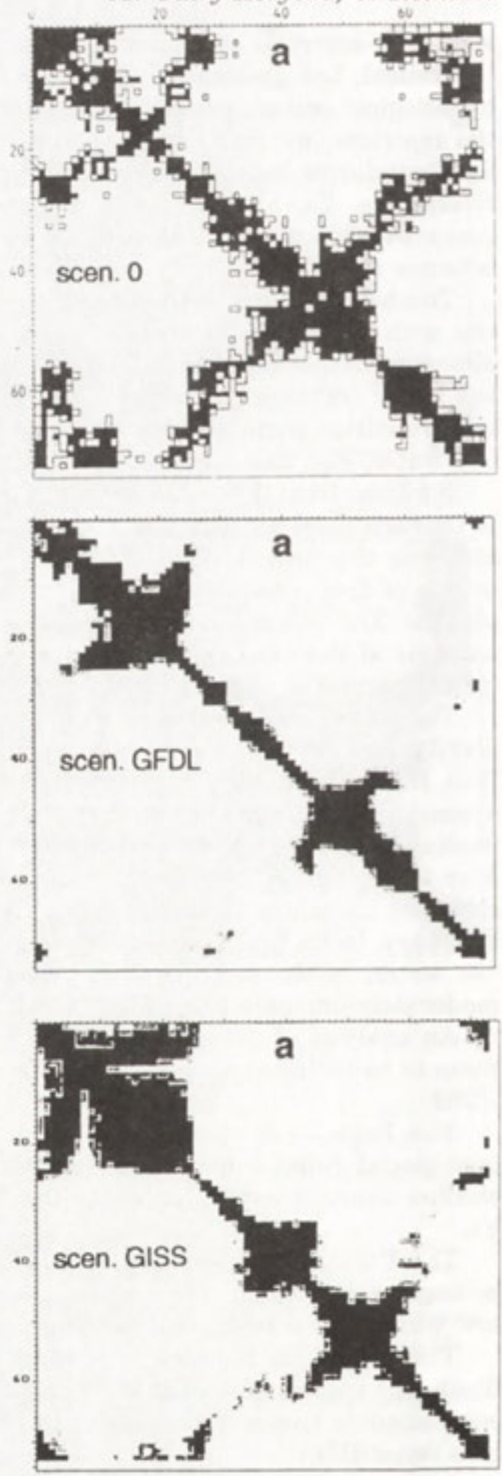
CHANGE IN THE HYDROLOGICAL REGIMES OF RIVERS AS A RESULT OF GLOBAL CLIMATIC CHANGE

Will the hydrological regime of the rivers be disturbed as a result of global climatic change? To answer this difficult question, it is necessary to examine how the type and structure of their discharge may alter in the conditions of the assumed scenarios of climatic change.

At present there are 9 models of global climatic change. Unfortunately, as none of the scenarios can be expressed in terms of probability theory, the long-term forecasts have a high degree of uncertainty.

The results of many authors, both at home and abroad, indicate that the hydrological cycle is very sensitive to climatic change, that is usually simulated with the aid of the GFDL and GISS scenarios (Kutzbach 1981; Kutzbach, Street-Perrot 1985; Bultot et al. 1993; Gellens 1993; Kaczmarek 1996; Gutry-Korycka et al. 1994; Gutry-Korycka 1996).



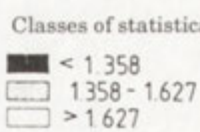


Fig. 2. Similarity matrices of pentad's river discharge according to 0, GFDL and GISS scenarios: a — Rega, b — Utrata, c — Soła

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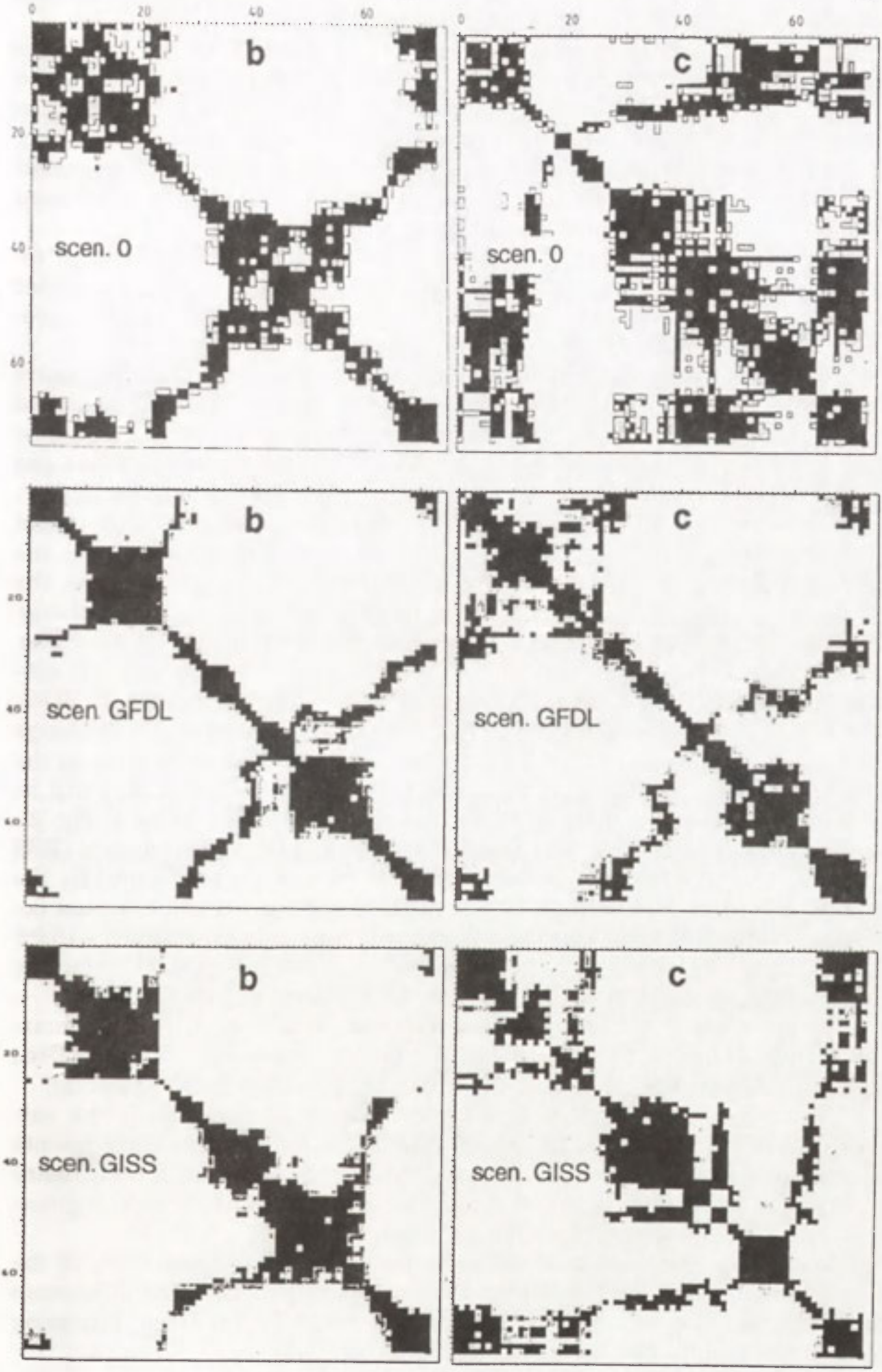

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Studies of the stability of the hydrological regimes of Scandinavian rivers were made by Krasovskaja and Gottschalk (1992); they confirmed that marked changes and fluctuations in monthly discharge would take place, both in dry and wet years, following an increase in air temperature and precipitation. The effects of changes in the meltwater flow, accumulation and snowmelt in the catchments of Scandinavian rivers were investigated by Vehilainen and Lohansuu (1991) and Saelthun et al. (1990).

The question that arises now concerns the stability of the discharge regimes, and whether the regime type will change in the catchments under study as a result of global climatic change, assuming that the physico-geographical properties of the catchments remain the same.

An attempt was made to estimate changes in the quantitative and qualitative characteristics of the rivers' hydrological regimes using the CATMOD conceptual model (Gutry-Korycka et al. 1996), which allows discharge values over the period 1961–1990 to be generated. As an input, altered diurnal air temperatures and rainfall figures according to the GFDL and GISS scenarios were supplied (Table 1).

Assuming the bleak (GFDL) scenario of global climatic change, mean annual discharge figures for each of the rivers will be smaller than the current normal ones: the Utrata's by 14.9%, the Rega's by 3.2%, and the Sola's by only 2.9% (Table 1). In turn, annual deviations of the discharge from the actual figures will be greatest on the Utrata (from +46.8% to –2.4%), smaller on the Sola (from +30.4% to –3.9%), and smallest, though still substantial, on the Rega (from +15.0% to –27.6%) (Gutry-Korycka et al. 1996). There will also be marked changes in the seasonal discharge. The discharge of summer and autumn (from July to January) will be smaller than in the actual conditions on the Utrata and Rega, while on the Sola they will be smaller in spring and summer (from March to September, Table 1, Fig. 3).

Generally-increased discharge were obtained using the more optimistic GISS scenario. The greatest increase in the annual discharge was obtained for the Soła (+23.1%), then the Utrata (+18.9%), and the Rega (+14.6%). Annual deviations of the discharge from the zero scenario ranged from +65.0% to –15.9% on the Rega, and as widely as between +87.1% to –43.6% on the Utrata. The Sola's discharge could increase by 67.4%, or diminish by 1.1% (Table 1).

The differences in the seasonal discharge are usually positive. Their maximum values are: +6.5 mm (Feb.) in the Rega's catchment, +5.5 mm (Dec., Jan.) in the Utrata's river, and +50.7 mm (Feb.) in the Sola's (Table 1).

The analysis of simulated monthly coefficients of discharge in the successive years of the period 1961–1990 (Fig. 4), as well as pentad coefficients of discharge for the same multi-year period (Fig. 5), allow for a preliminary determination of changes in the general characteristics of the river regimes under the influence of global climatic change.

Changes in the discharge differ for each river, but irrespective of the scenario, its yearly rhythm follows their seasonal patterns. The differences are widest for the Sola and the similarity greatest for the Rega, indicating that it has maintained its equalised discharge.

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TABLE 1. Runoff (mm) from the investigated catchments in actual climate conditions (H_0) and in those changed according to the H_{GFDL} and H_{GISS} scenarios in the multi-year period 1961–1990: means and summary runoff, deviations Δ

Months	Rega					Utrata					Soła				
	H_0	H_{GFDL}	Δ	H_{GISS}	Δ	H_0	H_{GFDL}	Δ	H_{GISS}	Δ	H_0	H_{GFDL}	Δ	H_{GISS}	Δ
I	27,0	26,5	–0,5	31,9	+4,9	12,2	13,2	+1,0	17,7	+5,5	34,5	61,3	+26,8	73,5	+39,0
II	25,5	27,5	+2,5	32,0	+6,5	12,3	12,3	0,0	16,8	+4,5	34,5	74,0	+39,5	85,2	+50,7
III	29,9	31,4	+1,5	33,5	+3,6	20,1	15,2	–4,9	19,3	–0,8	73,6	70,2	–3,4	76,6	+3,0
IV	27,2	30,7	+3,5	31,7	+4,5	13,7	13,5	–0,2	18,4	+4,9	86,0	55,6	–30,4	67,7	–18,3
V	21,0	25,4	+4,4	26,8	+5,8	10,6	10,5	–0,1	11,4	+0,8	58,2	58,0	–0,2	55,3	–2,9
VI	16,2	17,7	+1,5	19,8	+3,6	8,0	7,1	–0,9	7,6	–0,4	63,9	40,0	–23,9	59,5	–4,4
VII	16,0	14,1	–1,9	18,9	+2,9	5,5	4,4	–1,1	6,4	+0,9	61,4	32,6	–28,8	61,5	+0,1
VIII	15,1	11,1	–4,0	16,9	+1,8	6,3	3,8	–2,5	6,9	+0,6	50,0	32,0	–18,0	55,7	+5,7
IX	14,9	10,8	–4,1	14,5	–0,4	6,0	4,1	–1,9	5,4	–0,6	37,3	37,2	–0,1	36,4	–0,9
X	16,8	12,9	–3,9	16,6	–0,2	8,5	4,3	–4,2	7,4	–0,9	31,9	36,2	+4,3	37,8	+5,9
XI	20,7	16,7	–4,0	21,8	+1,5	9,5	6,5	–3,0	13,4	+3,6	32,3	42,9	+10,6	57,7	+25,4
XII	26,4	22,3	–4,1	28,7	+2,3	12,1	11,3	–0,8	17,6	+5,5	49,1	55,0	+5,9	78,5	+29,4
H_r	21,4	20,6		24,4		10,4	8,9		12,4		51,1	49,6		62,1	
ΣH_r	255,8	247,6	–8,2	293,1	+37,3	124,8	106,2	–18,6	148,4	+23,6	612,9	595,1	–17,8	754,4	+141,5
Δ			–3,2%		+14,6%			–14,9%		+18,9%		–2,9%		+23,1%	

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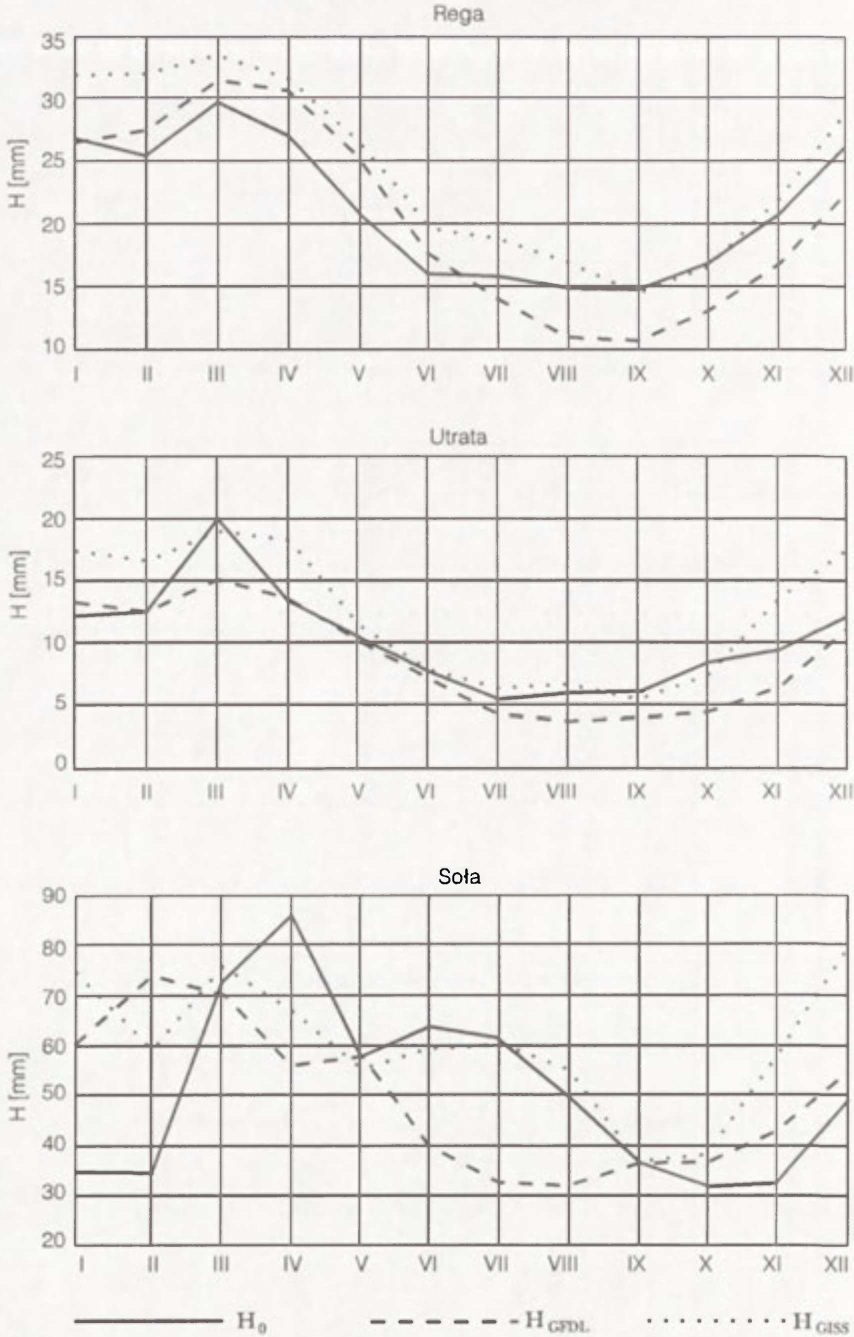

Fig. 3. Mean monthly discharge from the catchments of the Rega, Utrata and Sola rivers in actual conditions (H_0), and those modified according to scenarios GFDL (H_{GFDL}) and GISS (H_{GISS})

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TABLE 2. Changes in the hydrological regimes of the Rega, Utrata and Sola rivers

GFDL scenario	GISS scenario
REGA	
1. Preserving two basic seasons, but: — winter–spring rise delayed about 2 months — low-water season prolonged 1.5 months and passing into deep low water, a stage not observed in actual conditions — shift of normal season tending to a rise from autumn to winter months (because of prolonged low-water season) 2. Change of the type of high- and low-water seasons from unstable to stable 3. Sharper boundaries between seasons	1. Seasonal rhythm of discharge similar to actual (similar dates of transition periods and winter snowmelt rise) 2. Appearance of two distinct low-water seasons, one immediately after another (shallow low water, then deep low water), that jointly last 4 months — somewhat shorter than in reality 3. Sharper boundaries between seasons
UTRATA	
1. Snowmelt rise nearly a month earlier and longer, but lower than in actual conditions 2. Shift of deep low water to late autumn 3. Sharp boundaries between seasons	1. Snowmelt rise nearly two months earlier than in actual conditions, and even earlier than in GFDL scenario 2. Three-stage low-water season as in scenario 0, but with low-water types reversed in comparison with GFDL scenario 3. Sharp boundaries between seasons
SOŁA	
1. Spring–summer rain-induced rise indistinct as a season 2. Two normal seasons appear: one before snowmelt rise, the other before summer low water; they 'replace' low rain-induced rise and shallow winter low-water season respectively 3. Boundaries between seasons sharper than in scenario 0	1. Discharge rhythm similar to actual one 2. Disappearance of distinct rain-induced rise. There is a normal unstable season instead, resembling very shallow low-water season 3. Lengthening and earlier appearance of three-stage snowmelt-rise season with peak in February–March 4. Considerable shortening of low-water season (through disappearance of winter low water) in comparison with actual conditions and GFDL scenario 5. Maintaining three-season type of discharge, but with shift of stages and altered discharge characteristics

The differences in the seasonal patterns for simulated discharge and actual discharge mainly entail a marked flattening of the amplitudes for the Sola (from 3.0K to 2.1K in the GFDL model and to 2.0K in the GISS model) and the Utrata from 2.6K to 2.4K in the GFDL model and to 2.3K in the GISS model), as well as an earlier (by almost two months) occurrence of the snowmelt rise, irrespective of the scenario. The rain-induced rise is also less conspicuous, the base-flow season prolonged, and the low-water stage deeper, mainly in the GFDL model (Fig. 5). No such changes are observed on the Rega. Its seasonal pattern of discharge in each of the scenarios 'imitates' the actual one. In the GFDL model, however, the discharge amplitude

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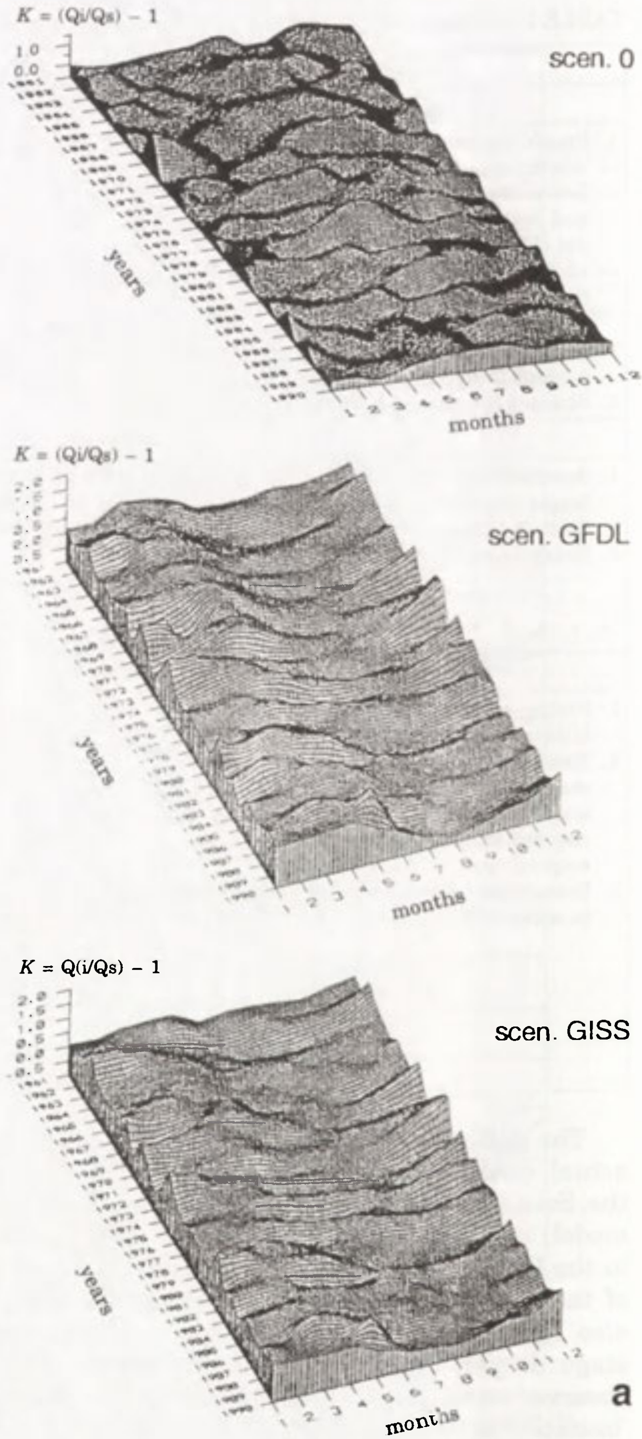

Fig. 4. Patterns of the coefficient of monthly discharge (*K*) in successive years of the period 1961–1990, according to the 0, GFDL and GISS scenarios
a — Rega, b — Utrata, c — Soła

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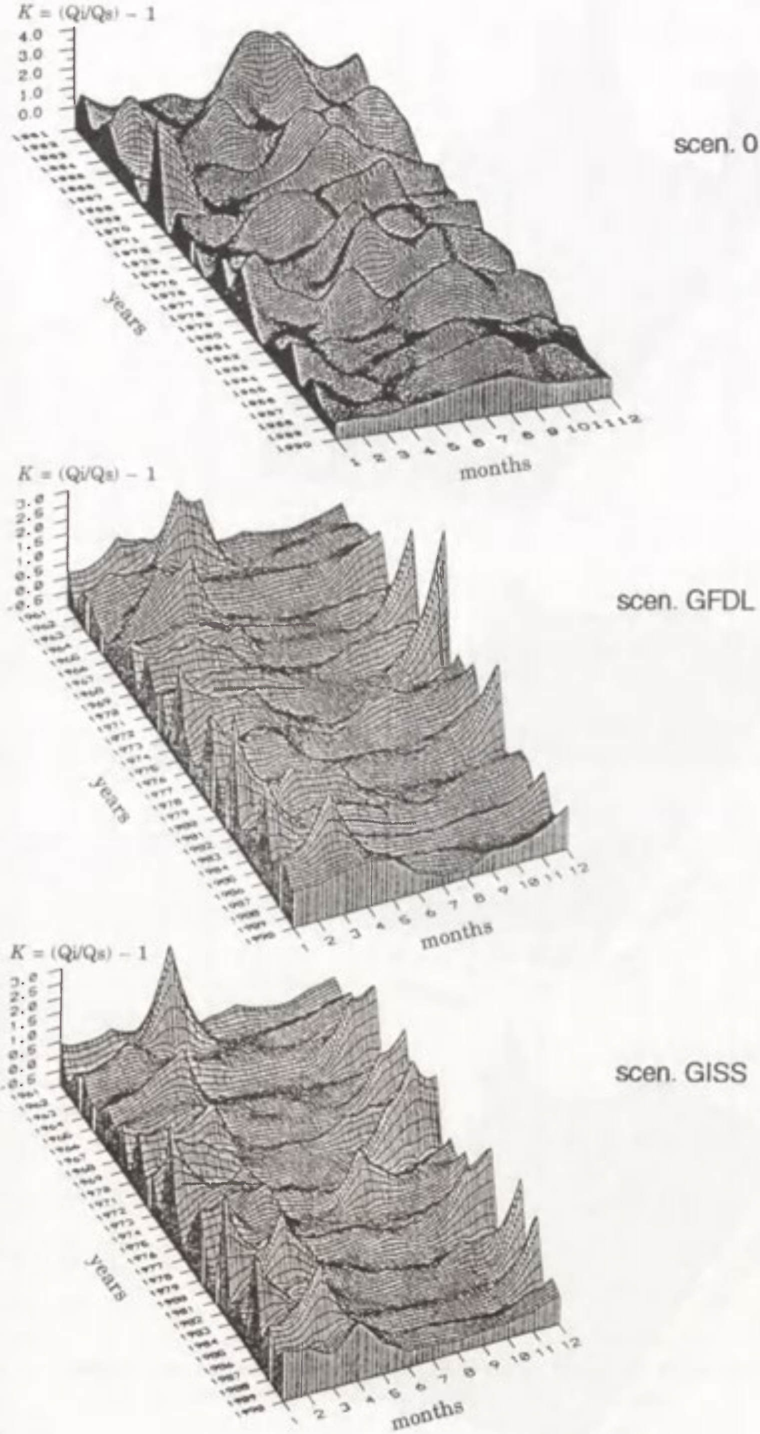

b

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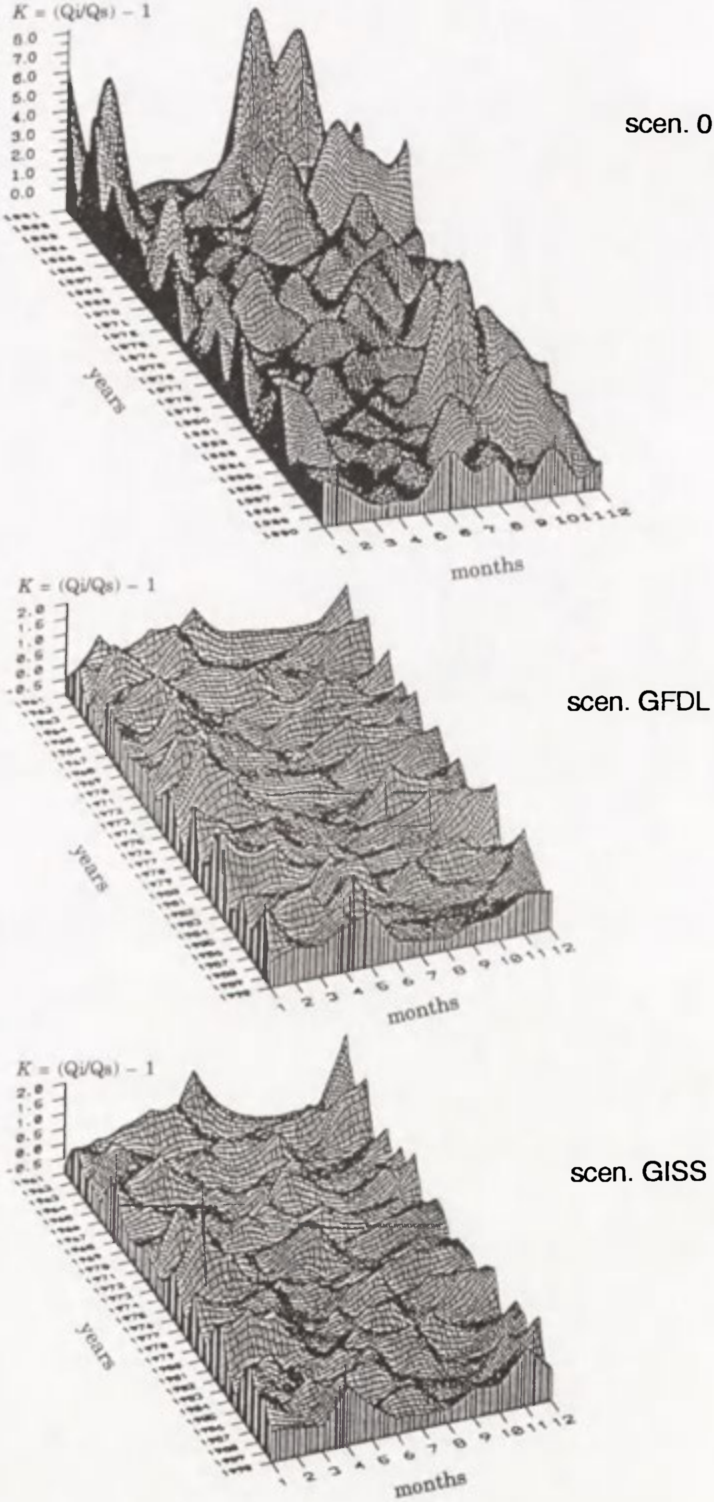

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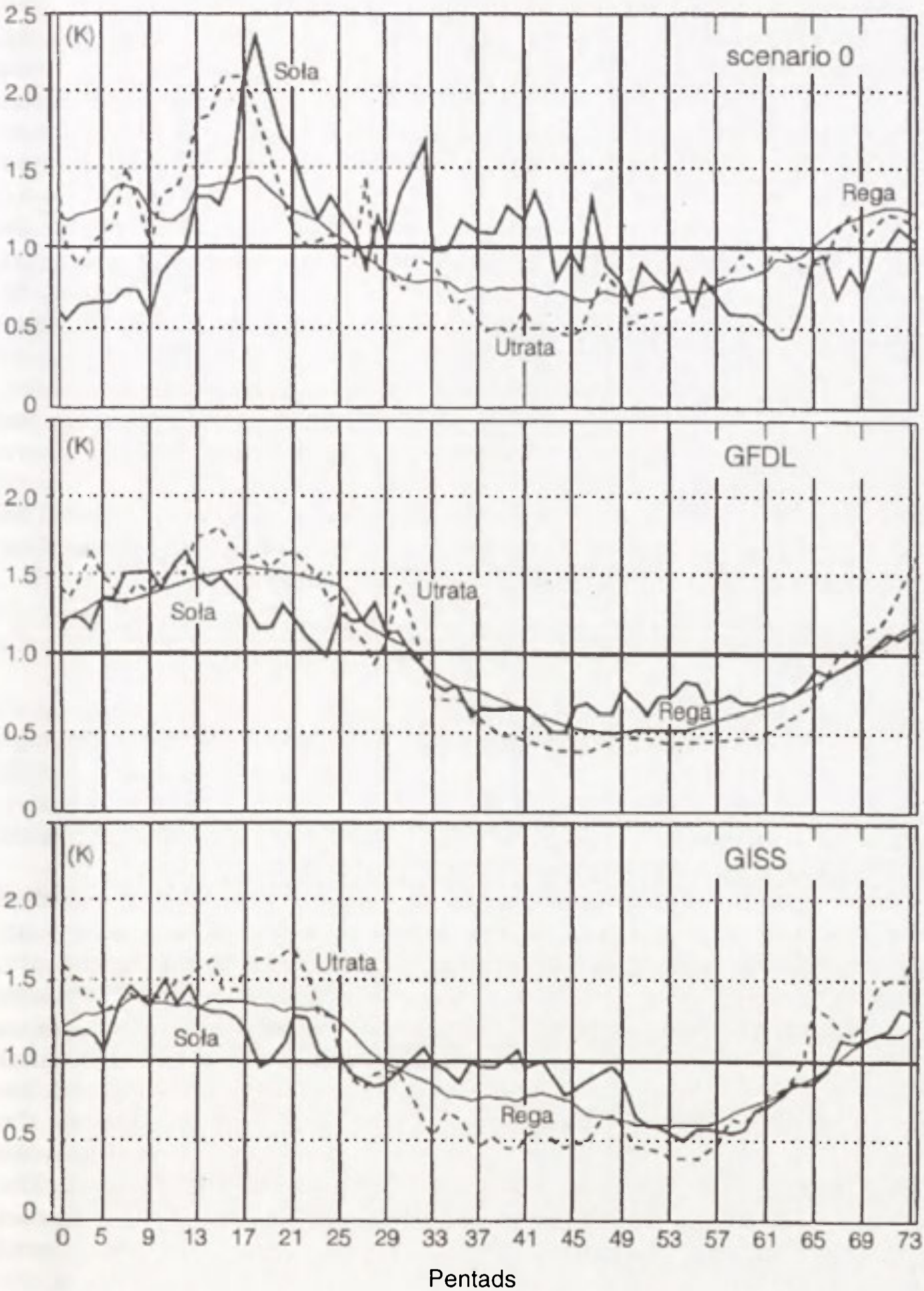

Fig. 5. Iatterns of the coefficient of mean pentad discharge (K) of the Rega, Utrata and Soła rivers, according to the 0, GFDL and GISS scenarios

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is unlike that of the Sola and Utrata: it increases from 1.7*K* to 2.0*K*. The base-flow season, while preserving its length, comes a month later, moving toward winter on the time scale.

The similarity matrices of the simulated river discharges based on the adopted scenarios of global climatic change differ from those of the actual discharge; they also differ from one another (Fig. 2). The observed changes in the river regimes are listed in Table 2.

As Table 2 shows, the temporal patterns of discharge in the conditions of an altered climate (in both the GFDL and GISS models) will undergo a fundamental transformation while the rainwater-snowmelt type of nourishment will be preserved. However, the proportions of these two components will alter.

The transformation will affect, not the number of hydrological seasons, but rather the temporal sequence of the particular types of season (stages of discharge). In the annual distribution of the simulated discharge there will be a clear shift of the stages.

A detailed definition of the discharge characteristics of the rivers will be possible after a multivariate statistical analysis has been carried out. The most pertinent characteristics have been documented.

CONCLUSIONS

On the basis of simulation, the anticipated effect of global climatic change on the hydrological regimes of rivers was determined in quantitative terms. The results, which come from selected regions of Poland and are based on two scenarios of climatic change generated using general circulation models (GCMs), allow the following conclusions to be drawn.

1. Presumably, the warming of the climate will not affect the kind of river nourishment, but its proportions and distribution throughout the year. While at present snow-rain alimentation predominates in the catchments, in the conditions of the anticipated climatic change, a marked dominance of the rain alimentation type over the snow type may be expected.

2. The increase in air temperature and modification of annual rainfall in comparison with the actual figures will bring about similar types of disturbances in the hydrological regimes of the various catchments, but the extent of the changes will differ. The total annual discharge will increase significantly in the GISS model, and diminish in the GFDL model. The increase in discharge will be the sharpest in the catchment of the mountain river (the Sola), less marked in that of the lowland river (the Utrata), and least distinct in that of the coastal one (the Rega). The response of the lowland river to reduced alimentation (the GFDL model) will be the strongest and that of the mountain and coastal rivers, the weakest.

3. The most distinct changes will occur in the pattern of snowmelt rises on the lowland and mountain rivers. Irrespective of the scenario adopted,

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the rises will appear 2 months earlier, will be longer, and will have peaks of decreased magnitude. The reason will be the growing instability of the spatio-temporal distribution of snow cover and its wastage (mainly in the mountain areas).

4. The 'disturbing' effect of climatic warming will also be observed in the base flow of rivers. The considerable intensification of storm rainfall in summer and the longer rainless spells anticipated in the forecasts will be conducive to the development of low-water stages. The duration of low-water stages will vary depending on the geographical type of the catchment and the change scenario. In the GFDL model, they may be prolonged and become much deeper, especially in the lowland and mountain areas; less so in the coastal regions.

5. The coastal river Rega will preserve the greatest regularity of annual discharge, indicating stabilisation of its hydrological regime; the regime will be most chaotic on the mountain Sola river. A characteristic feature of the 'disturbed' regime will be smaller amplitudes of the discharge of the Sola and Utrata, and greater equalisation of it in the particular years of the three decades.

6. In the conditions of global climatic change the time patterns of the discharge in the yearly cycle (the river regimes) will be modified in the following ways:

— The Rega's discharge will maintain its two hydrological seasons: the winter rise and the summer low-water stage. The low-water season will be homogeneous according to the GFDL model, and bipartite according to the GISS scenario. In the first, the rises will be lower and more flattened, while in the second, they will be close to the actual values as far as duration and distinctness are concerned.

— In the GFDL model the Utrata's regime will preserve its 5-season structure, while in the GISS model it will 'lose' one season (a low-water type). Snowmelt rises will be longer and will appear earlier.

— The Sola's discharge will keep its 3-season structure in the GISS model, and assume a four-season one in the GFDL model. There will be a marked shift in time of the types of hydrological seasons. There will be an earlier snowmelt rise that will 'replace' the early-winter normal season. The rain-induced rise will be reduced, or even disappear altogether, substituted by a normal season lasting 3.5 months. The low-water season will be shorter in the GISS model.

The above conclusions justify the statement that climatic change will produce the strongest reaction in the mountain Sola river, and a weaker one in the Utrata, and the coastal Rega will maintain the most stable regime.

The different responses of the rivers to nourishment conditions altered by global warming of the climate reflect the influence of widely different, almost contrasting physico-geographical properties of their catchments. Their choice was not made at random, but was intended to provide an insight into the direction and intensity of change in the hydrological regime at the

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regional scale. The generated discharge regimes confirm that global climatic change will have an effect on rivers, both at the meso-scale of Poland and at the regional scale. The consequences of the change, its direction and rate, may, however, be highly diversified.

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TEMPERATURE AND NUTRIENT DYNAMICS IN EUTROPHIC FRESHWATER ECOSYSTEMS

MACIEJ ZALEWSKI, IWONA WAGNER
Department of Applied Ecology, University of Łódź
ul. Banacha 12/16, 90-237 Łódź, Poland

ABSTRACT: If properly situated in the landscape mosaic, ecotonal land-water vegetation can reduce effect of catchment degradation on freshwaters. The development of ecotones positively depends on temperature, rain and water level. If long dry period appear due to climate changes, vegetation in ecotone zones may decline so during heavy rains the surface flow may cause high external nutrient load to freshwaters. Internal load may also be intensified because of acceleration of organic matter mineralization due to higher microorganisms and phosphataze activity and also higher rate of organisms excretion.

At elevated temperatures primary production will be higher. Consequently, acceleration of phytoplankton succession, and extension of the period of blue-green algac (cyanophyta) blooms is probable. During periods when the temperature is above 18°C winds intensity may regulate blooms appearance. Long periods of epilimnion stability intensify cyanophyta blooming, contrary strong winds may be an inhibitor of blooms appearance. In elevated temperatures toxicity of blue-green algae tends to be higher.

Zooplankton communities regulate phytoplankton density, if not reduced by zooplanktivorous fish. Due to higher energy needs with increasing temperature, pressure of fish on zooplankton will result in zooplankton number reduction. At temperatures above 15° (data for *Daphnia sp.*) zooplankton body size is reduced because smaller specimen posses energetic and behavioral advantages. Lower number of large filtrators may reduce filtering ability of zooplankton and intensify phytoplankton growth.

Freshwaters biota is mostly composed of polikilothermie organisms (zooplankton, fish). The temperature dependent physiological processes have been characterised by right skewed parabolic function. In consequence, water temperature increase may seriously modify (mostly accelerate) rates of energy flow and matter cycling in temperature freshwaters.

Concerning the above processes, especially shallow, eutrophic reservoirs will respond to climate changes by intensification of biological processes. To prevent intensification of eutrophication symptoms it is necessary to consider environmentaly sound management of the catchment and tributaries and control of internal hydrological and biological processes in the reservoir.

KEY WORDS: eutrophic ecosystem, global climate changes impact, nutrient dynamics.

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INTRODUCTION

The metabolic rates of aquatic organisms depend closely on air or water temperature. However, the life cycles of all organisms are precisely adjusted by ecoevolutionary processes to the climatic conditions prevailing is a given region. For this reason, a change in water temperature, and consequently in other abiotic factors (nutrient load, water flow, oxygen concentration, pH, light intensity) may strongly modify the structure and dynamics of aquatic ecosystems.

From among the many scenarios of global climate change, two: the GISS and GFDL scenarios have been considered in these analyses in relation to their effect on freshwater ecosystems. Regional scenarios for the Pilica catchment in Sulejów (central Poland) for $2 \cdot CO_2$ conditions were computed on the basis of the above data (Table 1). The most striking difference between the GISS and GFDL scenarios is the disagreement in predictions of hydrological parameters: GISS predicts an increase in the Pilica flow, while GFDL a decrease. On the other hand, both of the considered scenarios predict an increase in the variability of precipitation, with more frequent extreme events such as flood pulses and droughts.

Changes in temperature and hydrological regime will result in change and acceleration of nutrient and energy flows through ecosystems:

1. the increase in temperature and variability of precipitation may disturb and enlarge external nutrient supply to freshwaters;
2. the increase in temperature will intensify processes of nutrient cycling in ecosystems;
3. the rate of biological processes will be accelerated and may desynchronise evolutionaliry-established biotic interactions.

The consequence of the above processes will be an intensification of freshwater eutrophication, of which the most dangerous symptom, especially in reservoirs which supply drinking water, is the appearance of toxic algal blooms that may be enhanced as a consequence of global warming.

EXTERNAL NUTRIENT SUPPLY

Increase of temperature and variability of precipitation will disturb and intensify surface flow from a catchment area. In consequence, there may be higher external flows of nutrients (P-phosphorus and N-nitrogen) from catchments to freshwater ecosystems.

This process may be modified by catchment morphology and land use. In a flat catchment area, intensive evapotranspiration may reduce surface flow and freshwater nutrient supply. In a catchment of steep slopes, heavy rains may significantly enlarge the external nutrient load into freshwater ecosystems. The most intensive soil erosion and leaching of nutrients will appear in agricultural catchments. These processes may be further intensified

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TABLE 1. Changes in water temperature, precipitation and river flow under 2 · CO_2 conditions due to GFDL and GISS scenarios for the Pilica catchment in Sulejów

Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year	Δ
WATER TEMPERATURE														
1 · CO_2	0,21	0,36	2,43	8,31	15,32	19,29	21,02	20,68	16,21	10,72	3,90	0,50	9,91	0
GISS	2,87	3,59	6,11	11,48	18,12	21,39	23,14	22,51	19,49	13,65	8,29	5,18	13,03	3,12
GFDL	2,85	2,62	7,66	12,29	19,61	23,26	25,79	25,45	21,03	14,85	8,40	3,67	14,00	4,05
PRECIPITATION														
1 · CO_2	0,90	1,41	1,99	1,99	2,27	3,04	3,16	2,75	1,90	1,44	1,66	1,30	724	0
GISS	2,05	2,63	3,24	3,34	3,45	4,15	4,39	3,82	2,67	2,69	2,95	2,37	1148	424
GFDL	1,93	2,47	3,11	3,06	3,54	3,91	3,94	3,69	2,98	2,54	2,67	2,19	1095	372
WATER FLOW														
1 · CO_2	26,1	30,1	36,8	32,5	23,3	22,6	22,9	23,2	19	22	23,9	26,2	25,7	0
GISS	27	31	45	35	31	26	23	20	18	18	27	22	26,9	1,2
GFDL	24	28	33	29	26	22	20	18	17	17	23	20	23,1	–2,6

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by a longer growing period leading to the extension of the period of agricultural activities and the use of fertilisers. Fig. 1 shows differences between the reactions of two rivers, feding the Sulejów reservoir to surface flow resulting from high precipitation. The Luciąza is a small river with both non-point and point sources of pollution. The contribution of point-source pollution is distinct in low-water flow as high $P\text{-}PO_4$ concentrations. The Pilica is a large, moderately-polluted river with a high contribution of diffuse pollution, so nutrient concentration increases with water flow. On the basis of these data, it may be predicted that increased intensity and variability of precipitation in both the GISS and GFDL scenarios will result in intensification surface flow.

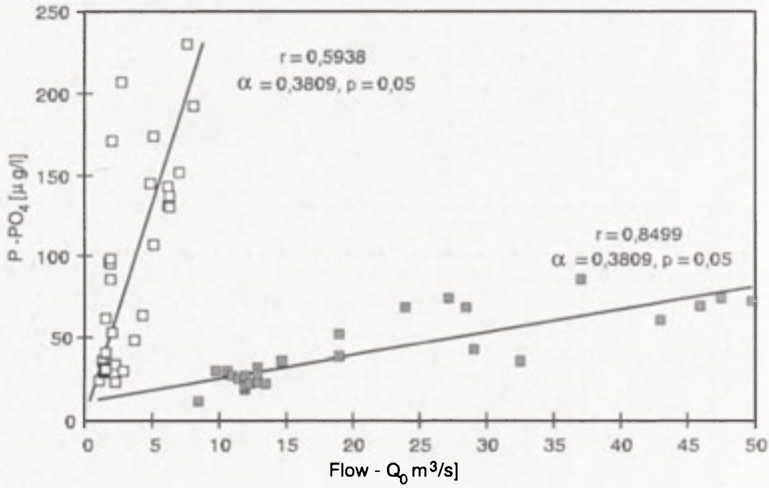

Fig. 1. Correlation between river flow and $P\text{-}PO_4$ concentration in rivers feeding the Sulejów reservoir; Luciąża (upper line) — a small, polluted river with point and non-point pollution sources; Pilica (lower line) — a large, moderately polluted river (Wagner, in preparation)

The barriers that can stop pollution flowing into a ecosystem are properly-managed littoral and riparian — land/water ecotone zones. Where temperature and water availability are high (GISS), ecotones of high complexity are able to stop up to 88% of the pollution from a catchment area (Gilliam et al. 1986; Hillbricht-Ilkowska et. al. 1995) and take up even up to 68-89% of nitrate before it reaches aquatic ecosystems. Nevertheless the change of hydrological regime and appearance of periods of high temperature predicted in the GFDL scenario may result in ecotone desiccation, a decrease in the buffering function and an intensification of external load. An increase in precipitation intensity and variability may lead to processes of nutrient "by-passing" in degraded ecotones. During the frequent appearance of intensive rain on valley slopes, water brooks with high nutrient concentration may be formed. In such a situation nutrient will be not sedimented and trapped by the processes of soil absorption and primary production in ecotones.

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PRIMARY PRODUCTION

Higher nutrient supply and temperature increase will intensify primary productivity in freshwater ecosystems. In natural, unregulated rivers a higher concentration of nutrients may be transferred into stream bottom macrophytes (e.g. *Berula sp.*). Intensive plant development will increase the ability of rivers to self-purify and increase nutrient retention, with the result that productivity is enhaced and biodiversity maintained. In consequence, the transfer of matter and nutrients into reservoirs and lakes situated downstream will be reduced. Canalised rivers with no macrophytes in their beds have no possibility to buffer pollution entering significantly diminishes ability to self-purify (Puchalski et al. 1995). Temperature increase will lead to a progressive decline in water quality due to higher rate of decomposition organic matter. In consequence, the water quality of reservoirs situated downstream, and much more vulnerable to eutrophication than rivers, may decline. In stagnant waters, the main primary producers are in the phytoplankton community. Experiments conducted under natural and laboratory conditions show positive correlation between temperature and the growth rate of phytoplankton (Westhuizen et al. 1985; Sivonen 1990; Rapala et al. 1993; Lethimaki et al. 1994). Interspecific differences in phytoplankton physiology result in dissimilar responses of various species to temperature increase, which will in turn result in different species development and changes in community structure.

Factors other than temperature also modify rates of phytoplankton production (Reynolds 1984; Varis et al. 1994; Kawecka et al. 1994), and some of these will vary with climate warming (Varis et al. 1994; Meyer et al. 1994; Zalewski, Wagner 1995). A number of biotic and abiotic factors regulate succession of freshwater phytoplankton community structure as summer progresses. Development of the alga community (e.g.: *Diatoma, Chlorophyta*) in the first step of succession at the beginning of the summer leads to an increase in pH and CO_2 concentration, and a decrease in P-availability and the N:P ratio. These factors control subsequent development of algae species. Blue-green algae, which are more efficient where light conditions and CO_2 concentration are low and pH high, start to appear. They are also competitive with low nutrient availability because of some species' ability to store phosphorus and fix nitrogen. In paralell, the activity of aquatic zooplankton (e.g. *Cladocera-Daphnia sp.*) eliminates fine phytoplankton competing with blue-green algae and successively allows them to dominate (Holm et al. 1983). Increased temperature and high epilimnion stability during late summer enhance the appearance of blue-green algae. Temperature decline and consequent changes in other abiotic conditions at the end of the summer lead to the outcompeting of blue-green algae and the renewed dominance of other phytoplankton (Harper 1986).

The earlier generation and longer duration of elevated temperatures will accelerate the annual phytoplankton succession in freshwaters. The conse-

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quence may be longer duration and higher intensity of blooms of blue-green algae: *Aphanizomenon flos-aquae,* which dominates summer algal blooms in many temperate freshwater lakes reaches its maximum growth rate at temperatures of 25–30°C (Fig. 2) (Rapala et al. 1993). Observations of the phytoplankton community of the Konin lakes, which are heated by power-plant cooling, confirm that hypothesis, showing a decrease in Diatoma, or increase in *Chlorophyta* species abundance and the appearance of *Cyanophyta* with increased water temperature (Kraska 1968).

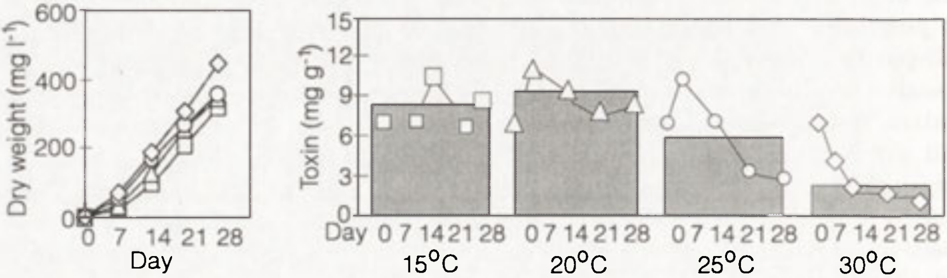

Fig. 2. Effect of temperature on *Aphanizomenon flos-aquae* strains. Growth (left) and anatoxin-a concentration in cells (right). Columns: mean toxin concentration at each temperature, curves: values at different times (Rapala et al. 1993)

Wind intensity is an important additional factor that may modify blooms of blue-green algae by influencing epilimnion stability. At mean temperatures above 18°C, a stable epilimnion will support such blooms. In contrast, strong winds disturbing the water surface cause their sedimentation and may inhibit blooming.

NUTRIENT CYCLING

An increase of temperature may intensify the processes of nutrient cycling and internal nutrient load of freshwater ecosystems. These depend highly on temperature and are connected with processes of animal excretion, enzyme activity, microbial organic matter decomposition, and physical processes of nutrient exchange between bottom sediment and water.

A large amount of P is excreted by organisms, mostly in forms that can easily be assimilated for algal growth (Ejsmond-Karabin 1983). Zooplankton (*Daphnia pulex*) may recycle between 1.5 and 2.5% of total body P per hour (Lheman 1980). Gulati et al. (1995) computed that the amount of P regenerated by zooplankton during different study periods on Lake Vechten covered 22% to 239% of phytoplankton P-demand. An increase in water temperature will result in intensification of P excretion by organisms (Fig. 3).

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Another mechanism of phosphorus recycling is connected with the egzoenzyme-phosphatas that allows some species of algae to obtain P from dead organic matter in the absence of available phosphorus from the environment (Romanowska-Duda et al. 1997). The activity of phosphatase will be elevated, at higher temperatures, which is why reduction of the nutrient supply may have various effects in reducing algal blooms.

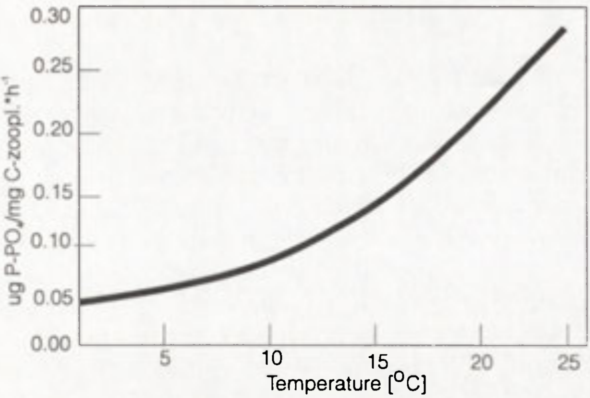

Fig. 3. Regression between measured rates of phosphate excretion of zooplankton assemblage (> 150 μm) and prevailing water temperature in Lake Vechen (Gulati et al. 1995)

Rates of decomposition of dead organic matter increase with temperature at high oxygen concentration (Fig. 4) (Kamp-Nielsen 1989; Wagner 1995), thus climate warming may intensify the decomposition processes in rivers and shallow, well-mixed lakes. In consequence, the amounts of avaliable nutrients in freshwaters may incease. Investigations done on the anthropogenically-heated lakes which may be considered a model for evaluating the effect of climate warming on processes in freshwaters show that mineralization may accelerate faster that primary production processes, with the result that the rate of nutrient release is higher (Pasternak et al. 1978). In deep lakes, or when mixing is stopped (Meyer et al. 1994), an oxygen deficit over bottom sediment may arise and decomposition processes may be inhibited. On the other hand, low oxygen concentration and red-ox changes may result in physical P release from bottom sediments.

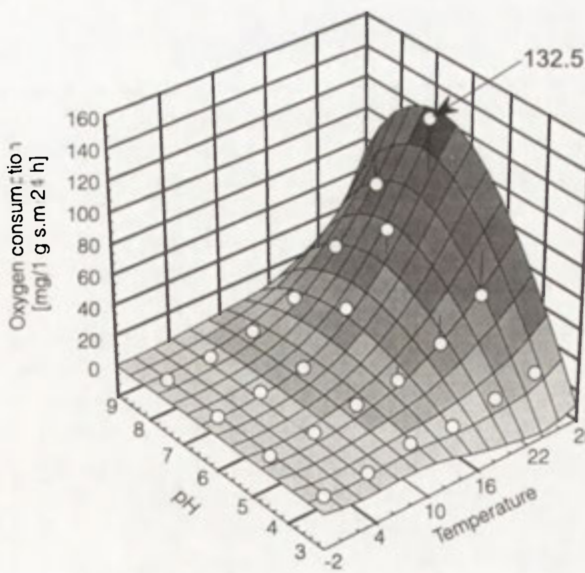

Fig. 4. Relationship between temperature, pH and processes of decomposition of dead organic matter in freshwater ecosystems (Wagner 1995)

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SECONDARY PRODUCTION

The physiological processes of polikilotherms are highly dependent on temperature, and the relationship is described by a right-skewed function. The rates of metabolic reactions and energy requirements increase with temperature. Within certain temperature ranges, rates of organism respiration accelerate faster than rates of assimilation processes, energy demand occurs and body size may decrease (Elliott 1996; Moore et al. 1996).

At low temperatures, the mean body size of a single population of zooplankton (*Copepoda, Cladocera, Rotifera*) is positively correlated with temperature. At higher temperature (for *Daphnia pavula* over 15°C), energy demand reduces the energy available for growth and body size decreases (Orcutt et al. 1983; Moore, Folt 1993, Moore et al. 1996). An increase in water temperature may also lead to change in zooplankton species assemblages, enhancing the role of small species over large ones. A decline in temperature of only 2-3°C may alter community structure (Moore, Folt 1993, 1996 from Patalas et al. 1984).

There are some advantages of reduced body size at high temperature. Smaller zooplankton are less stressed by increasing energy demand because the efficiency of food collecting increases more rapidly than energy requirements. In addition, the threshold food concentration (the food level that should be ingested to balance processes of respiration and assimilation exactly and maintain constant biomass of zooplankton) is higher and increases more rapidly for large zooplankton than for smaller ones with temperature growth. For this reason, small zooplankton are more likely to survive high temperatures at the same level of food availability (Moore, Folt 1993).

Increasing rates of metabolism at elevated temperature make the effects of food limitation more severe at high temperature than at low. Climate warming may restrict the development of zooplankton more severely in less-productive lakes (Moore et al. 1996), unless the availability of food increases as a consequence of climate change.

A decrease in body size may affect the fitness of an individual and lead to the production of fewer, and often smaller, eggs and clutches (Orcutt et al. 1983; Moore, Flot 1993, Moore et al. 1996). On the other hand, fecundity decline is more than compensated by accelerated development rates, and the net effect is a higher rate of zooplankton population growth with increased temperature. All changes in survival strategy and community structure influence the biomass and growth of adjacent trophic levels, and consequently the flows of energy and nutrients through the ecosystem. Small zooplankton recycle more nutrients per unit body than large zooplankton, and can induce a shift from phosphorus-to nitrogen-limitation of phytoplankton growth in low-nutrient lakes (Henry 1995). This situation will support development of blue-green algae, because they possess the competitive adventage of N-fixing over other phytoplankton species (Gulati et al. 1995).

Filtering zooplankton reduce phytoplankton development, and their effi-

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ciency increases at higher temperature. For *Ceriodaphnia reticulata*, the ingestion rate increases over the temperature range of 15–27°C. There is no evidence of selection for or against *A. flos-aquae* in *Daphnia* feeding so it may also be grazed when another edible alga is present in the environment. On the other hand, *A. flos-aquae* usually occurs in colonies or flakes of hundreds of filaments aligned in parallel, that are too big for zooplankton to feed on (Holm 1983). Flakes larger than < 0,2 mm wide and < 1,5 mm long are not use as a food by *D. pulex*. A lowering of zooplankton body size will result with reduce the efficiency of zooplankton filtering and intensify algal blooms. The correlation between zooplankton body size and filtering rate is presented in Fig. 5. A decrease in body length of *D. pulex* of 0.2 mm (about 7% of the mean body size of the analysed population) results in a halving of the filtering rate.

A temperature increase will result in higher metabolic rates and consequently higher energy needs of fish (Elliott 1996). Small zooplankton may avoid predation by visual fish predators and planktivorous fish foraging and growth rates can be affected in consequence, because smaller individuals may be less valuable as food for fish. In conditions of higher temperature and food limitation, the growth rate of fish will be lower (Fig. 6).

The high energy needs of fish will result in higher predation pressure on zooplankton, and may lead to a reduction in the density of zooplankton assemblages. According to the top-down effect, a lower density of zooplankton will result in a larger algal bloom during warm periods.

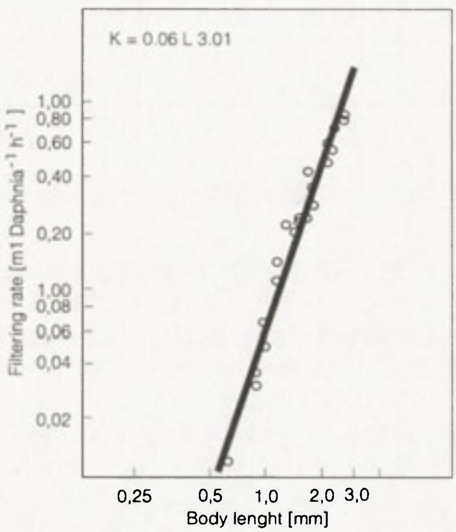

Fig. 5. Relationship between log10 filtering rate and log10 body length of *Daphnia pulex* fed a concentration of 4 000 cells · ml^{-1} of *Aphanizomenon flos-aquae* (Holm et al. 1983)

Warming of the water surface will change the thermal conditions of bodies of water and cause a shifting or even extinction of, the habitat space of sensitive species (Regier et al. 1990). The desynchronisation of the timing and intensity of the abiotic factors that stimulate species development and activity will induce desynchronisation of species spatial and temporal activity. These processes may result in the overlapping or discontinuity of predator and prey habitats and enhance or diminish of trophic interactions in ecosystem (Hillbricht-Ilkowska 1993). In ecosystems of degradated biodiversity and hence low stability and low resistance to stress, a disturbance of ecosystem equilibrium may occur.

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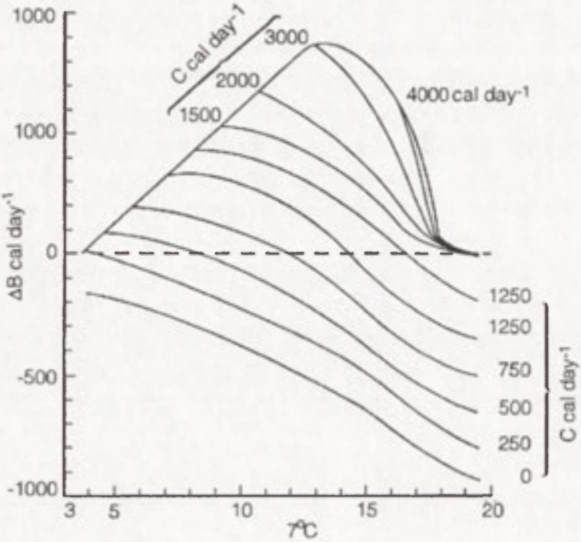

Fig. 6. Relationship between mean change in energy content (DB cal day^{-1}) and water temperature (T°C) at fixed levels of energy intake (C cal day^{-1}) for trout of initial weight close to 50 g (Elliott 1976)

CONCLUSION AND REMARKS

Climate warming may increase eutrophication of freshwaters and will be especially dangerous for shallow non-stratified lakes and reservoirs, where the effect of higher nutrient load and temperature will be especially amplified by biological processes.

The most striking effect will be the intensification and longer duration of blooms of toxic blue-green algae. Both the growth and toxin production of different blue-green algae species are correlated positively with temperature (Fig. 2) and may be higher in $2 \cdot CO_2$ conditions. Toxic algal blooms may seriously restrict the use of eutrophicated reservoirs as a sources of drinking water supply and recreation. They may also be responsible for reduced fish yield or even extinction. The danger of cyanobacterial toxins is illustrated by the reaction of human chromosomes to cyanobacteria extract, with serious damage to the genetic apparatus and toxic and carcinogenic effects on human cells (Osiecka et. al 1996).

There are three main effects of climate change that will intensify freshwater eutrophication and may enhance the appearence of blooms of toxic blue-green algae:

1. Increased temperature and precipitation, especially in the GFDL scenario, will intensify the external supply of freshwater ecosystems in nutrients;

2. Processes of internal loading in ecosystems will be accelerated at higher temperature, due to the intensification of the nutrient cycling rate (excretion and decomposition processes);

3. The specifics and strengths of biotic interactions will be changed due to accelerated rates of biological processes and desynchronisation of evolutionarily-established trophic interactions;

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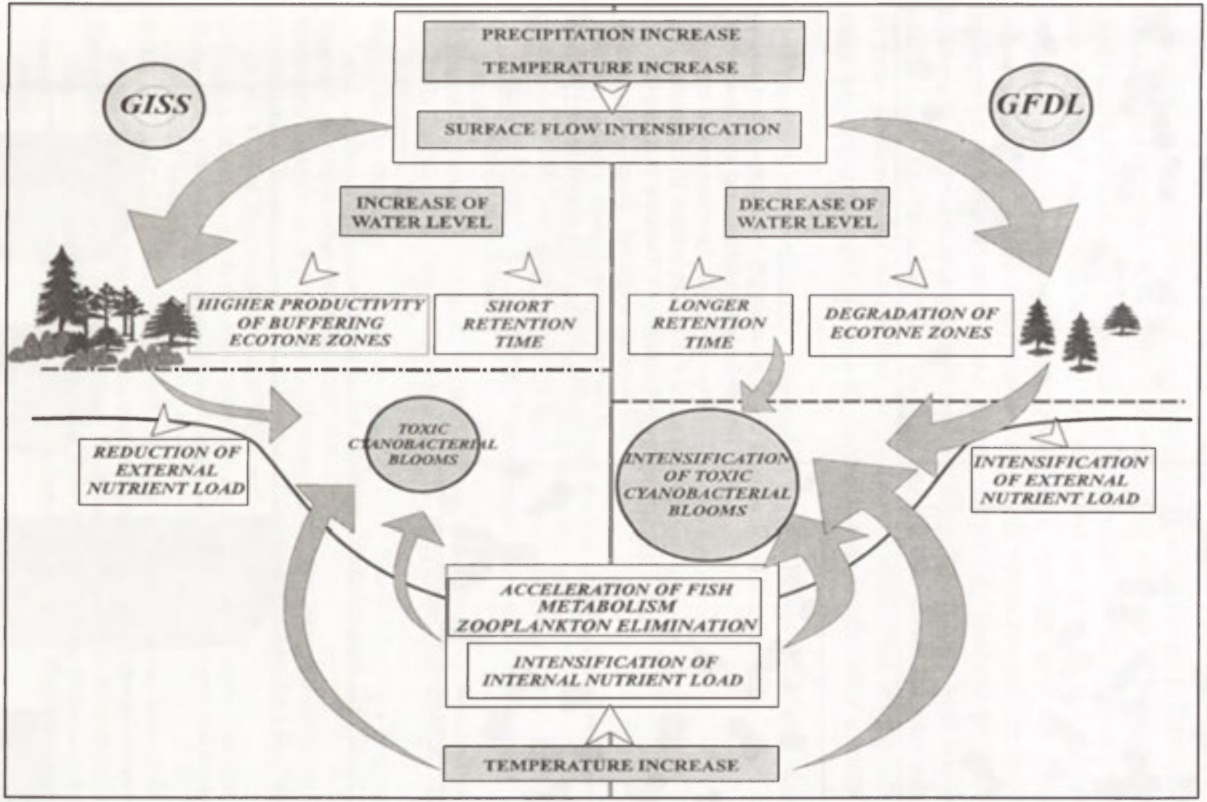

Fig. 7. Alternative scenarios (GISS and GFDL) for effect of climate warming on biological processes in inland waters on the example of lowland reservoir. GFDL: symptoms of eutrophication, including toxic cyanobacterial blooms, will be intensified by: temperature increase (intensification of primary production and internal load), intensification of surface flow due to intensive precipitation and external load resulting from degradation of ecotone zones (water level decrease), increase in retention time; GISS: smaller temperature increase (lesser intensification of primary production and internal load), intensification of surface flow due to intensive precipitation, higher water level (better functioning of ecotone zones), decrease in retention time

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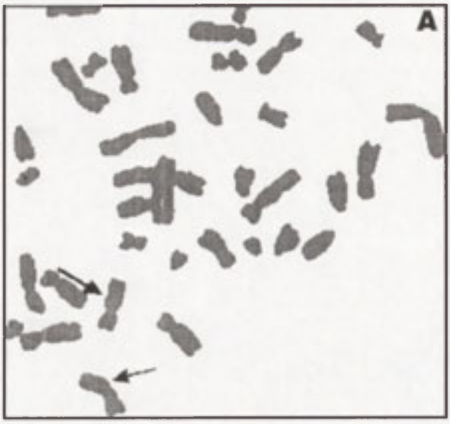
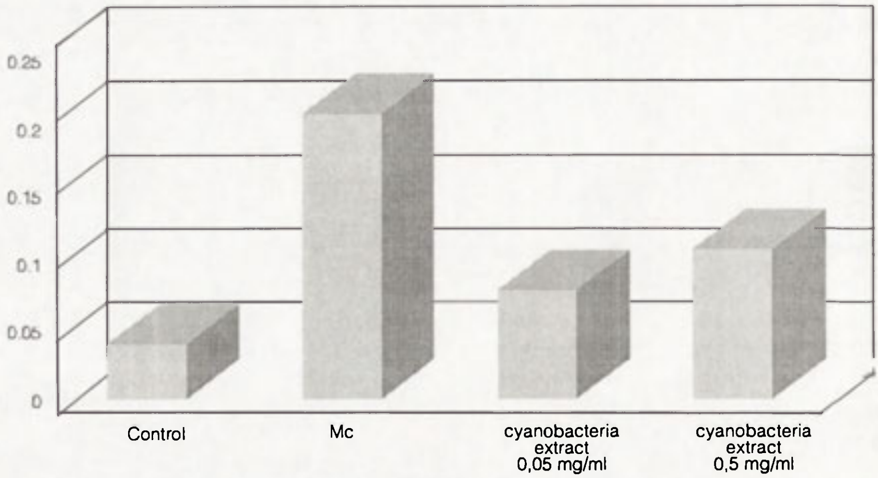


Fig. 8. Photograph — Chromosomal aberration induced by extract from cyanobacterial bloom in human lymphocytes in vitro: A) chromatid breaks, B) chromatid exchanges, C) dicentric chromosome and acentric fragment. Chart — Frequency of aberrations in human lymphocytes induced by extract from cyanobacterial bloom from Sulejów Reservoir (Mc — mechloretamina 10^{-7} M — model mutagen) (Osiecka et al. 1996)



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The symptoms of eutrophication will be enhanced by temperature increase. This is why effective action will be needed in catchments and reservoirs. The development of high complexity in landscape and ecotone zones may reduce nutrient supply from catchment areas to freshwater ecosystems. Management in floodplains and reservoir catchments may reduce nutrient inputs during heavy rains and spring floods. The control of biological processes in reservoirs through the regulation of ecosystem biotic structure may diminish the effect of high temperature if nutrient supply to reservoirs is reduced. Recently-observed progress in freshwater ecology, and its integration with other sciences, has been improving our understanding of the regulatory mechanisms in aquatic systems, and hence our ability to make predictions. Present attempts at integrating landscape ecology, hydrology and the biological sciences (e.g. Zalewski et al. 1996) generate the development and application of new methods by which the impact of a catchment on aquatic ecosystems may be reduced, and biological processes in freshwater controlled.

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IMPACT OF CLIMATE CHANGE ON WATER TEMPERATURE IN RESERVOIRS (SULEJÓW RESERVOIR CASE STUDY)

DANUTA JURAK
Institute of Meteorology and Water Management
ul. Podleśna 61, 01-673 Warszawa, Poland

ABSTRACT: This paper investigates the possible impact of climate change on physical and biological processes in storage reservoirs supplying water for domestic use and industry. As a case study the water temperature and evaporation in Sulejów Reservoir, Central Poland, will be simulated for a number of climate scenarios. An energy balance model for a non-stratified (or weakly-stratified) lake was applied. Reservoir temperature is shown to be highly sensitive to changes in air temperature. Further research is needed to reduce the level of uncertainty in freshwater ecosystem impact assessments, focusing mainly on developing more credible climate scenarios.

KEY WORDS: temperature of water, reservoirs, climate impact.

INTRODUCTION

As most climate-induced impacts on water quality depend on changes in a large number of counterbalancing processes, it is difficult to assess general trends. However, an important feature influencing aquatic ecosystems is, temperature pattern. As in many countries, Poland's water resource systems are increasingly being managed to maintain and improve quality, but expected changes in water temperature and flow regime may create serious problems related to oxygen balance, thermal pollution, nutrient balance and eutrophication, nitrate contamination, toxicity, salinization and acidification (Orlob et al. 1996). Because the rates of chemical reactions and biochemical processes in living organisms are controlled by 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 (Zalewski, Wagner 1995).

The potential impact of climate change on the temperature of rivers and lakes in Poland, was investigated previously by Jurak for the $2 \cdot CO_2$ equilibrium GFDL and GISS scenarios (1992, 1996). Some of the simulation results are shown in Figs 1 and 2 (source: Jurak 1996). For example, the

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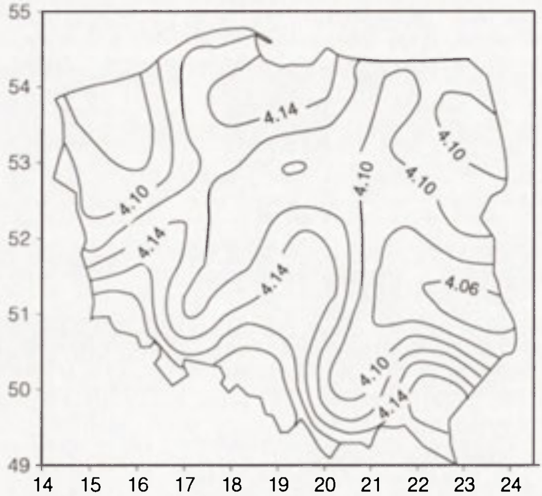

Fig. 1. Water temperature increase (°C) in summer: GFDL scenario

highest possible increase in water temperature in the summer months, predicted for the GFDL scenario, is equal to about 4°C. This creates a possibility of ambient temperature (26°C according to Polish standards) being exceeded. Other physical characteristics, e.g. the frequency of freezing conditions would also decline in a warmer climate in most of Poland's rivers, lakes and reservoirs.

CLIMATE SCENARIOS

GCMs are at present the most sophisticated tools for evaluating the likely effects of increasing concentrations of GHG on global climate. A comprehensive review of GCMs may be found in IPCC reports (IPCC, 1996a,b), and in a number of papers. The main classes of GCMs are: (a) the equilibrium type response to a certain level of change (usually a doubling) in "greenhouse gass" concentrations, and (b) the transient reaction of the climate system to time-dependent changes in the chemical composition of the atmosphere. Global atmospheric models estimate meteorological variables for a network of grid points across the globe.

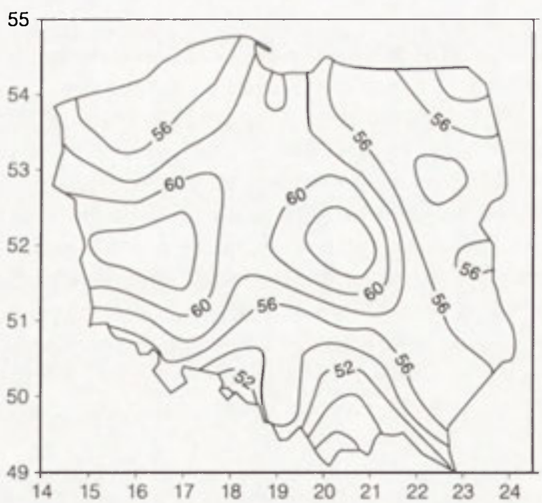

Fig. 2. Evaporation increase (mm) in summer period: GFDL scenario

This study used climate change data collected at the Institute of Geophysics of the Polish Academy of Sciences. The Institute's database contains expected temperature and precipitation changes extracted at the U.S. National Center for Atmospheric Research, on the basis of results from several global atmospheric models. Other climate change data were obtained within the framework of a Project on the *Impact of*

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Climate Change on Water Resources in Europe, supported by the European Union. The five scenarios used in our study to investigate the impact of climate change on water temperature and reservoir evaporation are based on the following GCMs:
The Geophysical Fluid Dynamic Laboratory Model (GFDL-2 · CO_2)
The Goddard Institute for Space Studies Model (GISS-2 · CO_2)
The Canadian Climate Change Model (CCCM-2050),
The Geophysical Fluid Dynamic Laboratory Transient Model (GFTR-2050)
The Hadley Centre Transient Model (HCTR-2050)

Average air-temperature changes predicted by these models for grid cells covering Central Poland are shown in Table 1. The GFDL-2 · CO_2 and GISS-2 · CO_2 scenarios relate to climatic conditions simulated for a doubling in concentrations of "greenhouse gases" (which may have happened, by around the last decades of the next century), while the CCCM, GFTR and HCTR transient scenarios refer to the climate in the year 2050.

It should be pointed out that most published GCM data concern changes in only few meteorological characteristics, mainly air temperature and precipitation. Such information is insufficient for assessing the impact of climate change on the temperature and energy budget of lakes and reservoirs, which depend on several other meteorological elements. It was therefore necessary to introduce additional assumptions concerning the future behaviour of these elements.

TABLE 1. Scenarios of air temperature increase (^oC) in central Poland

Month	GFDL-2 · CO_2	GISS-2 · CO_2	CCCM-2050	GFTR-2050	HCTR-2050
	ΔT	ΔT	ΔT	ΔT	ΔT
XI	4.8	5.0	1.2	1.3	3.6
XII	3.9	5.7	.8	2.3	4.3
I	5.2	5.1	1.1	2.8	3.8
II	5.3	6.7	1.6	.8	4.1
III	6.1	3.4	1.5	2.9	5.6
IV	3.7	3.4	.9	2.8	3.0
V	5.0	3.0	.8	.5	2.6
VI	4.5	2.3	.8	.7	1.7
VII	5.7	2.5	.9	.9	2.2
VIII	5.4	2.0	.8	2.3	2.2
IX	5.8	4.5	1.1	3.6	2.6
X	4.0	2.8	1.0	2.3	2.2

Particularly important — because of its great impact on the energy balance of water bodies — is the controversial question of a possible change in relative humidity in the warmer climate. Most authors express the opinion that the relative humidity will remain unchanged near the surface, which means that, for the changed climate, vapour pressure may be recalculated based on constant R_h and increased air temperature. Such an opinion is

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presented *inter alia* by Manabe, Wetherland (1985), Bultot et al. (1988), and Del Genio (1991). The latter author has shown that the simulated relative humidity in the lower troposphere with the GISS model does not change for $2 \cdot CO_2$ conditions. However, some authors have taken a different position, so further analysis of the sensitivity of hydrological models to changes in relative humidity is therefore required.

In this study, the following assumptions concerning possible changes in meteorological elements under increased concentrations of greenhouse gases were made:

(a) the assessment of the increase in air temperature is based on the above five climate scenarios;

(b) the relative air humidity is assumed to be unchanged, and the vapour pressure calculated using the formula:

$$e_{2\times CO_2} = RH \; e_o \, (T + \Delta T) \tag{1}$$

which after simple transformation may be used in the form:

$$e_{2\times CO_2} = \frac{e_o\,(T_{2\times CO_2}) + 9\, e_o''\,(T_{2\times CO_2})}{e_o\,(T_{1\times CO_2}) + 9\, e_o''\,(T_{1\times CO_2})} \cdot e_{1\times CO_2} \tag{2}$$

where: $e_o(T)$ is the saturated vapour pressure corresponding to temperature T, and the second element in the numerator and denominator of formula (2) is the so called Oldekop factor, introduced to account for non-linearity in the relation between air temperature and $e_o(T)$.

(c) the expected minor changes in shortwave radiation were calculated after Bultot et al. (1988).

(d) changes in wind speed and cloudiness are assumed insignificant, and may be disregarded.

SIMULATION METHODS

To assess the energy budget and water temperature in weakly-stratified lakes and storage reservoirs, a set of models were elaborated at the Institute of Meteorology and Water Management (Jurak 1985). For the current climatic conditions the input data include:

— standard meteorological data measured at the station nearest to the impoundment under consideration;

— lake (or reservoir) characteristics like surface area, average and maximum depth, etc.;

— time series for inflow discharge and temperature.

For an assumed climate-change scenario, the time series for disturbed input characteristics, like changed meteorological data and inflow properties may be estimated, in order to assess the sensitivity of water temperature, evaporation and energy fluxes to climate change.

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The energy-balance equation for any non-stratified water impoundment may be written in the form:

$$\rho_w c_w h = \frac{dT_w}{dt} = \alpha + \beta T_w + \gamma T_w^2 + \rho_w c_w \frac{Q}{A}(T_d - T_w) + G, \tag{3}$$

where: ρ_w — density of water, c_w — specific heat of water, h and A — mean depth and surface area of reservoir, T_w — average water temperature in reservoir, Q and T_d — inflow discharge and temperature of inflow, G — net heat exchange at soil-water interface, α, β, γ — heat exchange coefficients at air-water interface.

The latter coefficients are calculated as functions of meteorological data by means of the formulae (Jurak 1978):

$$\alpha = R_s(1 - alb) + QLRT_a) - 28.83B(\mu(u + u_o)^{0.8} \times$$
$$\times \left[(e_o(T_a) - T_a e_o'(T_a) - 0.61T_p - e) \left(1 - \frac{0.018}{B(\mu)u^2} T_a \right) + 0.5T_a e_o''(T_a) \right] + 2.373T_a \tag{4}$$

$$\beta = -28.83B_\mu(u + u_o)^{0.8} \times$$
$$\times \left[0.61 + \frac{0.018}{B_\mu u^2} \{ e_o(T_a) - e - 2T_a e_o'(T_a) - 0.61(T_a + T_p) \} + e_o(T_a) - T_a e_o''(T_a) \right] - 2.37 \tag{5}$$

$$\gamma = -28.83B(\mu)(u + u_o)^{0.8} \left[\frac{0.018}{B(\mu)u^2} [e_o'(T_a) + 0.61] + 0.5e_o''(T_a) \right] \tag{6}$$

By solving equation (3), the following relations were finally used to calculate water temperature for the time period $<0, t_k>$ (Jurak 1992):

$$\bar{T_w} = -\frac{\beta}{2\gamma} - \frac{\rho_w c_w h}{2\gamma t_k} \left[\ln \frac{[1 - \Phi(t_k)]^2}{\varphi(t_k)} - \ln \frac{[1 - \Phi(0)]^2}{\varphi(0)} \right] \tag{7}$$

where:

$$\Phi(t) = \frac{\beta + 2\gamma T_{wo} - \sqrt{\beta^2 - 4(\alpha + G)\gamma}}{\beta + 2\gamma T_{wo} + \sqrt{\beta^2 - 4(\alpha + G)\gamma}} \cdot \exp\left[\frac{t}{\rho_w c_w h} \sqrt{\beta^2 - 4(\alpha + G)\gamma} \right] \tag{8}$$

T_{wo} denotes water temperature at time $t = 0$. The above model is based on the physical laws of lake heat balance, requires no calibration, and can therefore be used for climate change impact assessment.

The water temperature model (7)–(8) has been applied to assess the impact of climate change on the thermal conditions of lakes and reservoirs. As it is based on physical laws of energy budget, includes few empirical assumptions and requires no identification of parameters, the model may be used for various atmospheric conditions. However, account should be taken of the fact that results obtained for various climate scenarios may differ markedly. This creates well-known difficulties in assessing the impact of climate change on aquatic ecosystems.

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In a case in which the temperature of inflowing water is measured at some distance from the reservoir, T_d may be calculated by means of the formulae:

$$T_d = \frac{-\beta}{2\gamma} + \frac{\sqrt{\beta^2 - 4(\alpha + G)\gamma}}{2\gamma} \times \frac{1 - \varphi_x}{1 + \varphi_x} \tag{9}$$

$$\varphi_x = \frac{\beta + 2\gamma T_o - \sqrt{\beta^2 - 4(\alpha + G)\gamma}}{\beta + 2\gamma T_o + \sqrt{\beta^2 - 4(\alpha + G)\gamma}} \exp\left[\frac{x}{\rho_w c_w q}\sqrt{\beta^2 - 4(\alpha + G)\gamma}\right]. \tag{10}$$

where: T_o is water temperature at a gauging station, modified if necessary for a given scenario, x the distance (in meters) from the station to the reservoir under consideration, and q the inflow rate divided by river width. Finally, based on estimated water temperature, monthly values lake evaporation in [mm] may be calculated using the following formula (Jurak 1992):

$$E = 0.314A^{-0.056}\left[1 + 0.073A^{0.04}(T_w - T)\,u^{-2}\right]u(e_o - e), \tag{11}$$

where e_o is the saturated vapour pressure at the water temperature.

SULEJÓW RESERVOIR CASE STUDY

The case study presented below relates to Sulejów Reservoir on the Pilica river. The average depth is 3.3 m, and the surface area 23,000,000 m^2. Meteorological data — temperature, wind speed, humidity and sunshine duration were measured at Sulejów meteorological station, while hydrological data — river discharge and water temperature-were obtained at the Przedbórz gauging station 40 km from the reservoir. All data were collected for the 15 years from April 1975 to March 1990. T_d values were calculated using equations (9)–(10). Mean monthly values water temperature in Sulejów Reservoir, calculated based on meteorological data for 1975–1990 are given in Table 2. Fig. 3 shows the increase of T_w for respective climate scenarios.

TABLE 2. Water temperature (°C) in Sulejów Reservoir for five climate scenarios

Period	1975–1990	GFDL-2 · CO_2	GISS-2 · CO_2	CCCM-2050	GFTR-2050	HCTR-2050
IV	8.3	12.3	11.5	9.6	11.2	11.6
V	15.4	19.6	18.1	16.4	16.7	17.8
VI	19.4	23.3	20.2	20.1	20.2	20.9
VII	21.1	25.8	23.1	21.9	22.1	22.9
VIII	20.8	25.4	22.5	21.5	22.7	22.6
IX	15.9	21.0	19.5	17.0	19.1	18.2
X	10.8	14.8	13.7	11.9	13.3	13.0
XI	3.9	8.4	8.3	5.4	5.8	7.2
IV-XI	14.4	18.8	17.1	15.5	16.4	16.8

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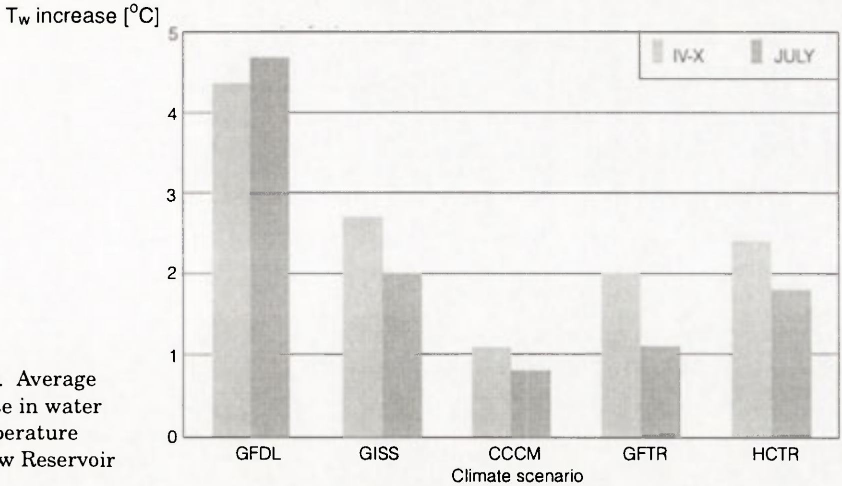

Fig. 3. Average increase in water temperature in Sulejów Reservoir

The greatest increase (4.0°C) was obtained for the GFDL-2 · CO_2 scenario, with the other models giving more moderate results. Large interannual and intraannual variability in weather conditions, in some years and particular climate scenarios, ensure that daily values for water temperature, exceed the ambient value of 26.0°C, which should not be surpassed under current Polish standards in reservoirs serving municipal supply systems.

The results indicate a high degree of concurrence in possible changes in the temperature of air and water, i.e. significant dependence of the latter on the assumed climate scenario. Water temperature can thus be considered a good physical indicator regarding the impact of climate change. Furthermore, it is not only the energy balance of the reservoir surface that will change under disturbed climatic conditions. Inflow characteristics (discharge rate and water temperature) are also sensitive to climate, and may thus play a significant role in shaping quality features of aquatic ecosystems in the warmer climate. The physical effects would be propagated through the biological components, affecting all organisms which rely on phytoplankton and aquatic plants. This in turn may impact on human health considerations.

Water losses due to evaporation from the reservoir surface were calculated for the climate scenarios using formula (11), with account taken of the respective (i.e. changed) values of T_w. The results are presented in Table 3, and changes for E compared to characteristics obtained for current climate conditions (1975–1990) in Fig. 4.

The results for most of the scenarios indicate rather limited sensitivity of reservoir evaporation to climate change. Only in the case of the GFDL-2 · CO_2 model is the increase for the whole summer period about 20 percent of the average summer evaporation for 1975–1990. This means that, in dry years with limited river discharge the losses due to evaporation may reach 10 percent of the inflow rate, and thereby have a potential negative impact on the efficiency of water supply in case of Sulejów Reservoir.

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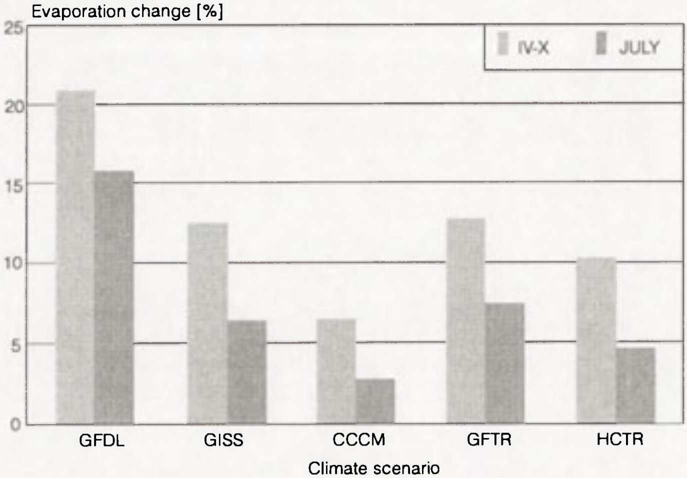

Fig. 4. Average changes in evaporation from Sulejów Reservoir (mm)

TABLE 3. Monthly and seasonal evaporation (mm) from Sulejów Reservoir

Month	1975–1990	GFDL-2 · CO_2	GISS-2 · CO_2	CCCM-2050	GFTR-2050	HCTR-2050
IV	39	53	46	45	48	50
V	70	82	80	76	83	79
VI	92	107	100	95	98	99
VII	107	124	114	110	115	112
VIII	99	118	106	102	108	105
IX	65	79	68	69	73	71
X	41	54	51	46	52	48
XI	17	25	32	21	23	19
IV–XI	530	642	597	565	598	584

A FINAL COMMENT

Differences in of climate scenarios still make it difficult to formulate definite conclusions concerning the possible impact of climate change on the energy budget, water temperature and evaporation losses in storage reservoirs in central Poland. The uncertainty is compaunded by the hierarchical nature of aquatic ecosystems and the inter dependence of physical and biological components of water quality further research is needed to reduce it for freshwater ecosystem impact assessments, by focusing mainly on the development of more credible climate scenarios (IPCC, 1996b). Specific research areas requiring serious improvement also include: the better understanding and modelling of lake processes under non-stationary conditions, the elaboration of methods for defining regional and local scenarios of weather patterns, and the assessment of the impact of possible changes in climate variability on freshwater ecology and the reliability of water supply.

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THE THERMAL BALANCE EQUATION AS A METHOD OF PREDICTING WATER SURFACE TEMPERATURE IN CARP PONDS

KRYSTYNA PIANKO-KLUCZYŃSKA
Institute of Meteorology and Water Management
ul. Podleśna 61, 01-673 Warszawa, Poland

KEY WORDS: thermal balance, carp ponds

ABSTRACT

In the years 1996–1997, the Institute of Meteorology and Water Management in Warsaw cooperated with the Department of Ichthyobiology and Fisheries Management of the Polish Academy of Sciences in Gołysz (49°52'N, 18°48'E, 273 m a.s.l.) in devising a mathematical model for changes in the surface temperature of water. The ponds analyzed had areas of between several and 10–20 ha and a mean depth of c. 1.5 m.

The basis for the drawing-up of the algorithm was a forcing-response model based on the thermal balance at the Earth's surface. The forcing is associated with heat flux, while the response is the reaction of deeper layers of the body of water. The factors considered here are processes ongoing in the boundary layer of the atmosphere and at the surface of a pond, as well as the averaged temperature of the interior of the body of water.

The experiments were done on the basis of measurements made at Golysz in 1994, three times a day (at 06.00, 12.00 and 18.00 GMT). The lack of information on cloud structure and the incomplete picture of the daily course of variability in atmospheric conditions led in some cases to differences between simulated and observed temperatures at the surface of ponds. In most cases, however, the differences in question did not exceed 3°C.

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POSSIBLE SECONDARY MOBILIZATION OF HEAVY METALS FROM BOTTOM SEDIMENTS UNDER CONDITIONS OF ANTICIPATED CLIMATE CHANGE

TERESA RUDZIŃSKA-ZAPAŚNIK

Polish Geological Institute
ul. Rakowiecka 4, 00-975 Warszawa, Poland

ABSTRACT: The forecast climatic warming will cause hydrological changes on Earth which will be accompanied by changes to the chemism and quality of waters. On account of their wide-spread occurrence and permanence, it is heavy metals in the bottom sediments of surface waters which pose the greatest endangering to the natural environment. Once introduced into it, they cannot be removed, and can in suitable conditions (i.a. of reduced pH, changed redox potential, increased salinity, increased content of organic compounds) be released from bottom sediments and give rise to secondary pollution of waters in their soluble forms. It is for that reason that heavy metals have been termed "chemical time bombs".

KEY WORDS: climate change, aquatic sediments, metal mobility in sediments, "chemical time bombs".

INTRODUCTION

As a result of the constant influx of pollutants, mainly of anthropogenic origin, the aquatic environment is enriched in a diversity of chemical substances. Some of these are submitted to the processes of self-purification, of which one of the more important is the sedimentation of suspended matter and the adsorption of pollutants by components of the bottom sediments.

On account of their universality of occurrence and stability, heavy metals like zinc, lead, copper and cadmium are the chemicals in sediments posing the greatest endangering.

FORMS OF OCCURRENCE OF HEAVY METALS IN SEDIMENTS

The most important factors determining the forms of occurrence, and physico-chemical conditions for migration of heavy metals in waters are:

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pH, defining the concentration of all acids and alkalis in waters; and Eh, the measure describing the concentration of all components entering into reversible oxidation and reduction reactions (Fresenius et al., op. cit. Witczak 1995).

In solution, heavy metals occurs as hydrated ions, in forms of compound with organic and inorganic ligands (other ions or molecules) and as organic molecules. Most ions of metals are bound up by molecules in bottom sediments or biological sorption. The forms of organo-mineral compounds of heavy metals depend to different degrees on the surface properties of molecules, the type and strength of bonding and the physico-chemical conditions of the natural environment comprising pH, Eh, salinity and the presence of organic matter (Kyziol 1994). They mainly accumulate in the finest-grained fractions and in the finely-dispersed solid phase of river suspended matter (Helios-Rybicka 1986, 1995; Helios-Rybicka, Kyziol 1991), which is their main carrier (Bojakowska 1995; Kyziol 1994).

The most important role in the binding-up of metals is played by clayey minerals, oxides and hydroxides of iron and manganese, as well as carbonates and organic substances.

TABLE 1. Relative mobilities of elements as a function of Eh i pH (Plant, Raiswell 1983)

Relative mobility	Electron activity		Proton activity	
	Reducing	Oxidizing	Neutral-alkaline	Acid
Very low	Al, Cr, Mo, V, U, Se, S, B, Hg, Cu, Cd, Pb	Al, Cr, Fe, Mn	Al, Cr, Hg, Cu	Si
Low	Si, K, P, Ni, Zn, Co, Fe	Si, K, O, Pb	Si, K, P, Pb, Fe, Zn, Cd	K, Fe (III)
Medium	Mn	Co, Ni, Hg, Cu	Mn	Al, Pb, Cu, Cr, V
High	Ca, Na, Mg, Sr	Ca, Na, Mg, Sr, Mo, V, U, Se	Ca, Na, Mg, Cr, Zn, Cd, Hg	Ca, Na, Mg, Co, (Mn)
Very high	Cl, I, Br	Cl, I, Br, B	Cl, I, Br, S, B, Mo, V, U, Se	Cl, I, Br, B

The chemical form of binding between metals and the sediment (and the associated capacity for further migration in the natural environment, i.e. "speciation") determines the degree of selective extraction (Bojakowska, Sokołowska 1992; Helios-Rybicka 1986; Kyziol 1994). Considerable amounts of heavy metals, especially cadmium and zinc, are present in readily-mobile exchangeable and carbonate forms, as well as in forms of compound with hydroxides of iron and manganese. These pose the greatest endangering to waters. Lead, present mainly in the sulphurous organic fraction, is generally bound tightly by alluvial components and is hence less mobile.

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THE POSSIBILITY OF THE MOBILIZATION OF HEAVY METALS FROM BOTTOM SEDIMENTS

Particular roles in changes of the mobility of metals in the aquatic environment are by the following parameters (Kyziol 1994, Stigliani 1988): a reduction in pH, a change in redox potential (e.g. as a result of insufficient oxygenation of sediment), an increase in salinity and the presence of organic compounds which create water-soluble complexes with the metals.

In the case of the anticipated changes in climate, especially such factors as elevated temperatures and precipitation levels and changes in humidity and flows, these parameters will undergo more or less dramatic changes, depending on the scenario applied. In addition, the process of the remobilization of metals from sediments will be reinforced by an increase in the intensity of geodynamic processes, such as changes in flow and enhanced turbulence (as a consequence of increased erosion in river corridors and along seashores, and the movement of sediments with serious flooding or augmented drainage).

This may all lead to a reversal of the process by which surface waters self-purify, and hence to their secondary pollution.

Changes in the solubility of heavy metals in conditions of changing physico-chemical parameters in the environment are well-documented. Selected examples of such changes are presented in Figs 1 and 2.

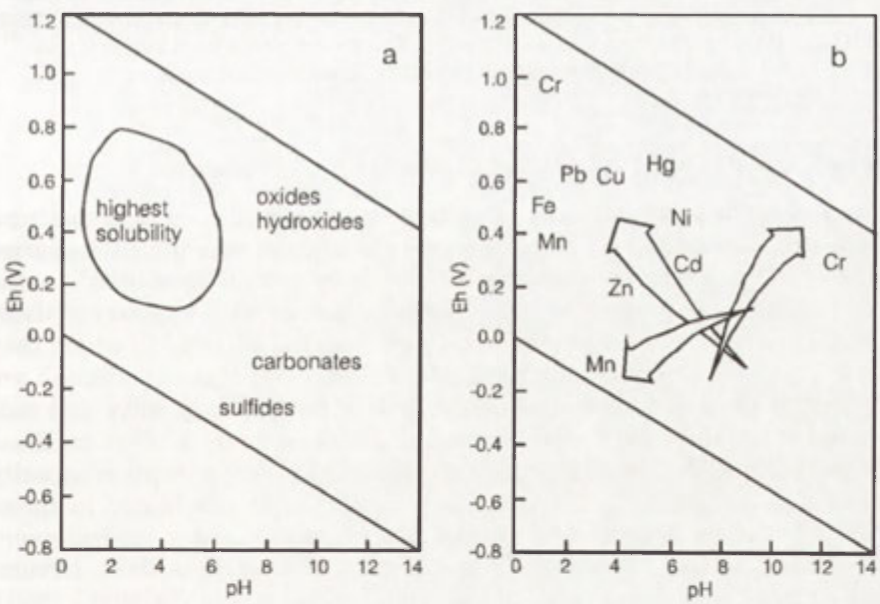

Fig. 1. Trends in solubility of heavy metals in relation to pH and Eh (in the absence of dissolved and solid organic matter; (a) main minerals controlling the solubility of heavy metals; (b) trends of increasing solubility (Forstner 1987)

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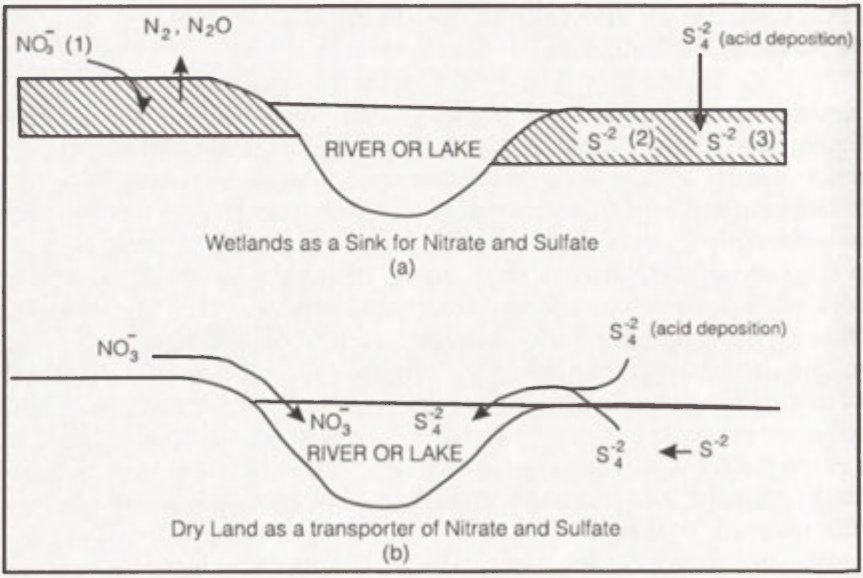

Fig. 2. (a) Ability of wetlands to buffer against nitrate and sulfate inputs to water bodies. Nitrate is reduced to molecular nitrogen (N_2) or nitrous oxide (N_2O), both of which are vented to the atmosphere. Sulfate (SO_4^{-2}) is reduced to sulfide (S^{-2}), which forms an insoluble precipitate in wetland soils. (b) Under construction where wetlands become dry, none of the protective reducing reactions occur. In addition, sulfides that were stored in wetland soils may become oxidized and leach into water bodies. Shaded area indicates region of wetlands (Stigliani 1992) (1) Nitrate from runoff of nitrogenous feritilizer, (2) sulfide minerals from former marine sediments, (3) sulfide reduced from sulfate inputs of acid deposition

CONCLUSIONS

As a result of a longlasting and complex process of pollution in the natural environment, large amounts of compounds of nitrogen, sulphur, phosphorus, heavy metals and toxic substances are (or have been) "deposited" in the bottom sediments of surface waters. However, the sorption capacity of these sediments is dependent on the defined geochemical conditions in which they are found. The most important parameters describing these conditions are the following physico-chemical ones: pH, redox potential, salinity and concentration of organic compounds. Having a direct or indirect effect on these parameters, climatic change may give rise to changes in the sorption capacity of sediments in relation to the chemical compounds acccumulated in them, and hence to the secondary release of the latter into the natural environment.

On account of the character of the process, compounds in these circumstances, it have been termed "chemical time bombs" (CTB) (Stigliani 1991). This alludes to the avalanche of harmful consequences induced in the natural environment as a result of the "sudden mobilization" of the toxic compounds accumulated in sediments.

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UNCERTAINTY IN WATER MANAGEMENT

JANUSZ ŻELAZIŃSKI
Institute of Meteorology and Water Management
ul. Podleśna 61, 01-673 Warszawa, Poland

ABSTRACT: Water management is choice in face of bounded uncertainty (Shackle 1961). Uncertainty may be limited (e.g. by improving scenarios for climate change), but the hope that it might be eliminated is an illusion. However, as a failure to take account of uncertainty leads to social, economic and ecological damage, there is a need for full use to be made of appropriate theories and the measures of uncertainty based on them. The paper thus presents some theories, as well as three principles of uncertainty, namely: of the minimum and maximum of uncertainty and of its immutability. Examples are cited of the undesirable consequences of a failure to heed these principles. Methods of rational decisionmaking in conditions of uncertainty are presented, while methodological considerations are supported by examples of applications in water management.

KEY WORDS: uncertainty, water management, decisionmaking, risk.

INTRODUCTION: "THE ONE SURE THING IS UNCERTAINTY"

This paradoxical statement came from Kołodziejski during discussion of the scenario for the country's socioeconomic development, but it might be applied equally well to scenarios of global climate change, and it well characterizes the main thesis of the present paper, which seeks to raise awareness as to the untransferrable nature of uncertainty, and to review the most important problems appearing in water management in connection with it. We treat uncertainty intuitively, as a shortfall in the information necessary to resolve a problem. Information may be incomplete, imprecise, fragmentary, not completely certain, conflicting or in some other way inadequate. Views on the chances of eliminating uncertainty as science progresses have evolved significantly in the last hundred years. The mechanistic concepts of deterministic conviction from the 18th century have been weakened. Quantum mechanics, which has gained experimental confirmation, points to the chaotic behaviour of elementary particles. The appearance of the theory of deterministic chaos has shaken the convition that the world is predictable on

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the macro scale (Grasseberger 1991). Complex, non-linear dynamic systems are, it is true, deterministic (i.e. may be described by a system of deterministic differential equations), but they are not predictable, which means that precise forecasting of states of the system is not possible. Both models of global climate and of socioeconomic development are complex and non-linear.

The humanities have also come up with views regarding the non-forecastable nature of the world. These were voiced most eloquently by the philosopher Popper (1996) as he sought to justify his non-deterministic convictions. Theses regarding the impossibilty of forecasting cannot be treated as a conviction that total chaos holds sway in the universe. One of the paradigms of science is the need to obtain repeatable results in experiments verifying scientific hypotheses, such that there is a basis for forecasting the results of experiments. It is thus more proper to talk of limited predictability, rather than total unpredictability. It is pragmatic to state that, irrespective of the achievements of science, uncertainty will never be eliminated completely, while decisionmaking on the basis of the best prognoses available now or in the future will also be linked to the risk of error. A thesis regarding limits on predictability is depressing for those in management and politics striving to make rational decisions using expert opinions and forecasts. But decisionmakers need to recall that uncertainty exists and that forecasts may only limit it, not eliminate it. Limitations on uncertainty may improve decisions, but it is not generally possible to make such improvements by treating prognoses deterministically. This statement is justified by the results of the author's research (Żelaziński 1987; Żelaziński et al. 1995).

THE NEED TO DECIDE AS A CONSEQUENCE OF UNCERTAINTY

Water management is among the problems characterized by Klir (1991) when he said that: "problems in the real world are rarely free from uncertainty and consequently, they require to make decisions. In justifying this conviction, Klir cites the British economist Shackle (1961) who stated that: "In a predistinate world, decision would be illusory, in a world of perfect foreknowledge, empty, in a world without natural order, powerless. Our intuitive attitude to life implies non-illusory, non-empty, non-powerless decision... Since decision in this sense excludes both perfect foresight and anarchy in nature, it must be defined as choice in face of bounded uncertainty" . The sense of the above may be illustrated by reference to chess, the classic decision-based game. Either predestination and full predictability, or a lack of rules, would make chess a senseless diversion. In turn, in water management, the level of uncertainty is particularly high and there are many examples of the fatal consequences of excessive faith in the correctness of the assumptions made, the socioeconomic scenarios accepted and the variety of prognoses offered. There are, however, possibilities of limiting the damage associated with un-

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certainty. It is merely necessary to dispense with the illusion that ideal solutions can be obtained, and instead to learn rational behaviour in the face of uncertainty. It is the opportunities for this kind of rationalization that are presented here.

THE MODELLING OF UNCERTAINTY

It was around the middle of the 17th century that the concept of probability expressed as a number from interval [0, 1] or as a percentage was first formulated. Until 1960, uncertainty was only considered in categories of the theory of probability. However, emerging subsequently were several different mathematical theories which were found to be suitable for the characterization of uncertainty. The best known are the theory of fuzzy sets (Zadeh 1965), the Dempster-Shafer theory (1976), the theory of possibility (Zadeh 1978; Dubois, Prade 1988), and the theory of fuzzy measures (Sugeno 1977).

Research taking advantage of the aforementioned theories has revealed the existence of several types of uncertainty which may appear in different decisionmaking processes and which should be described by a proper theory. The more general the theory, the greater the number of types of uncertainty. Klir (1991) provided a review of measures of uncertainty in line with the different theoretical bases of set theory, probability theory, possibility theory, fuzzy set theory and the Dempster-Shafer theory. The example presented below illustrates the need for modelling of uncertainty to have an adequate theory for decision situations at its disposal. In water management, consideration is often given to the several possible variants of an investment programme associated with possible variants of socioeconomic development and scenarios of global climate change. If the decision situation entails the choice of one variant from many possible ones, and the lack of a basis to discern probabilities, then the uncertainty takes the form of non-specificity. The greater the number of variants distinguished the greater their degree of indeterminacy. If only one variant is possible then the situation is fully determined. A measure of this type of uncertainty was introduced by Hartley (1928), in accordance with the function:

$$I(A) = \log_2 |A| \tag{1}$$

where: $|A|$ denotes the cardinality of set A, i.e. the magnitude of the information needed to eliminate the indeterminacy in the set. If there is a basis upon which to distinguish the probabilities of the different variants then we cannot make use of Hartley's measure. A measure of uncertainty taking probability into account (Shannon's entropy) was proposed by Shannon (1948), in accordance with the following formula:

$$H(p(x) \mid X \in) = -\sum_{x \in X} p(x) \log_2 p(x) \tag{2}$$

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where: $(p(x) \mid X \in)$ denotes the probability distribution of X. Like Hartley's function, Shannon's entropy is a measure expressing uncertainty in bits. The example cited illustrates the thesis regarding the necessity for theories and measures of uncertainty to be adequate to the decision problem. Hartley's measure described indeterminacy well but does not allow for any estimation of the uncertainty linked to a situation in which the probabilities of different variants being implemented vary. Well-founded mathematical measures of uncertainty are now available (Klir 1991) and there are three principles of uncertainty based on them: of the minimum and maximum of uncertainty and principle of uncertainty invariance.

The principle of the minimum of uncertainty entails the choice, from all possible solutions of a decision problem, of the solution best minimizing uncertainty. For example, a multi-purpose reservoir may serve particular functions with a limited guarantee; the lower the level of guarantee the greater the uncertainty of the objective being achieved. Conflict arises because, in reducing the level of uncertainty that any given objective will be achieved, we increase uncertainty as to achievement of the remainder. In applying the principle of the minimum of uncertainty to the dividing-up of the usable capacity of a reservoir to serve the attainment of different objectives, it is necessary to choose that strategy which produces the minimum overall uncertainty to the attainment of the objectives set (this may be a weighted sum of uncertainties, to the extent that their socioeconomic or ecological consequences are varied).

The principle of the maximum of uncertainty is of particular significance in each ampliative reasoning. It entails reasoning resulting from the premises held. A given ampliative reasoning must utilize full and available information. The principle requires that ampliative reasoning should maximize uncertainty within the framework of the limitations resulting from the premises held. This principle guarantees that full account is taken of our ignorance as we seek to extend knowledge from premises held, and also that all the information within these premises is fully utilized. Implied here is the retention of maximal reserves where information not contained within the premises is concerned. Ampliative reasoning is essential in this case. If we use a mathematical model in prediction then we apply ampliative reasoning. Thus all prognoses, including those of climate change, are based on ampliative reasoning. In hydrology and water management, we almost always apply ampliative reasoning, while in ignoring uncertainty, we rarely make use of the principle that it should be maximized.

The principle of uncertainty invariance entails consideration of the same decision problem within the framework of different theories, with use being made of the measures of uncertainty resulting from them. Within the framework of each of the theories, the amount of uncertainty (and information) must remain identical. A simple example of compliance with the principle of uncertainty invariance involves the move from Hartley's measure to Shannon's entropy. These two measures assume identical values in a decision

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problem including the same number of variants when the probabilities $p(x)$ in expression (2) are equal to one another and add up to 1.

An example of the results of a failure to heed the principle of the maximum of uncertainty. The main source of reservations in relation to stochastic hydrology is the non-heeding of the principle of the maximum of uncertainty. The example is provided by flood frequency analysis, which was critized and warned against by Klemes (1986a,b). The subject of analysis is a 50-year series of maximal annual flows which can be used to determine, with satisfactory accuracy, the maximal flow with a mean repeatability (in that period!) of the order of 2–5 years. The transfer of this assessment to subsequent years requires an assumption that maximal annual flows are part of a stationary process. This is doubtful, because the climate is undergoing constant change. Many factors linked with anthropopressure (e.g. emissions of greenhouse gases, regulation of rivers, changes in land use including urbanization, etc.) accelerate climate change significantly. If we study the stationariness of empirically-derived series and state that there is no basis for rejecting it, then account must be taken of the facts that: (a) research on the future is ampliative reasoning; (b) the result of a given test procedure is also uncertain, even in relation to the series studied (without any extrapolation in time). In addition, the concept of the return period implies assumed ergodicity of the flow process, i.e. an assumption that averaging over a time is equivalent of averaging over a realisations. This assumption is doubtful, because we know of only one world with one history. An assessment of a flow with a repeatability of the order of several years, on the basis of a several-decade-long observation series, requires ampliative reasoning generating additional uncertainty (in relation to the error of estimation associated with the size of the series). If we wish to determine flows with a return period of 100 or 1000 years, there is an increase in the number of assumptions not resulting from the premises held. There is an essential need for assumptions of the probability distribution type and this is ampliative reasoning, even if we utilize tests of goodness of fit and statistical matching criteria. For it must be recalled that: (a) we tested only a random sample, with the extrapolation in line with a selected distribution being ampliative reasoning; (b) we did not study all the theoretical distributions that are not in conflcit with the empirical one, with the limitation of the scope of research to just several types of distribution again being a case of ampliative reasoning. Beyond this lies what is perhaps the most important reservation, but one which often goes unheeded. It is not possible to rule out a separate origin for peak flows of catastrophic dimensions, as distinct from those occurring most often in the given region. This possibility may be illustrated using the example of the Loire — a river in the Atlantic Basin with headwaters in the Massif Central. Rainstorms in the nearby Mediterranean Basin are much more intensive than those in the Loire Basin, and occur in different meteorological situations. Nonetheless, every 10–20 years, rain of a kind typical for the Mediterranean climate takes in a certain part of the Upper Loire Basin and

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gives rise to the river's highest peak flows, which are of catastrophic proportions. Thus the series of maximal annual flows for the Loire contains events belonging to two geneticaly-different distributions. The possibility of any sensible statistical analysis of the distribution determining the level of the highest peak flows is an illusion: for such events occur rarely and may not appear at all in a short observational series. To sum up, conventional flood frequency analysis is augmented by four assumptions not resulting from the premises held, and this leads to an increase in the uncertainty of the estimate. Failure to heed the additional uncertainty in applications is probably one of the causes of the all-too-familiar revaluation by hydro-technicians of the base flows adopted when the scale of flood protection is originally determined. Without ampliative reasoning there is no real possibility of obtaining either an assessment of maximum flow serving in the setting of dimensions for hydrotechnical objects, or predicted scenarios of climate change. For this reason too, it will be essential for the uncertainty of these scenarios to be assessed in the light of the principle of the maximum of uncertainty, if they are to serve in decisionmaking.

Bootstrap. An assumption as to the type of statistical distribution may be avoided by applying the bootstrap approach, which appeared as a computer-based method by which to estimate the accuracy of statistical estimates. Its important feature is the lack of assumptions as to the type of distribution that the variables analyzed are subject to. A description of the method is given by Efron and Tibshirani (1993). Klemeš (1993) considers that the hydrometeorological phenomena having catastrophic consequences are not generally induced by factors (e.g. precipitation) of exceptional intensity, but rather by exceptionally unfavourable combinations of causes at intensities that are often encountered otherwise. On the basis of this assumption, Klemeš showed how estimates of the probability distribution of maximum precipitation might be obtained. Application of a simulation model for precipitation and flow may lead, in his opinion, to the determination of probability distributions for annual maximum flows — without invoking the need to assume a given distribution for these flows.

THE USE OF CONTROL THEORY AND METHODS OF OPERATIONAL RESEARCH

Work done in Poland in the 1970s concerned the use of these theories in water management. It involved algorithms with which to seek out extremes of functions, which were treated as an instrument aiding decisionmaking. These were concerned with the control of reservoirs using uncertain inflow forecasts. It was found that the standard control algorithms, though very effective in many applications, are unsuited to the problems of water management unless modified and adapted significantly. Spectacular successes were achieved with stochastic control theory in the cases of problems with

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ongoing correction of small random departures from a known optimal trajectory (Gelb 1973). In problems of water management, the optimal trajectory is unknown (it can be defined after completion of the process, i.e. in deterministic conditions — but for operational control this is of little significance). In addition, river outflow is part of a non-stationary, non-Gaussian stochastic process of complex autocorrelational structure, while the quality criterion for control should be non-linear and asymmetrical if it is to provide a sensible description of losses associated with control errors. Attention to these was drawn by Findaisen (1979). Their detailed description in relation to the flood-control of a single reservoir was provided by Żelaziński (1987).

The problem of criteria. Let us consider the example of the control of a reservoir involving efforts to minimize maximum outflows during flood periods. In the deterministic situation (with error-free forecast) the solution is simple, entailing the discharge from the reservoir of a constant outflow whose total volume is less than the inflow by an amount equalling the capacity of the reservoir. However, when we have an uncertain operating forecast for the hydrogram of peak high water, our efforts to implement the aforementioned control may lead to such unacceptable consequences as: (a) the emptying of the reservoir — with no possibility of its being refilled quickly, sometimes even for many months (this occurs when the predicted peak is greater than the actual one); or (b) the complete filling of a reservoir prior to peak water, leaving no possibility of reducing the maximum throughput (this occurs when the scale of the peak high water is underestimated by the forecast); or (c) the augmentation of a flood disaster by a reservoir — an all-too-frequent happening which is usually of interest to the public prosecutor (when the high water forecast is much greater than actually occurs and the dispatcher — acting in good faith — treats the forecast deterministically).

We can thus see that, with an uncertain forecast (i.e. the only kind that can ever really be available), the application of a natural criterion in decisionmaking is not permissible. The application of criterion of minimising of expected value of maximum outflow is not permissible neither. Żelaziński (1987) showed two important reasons which make unacceptable the application of expected value of maximum outflow (i.e. natural criterion in deterministic situation), as a single criterion: (a) because it leads to the same unacceptable results as the deterministic criterion described above, and (b) because it is ambiguous, as there are many different ways of control which lead to the identical minimum expected value, but which at the same time have very different and often very harmful consequences in the case of the concrete resolution of peak high waters. The author further showed, in studies of 19 resolutions of peak high floodwaters, that different control algorithms lead to identical mean values for maximal outflow from a reservoir, while the results differ markedly in relation to other important characteristics of the resolution. Certain algorithms increased maximum throughflows in the majority of the high-water situations, while others led in many cases to the

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emptying of a reservoir with no possibility of it being refilled rapidly. The problem was resolved by introducing the several additional criteria advocated by Kaczmarek (1984), alongside the basic criterion of the minimum expected value for maximum outflow.

From among the criteria discussed by Kaczmarek, I would like to present the so-called "criterion of robustness", which is postulated in such away that the proposed solution (strategy, policy, development, control algorithm) remains suitable even when there is a significant change in operating conditions, i.e. in water resources, demand, social preferences, etc. Undertakings in water management must count on large and unforecastable changes in water resources and in the threats of flood and drought (e.g. under the influence of global climate change), as well as in demand for water (e.g. under the influence of technological, political or demographic changes, etc.). The practice of water management furnishes examples of undertakings that do or do not meet the criterion of robustness. The dam at Dębe on the Narew was planned as part of a power-generating and navigational cascade, but its significance in the former area is marginal, while navigation along the Narew is not engaged in. On the other hand, the Zegrzyński Reservoir it created provides major recreational opportunities for the Warsaw agglomeration, with its proximity to the capital ensuring the worth of the development in spite of the superceding of the objectives for which it was first established. Equally, there are many agricultural reservoirs that are far from urban-industrial agglomerations, or close to basins more attractive to tourists than they themselves are. In the current and predicted situations for Polish agriculture, these reservoirs are effectively useless.

Awareness of the uncertainty of scenarios for climatic change and for socioeconomic development encourages us to heed the Hippocratic principle that entails the withholding of actions that might turn out to be harmful, and regretted, in the future. Sources of regret in water management include not only the money spent on unnecessary development, but also the generally-damaging effects of actions on the natural environment. It is alas possible to make a long list of unnecessary undertakings, engaged in as a result of reliance on wrong forecasts, and having no other result than the degradation of the environment. The so-called vicious circle of flood protection (Bobiński, Żelaziński 1996) is another case of the fatal consequences of ignoring the risky and unjustified conviction that we may eliminate risk through technical undertakings.

To sum up, in conditions of uncertainty, even simple one-criterion problems (rare in water management) become, of necessity, multi-criterion problems. Only by bringing in additional criteria and limitations may we exert a satisfactory level of control over the effects of actions taken. For the result is a random variable of unknown distribution, and efforts to limit the chances of it taking on unacceptable values, or the water-management system entering unacceptable situations, require the carrying-out of multi-criterion analysis. The solution of multi-criterion problems is a compromise, which implies the obtainment of a proper multidimensional criterion and utility function. In

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water management this is a problem of negotiating technique rather than mathematical modelling. Certain proposals regarding this matter have been presented in the works of Haimes and Li (1991) and Zelaziński (1995).

The obstacle of dimensionality. In discussing criteria, we assumed that we are able to optimize in conditions of uncertainty, i.e. denote actions that will lead to the attainment of an extreme for the adopted function of the objective (criterion). However, this is an assumption which cannot in general be met precisely because of the appearance of phenomena termed "obstacles of dimensionality" by Bellman (Bellman and Dreyfus 1967). We can illustrate these by example. If we take a decision with an awareness that harmful situations and results may arise, it is wise for us to anticipate the need for periodic corrections, and the taking of other necessary action. The uncovering of unfavourable effects is served by monitoring systems (including those addressing the issue of climatic change). In the field of automatic control engineering, the described mechanism for the taking and correcting of decisions is known as repetative control. This is usually applied routinely in water management. Unfortunately, the practical implementation of the procedure described creates great difficulties because, in ongoing decisionmaking we must account for the fact that the decisions in question will be corrected in the future. Zelaziński (1987) considered the control of a single reservoir during a flood period, with a one-hour repetition (correction) interval and with uncertainty represented by a set ("bunch") of 30 implementable flood hydrographs. It was found that the calculation of one value for a criterial function corresponding to one control value in the first one-hour interval required the analysis of 30^{48} different possibilities for the development of the situation. This is obviously unrealistic and constitutes one of the main problems with stochastic optimization. Zelaziński (1987), and Malinowski and Zelaziński (1990) propose several different methods by which to overcome the difficulties. In all of these solutions, a series of assumptions are made which are by their nature examples of ampliative reasoning. Simulatory calculations show that the algorithms described lead to similar results, and that progress probably requires improvements in the accuracy of forecasts, rather than refined optimization algorithms, which cannot take the place of hard information. An important advantage of the new algorithms is prediction (in accordance with principle of the maximum of uncertainty) of the possibility of occurrence of unacceptable results of control and states of a reservoir. The algorithms contain a system of "safety devices" excluding or limiting such possibilities, and taking the form of additional criteria (limitations) introduced into the multidimensional criterial function.

CONCLUSIONS

1. Water management is choice in face of bounded uncertainty (Shackle 1961). Uncertainty may be limited through the development of research,

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observation and measurement systems and forecasting models, but hopes regarding its total elimination are illusory;

2. Failure to heed uncertainty (i.e. the deterministic treatment of the best currently-available scenarios of climate change or development, forecast, expert opinions and other estimates) is, like faith in the infallibility of the best-planned, implemented and maintained technical installations, a cause of social, economic and ecological damage in water management, and even threatens lives at times;

3. The appropriate treatment of uncertainty requires the use of theories of uncertainty adequate to the decision situation, as well as measures of uncertainty based upon them. For water management includes many different kinds of uncertainty, of which some may not be described and evaluated properly using classical theories like that of probability;

4. There is a requirement to pay heed to three principles of uncertainty: the principle of the minimum uncertainty, the principle of the maximum of uncertainty and the principle of uncertainty invariance. In water management the principle most often going unheeded is that of the maximum of uncertainty, which states that account should be taken of the maximal uncertainty that so-called ampliative reasoning may give rise to. This entails the utilization of information not following from the premises held. In biology, water management and more generally in science, such inference is often unavoidable and cannot be treated as error. However, what is certainly in error — often with severe and life-threatening consequences — is the failure of the decision-making process to heed the uncertainty inevitably arising from ampliative reasoning;

5. In many cases, the bootstrap approach allows for the avoidance of assumptions as to the type of distribution hydrometeorological variables are subject to. Since assumptions of this kind are examples of ampliative reasoning, the bootstrap is better than conventional methods when it comes to taking the principle of the maximum of uncertainty into account;

6. The theories of control and of operational research may be put to good effect in water management, although this does require far-reaching adaptation and modification of the conventional methods these theories offer.

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DILEMMAS FOR DECISIONMAKERS ASSOCIATED WITH THE IMPLEMENTATION OF THE FRAMEWORK CONVENTION ON CLIMATE CHANGE

EDWARD RADWAŃSKI
Polish Foundation for Energy Efficiency
ul. Brodzińskiego 21, 01-557 Warszawa, Poland

KEY WORDS: greenhouse gas emission (GHG) and sink, GHG reduction options and strategies, GHG impacts on economy and society.

ABSTRACT

On the basis of an agreement reached between the governments of the United States and the Republic of Poland, a Country Study on climate change was drawn up in the years 1994–1996. This was a comprehensive attempt to assess the potential for long-term reducions in Poland's emissions of greenhouse gases, and the effects that climatic changes may have on the Polish economy. The actions proposed following the completion of the Study may have the defined social, economic and financial consequences, on condition that the appropriate decisions are taken by the relevant central authorities. The paper presents the main premises behind the proposals for a strategy to reduce emissions of greenhouse gases, as well as the dilemmas for decisionmakers linked with the implementation of such a strategy.

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THE INFLUENCE OF CLIMATE CHANGES ON DEMAND FOR IRRIGATION WATER IN POLAND

CZESŁAW SOMOROWSKI
Faculty of Land Reclamation and Environmental Engineering, Warsaw Agricultural University
ul. Nowoursynowska 166, 02-766 Warszawa, Poland

ABSTRACT: Possible future growth in Poland's demand for irrigation water is analyzed in relation to possible climate change by comparing demand for 1951–1990, estimated on the basis of hydrometeorological data, with that for 1991–2050 determined on the basis of hydrometeorological variables (precipitation, potential evapotranspiration) forecasted according to the Global Circulation Model with the GFDL (Geophysical Fluid Dynamic Laboratory, Princetown) scenario of doubled CO_2 content by the year 2080. The analysis was performed for the catchment of the Warta (c. 60,000 km^2) and the Wieprz (c. 15,000 km^2) rivers, with areas of future irrigation determined in relation to possible technical and agronomic factors. Use is made of results from the project entitled "Country Study-Poland, SE-12. Strategy for Poland's Water Resources Management in the Face of Climatic Change" (Kaczmarek et al. 1995).

KEY WORDS: Irrigation of agricultural land, water demand, climate change.

INTRODUCTION

In considering water demand for agricultural irrigation the following variables should be taken into account:

— amount of water used by plants during vegetation period,

— soil moisture dependent on hydrometeorological conditions and formed by irrigation, and

— quality of water used in irrigation.

Irrigation of agricultural areas in Poland has a supplementary character. The natural variability of hydrometeorological and soil-moisture conditions causes the seasonal or periodical occurrence of water deficits or water surpluses in the environment (Somorowski 1993). Irrigation should be supplied in order to meet the water demand of particular agricultural areas taking into account the intensification of cultivation and organizational conditions on farms.

The estimation of the demands for water of agricultural areas requires calculations based on:

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— future unit demand for irrigation water,

— future areas of irrigation.

As weather conditions during the vegetation period are of great variability, unit irrigation water supplies should be predicted taking with account taken of the probability of occurrence and the intensification of cultivation.

For the prediction of future irrigated areas trends to the development of agriculture should be considered with attention to regional and environmental aspects. Due to the great differentiation of forecasted hydrometeorological data obtained from Global Circulation Models using the scenarios of GFDL (Geophysical Fluid Dynamic Laboratory), GISS (Goddard Institute for Space Studies) and CCCM (Canadian Climate Centre Model) and possible errors in the forecasting of future irrigation areas, the approximation method for calculations was applied in this report (Darves-Bornoz 1963).

WATER DEMAND FOR IRRIGATION

The demand for water for crop irrigation was determined by means of the following simplified equation for water balance:

$$D = (ETP - P) - \Delta W \quad \text{(mm)}$$

where: D — water demand (net deficit), ETP — potential evapotranspiration, determined in the "Country Study-Poland, SE-12" (1995) according to the Budyko formula, P — precipitation (corrected value due to measurement error, efficiency factor not considered), ΔW — retention of available soil moisture, (ETP–P) — precipitation deficit.

Application of the above equation requires estimation of the precipitation deficit (ETP–P) and retention of available soil moisture (ΔW). The base dataset for estimation of precipitation deficit was adopted from the "Country Study-Poland, SE-12" (1995). The results for the GCM–GFDL scenario were adopted in this analysis as the most extreme values amongst the data obtained from the three applied Global Ciculation Models (GFDL, GISS and CCCM).

Values for precipitation deficit (ETP–P) were estimated from the above equation on a monthly basis. Thereafter the precipitation deficit was calculated for the following different growing seasons of crops:

— April–September (IV–IX); whole vegetation period,

— April–June (IV–VI); first grassland cut and main growing period for cereals,

— July–September (VII–IX); second grassland cut and main growing period for root crops,

— May (V) and August (VIII); months of the greatest water demand.

Values for mean precipitation deficit in the catchments of the Warta and Wieprz rivers were calculated for the period 1951–1990 and then compared with that determined for the hypothetical conditions of double CO_2 content according to the GFDL scenario. The results are shown in Table 1.

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TABLE 1. Precipitation deficit in Warta river and Wieprz river catchments

Period	Precipitation deficit (mm)			
	Warta river catchment		Wieprz river catchment	
	1951–1990	GFDL-2 · CO_2	1951–1990	GFDL-2 · CO2
IV–IX	164	274	118	211
IV–VI	88	126	53	62
VII–IX	76	147	65	149
V	40	43	30	28
VIII	33	56	29	51
Mean relative value	1.00	1.57	1.00	1.58

The index of increase in the precipitation deficit (relation between mean precipitation deficit 1951–1990 and future deficit in the year 2080) is 1.57 for the Warta river catchment and 1.58 for the Wieprz river catchment. Based on these results, the index of increase in the precipitation deficit was calculated with regard to the hypothetical situations in the years 2020 and 2050. It equals 1.19 and 1.38 for these respective years in both catchments.

Design values for precipitation deficit were determined to estimate a precipitation deficit that approximates dry-year conditions (Table 2). Exceedance probabilities of p = 25% and p = 10% were chosen for further analysis as they correspond to mean dry year and very dry year conditions respectively.

TABLE 2. Design precipitation deficit for different exceedance probabilities on the basis of 1951–1990 data

Months	Warta river catchment			Wieprz river catchment		
	Design precipitation deficit (mm) for the exceedance probability of					
	50%	25%	10%	50%	25%	10%
IV–IX	140	260	320	120	210	270
IV–VI	90	130	170	65	130	200
VII–IX	80	135	180	65	110	140
V	40	65	80	35	55	70
VIII	45	65	80	30	60	85
Design value reffered to mean relative value for 1951–1990	1.06	1.68	2.07	1.09	1.96	2.69

In natural conditions, retention of available soil moisture (ΔW) ranges from 25 mm to 125 mm depending on soil type and rootzone thickness. Retention for both catchments was estimated to equal 50 mm.

The demand for irrigation water was calculated from the estimated values for precipitation deficit and available soil moisture retention for the mean and very dry year conditions. Thereafter, unit irrigation demand was calculated. The results are shown in Table 3.

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TABLE 3. Historical and future precipitation deficit and demand for water irrigation for vegetation period in mean and very dry year conditions

Exceedance probability	Warta river catchment			Wieprz river catchment		
Design precipitation deficit (mm)						
p = 25%	260	309	359	210	250	290
p = 10%	320	381	442	270	321	373
Water demand (mm)						
p = 25%	210	259	309	160	200	240
p = 10%	270	331	392	220	271	323
Unit irrigation water demand (dm^3/s ha)						
p = 25%	0.132	0.163	0.195	0.103	0.126	0.151
p = 10%	0.171	0.210	0.248	0.139	0.171	0.204

Considering the months of greatest demand for irrigation water (May and August), the required unit demand for irrigation water in future dry-year conditions is estimated to be higher and to amount to about 0.3 dm^3/s ha.

The values for unit demand presented in Table 3 are net values calculated for intensive agricultural use. They do not include losses during the operation and maintenance of irrigation systems.

In the case of the extensive agricultural use of grasslands and other areas irrigation water demand should warrant the maintainance of high soil-moisture retention, a reduction in process of mineralization of organic matter in peat soils and the supply of natural and artificial wetlands. In these cases, unit demand for irrigation water can be half of the unit demand included in Table 3.

FUTURE IRRIGATION AREAS

According to statistical data the irrigated agricultural area is c. 500,000 ha, including about 60,000 ha of arable land and about 420,000 ha of grassland. These are approximate values that concern areas with technical equipment. The real irrigated area is smaller and amounts to about 230,000 ha, according to data on water consumption for irrigation (*Environment Protection* 1994).

The assessment of areas requiring future irrigation has been done for grasslands, arable land and orchards for the conditions of the GFDL scenario and the probable scenario for development of agriculture and the food economy in Poland.

The intensification of production on grasslands and the extent of irrigated areas are mainly dependent on the predicted needs of the development of breeding.

The existing results of research indicate that it is possible to obtain hay yield of 5–6 t/ha without irrigation. Planning on higher yields of 7–8 t/ha and more it is necessary to apply supplementary irrigation. Supplementary

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irrigation will also be indispensable for grasslands in non-productive use, wetlands, or areas with a controlled outflow regime and regulated groundwater table.

Table 4 presents total grassland area and estimated future irrigation areas according to production and ecological criteria.

TABLE 4. Estimated future area under irrigation in Poland

Grasslands	Area in 1000 ha	Areas subject to irrigation in 1000 ha according to:	
		production criterion	ecological criterion
Total area	4050		
Lowland grasslands:	3560	785	325
– dry-ground meadow	1530	450	70
– riverside marshy meadow	640	–	35
– swampy meadow	1390	335	220

Areas of arable land and orchards requiring irrigation have been estimated by Górski (1995) with assumed structural changes in agriculture, technological progress and stabilized agricultural production. According to these data future areas for irrigation in Poland should total about 950,000 ha by the year 2080. By the year 2020 c. 350,000 ha and c. 670,000 ha should be irrigated by the years 2020 and 2050 respectively.

More detailed estimation of areas requiring irrigation in the Warta and Wieprz river catchments would require specific analysis with consideration given to environmental and agricultural factors.

CONCLUSIONS AND REMARKS

In the "Country Study-Poland, SE-12. Strategy for Water Management in Poland in the Face of Climatic Changes" (Kaczmarek et al. 1995) prepared for the "Climate Change 1995: Second Assessment Report of the Intergovernmental Panel on Climate Change" (Watson et al. 1996) premises of future water management policy were characterized. It was stated that the influence of climatic changes on water resources and demand for water might be crucial taking into account limitations on water resources. Areas requiring irrigation might increase significantly as well as demand for water in irrigated areas.

The analysis performed has shown that doubled atmospheric CO_2 content in the year 2080 might cause an increase in the precipitation deficit of 19% by the year 2020 and 38% by the year 2050, assuming the most extreme hydrometeorological conditions evaluated by the GCM-GFDL scenario. For the conditions of the mean dry year the level of unit demand for irrigation water is estimated to be within the range 0.15–0.3 dm^3/s ha.

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The extent of future irrigation areas depends on the availability of spatially and temporally limited water resources as well as on the strategy for development of agriculture and the food economy. It is estimated that approximately 1,000,000 ha of grassland and 950,000 ha of arable land will require irrigation.

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THE INFLUENCE OF POSSIBLE CLIMATE CHANGE ON THE SYSTEM OF RESERVOIRS OF THE UPPER VISTULA RIVER

JAROSŁAW J. NAPIÓRKOWSKI, TOMASZ TERLIKOWSKI
Institute of Geophysics, Polish Academy of Sciences
ul. Księcia Janusza 64, 01-452 Warszawa, Poland

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ABSTRACT

The system considered comprises two retention reservoirs on two rivers, namely the Goczałkowice Reservoir on the Vistula river and the cascade of the Tresna, Porąbka and Czaniec Reservoirs forming one body on the Soła river. The system's main task is to supply industrial and municipal consumers, specifically the urban agglomerations of Katowice and Bielsko-Biała, the Katowice Steelworks via the Dziećkowice Reservoir, the chemical plants in Oświęcim and the fish ponds around the town of Kęty. At the same time, the concentration of pollution, mainly discharged below the Przemsza river should be kept down to a level in line with water-quality requirements.

The system was analyzed using optimization techniques, with simulations for selected climate scenarios being run for a 90-year period. The following criteria were proposed to assess the working of the system: the total duration of deficit; the maximum duration of continuous deficit; the mean value for the relative deficit; the maximum mean value for continuous relative deficit and the maximal value for relative deficit. The final form of the results serving in comparative analysis are diagrams for reliability criteria derived on the basis of simulations for each consumer.

The full text has been published in "Impact of Climate Change on Water Resources in Poland", publication of the Institute of Geophysics No. 295, 1997.

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DISCUSSION ON PAPERS PRESENTED (abbreviated)

Session I: CLIMATE VARIABILITY AND CHANGE — IDENTIFICATION AND SCENARIOS

Professor Z. Kaczmarek (Institute of Geophysics PAS)

Questions as to how to take decisions in conditions of uncertainty are a basic problem with the present level of knowledge and possibilities for climate modelling. We should be aware that current technology for the modelling of atmospheric processes does not offer unambiguous answers to a series of questions that are important in practice. This is true of water management. The similar dilemmas facing agriculture have been addressed in the IPCC's work. Some models point to possible improvements for crop-growing over large areas of the globe, while others anticipate deteriorating conditions for the self same areas. It is by no means certain whether we will be able to find a convincing solution as to how to take decisions in such a situation. One of the climate models — devised by the Institute of Meteorology in Hamburg and assuming a doubling of CO_2 concentrations — predicts desert conditions for Poland in summer, with the simulated precipitation total for May to September being as low as 10 mm. So this is how the accuracy of climate models in relation to decisionmaking looks.

However, the papers presented offer some signs of hope because similar results are obtained when the same scenarios for climate change are used in connection with different hydrological models. Assessment of the sensitivity of hydrological processes depends mainly on the scenario of climate change adopted. Also similar are the conclusions drawn using different hydrological models concerning changes in the phases of flow, e.g. a shift in spring high water to an earlier date. So there are signs of a certain "robustness" of estimates to the hydrological model applied, on condition that the input data are the same, and hence also the model.

Docent H. Mitosek (Institute of Geophysics PAS)

GCMs adopt a scenario in which there is an increase in amounts of CO_2. On the other hand, such a trend has been known and recorded for more than 30 years. So is the observed trend for rising air temperature corresponding to the concentration of carbon dioxide appropriately reflected by

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the global models? A Global Circulation Model resembles any other in tending to smooth out the courses of the lines generated. How does the matter look in the shorter term? Should this be taken into account in the case of the adaptation or interpretation of global results?

Professor W. Strupczewski (Institute of Geophysics PAS)

My view is that we should not go too far with prognoses. Let us look at them in relation to the length of our own lives and not extend them too far into the future. I agree with Professor Kaczmarek when it comes to barriers to climate modelling, but I must say that this is not the majority view. As proof of this I might cite the response of a certain Deputy Minister in the Ministry of Environmental Protection, who stated that the issue of climatic change and its influence on hydrological processes and water management is a problem of little bearing to society. The Ministry has given it to be understood that it does not want to get involved in this, while the group of interested scientists who depend on such research may turn directly to the parliamentary commission to obtain funding. The Minister probably spoke for a large group in society. I speak of this to illustrate how assessments differ in relation to the circles in which these matters are being discussed. If we were to ask the man or woman in the street what his/her priorities were, we would certainly be told healthcare, security in old age, etc., and only at the end would we hear about living in a healthy environment — even though this is in no way in conflict with these other priorities. It is just that people do not associate these problems with one another. So there is an urgent need to propose action and research of the kind that would gradually break down this passivity, or even negativeness and passivity, in the different decisionmaking circles. So the question is this: which directions of study should be developed in the near future, for example as part of the National Climate Programme that a large group of people have been fighting for, for some time now.

Session II: SENSITIVITY OF WATER RESOURCES TO CLIMATE CHANGE

Professor Z. Kaczmarek (Institute of Geophysics PAS)

We come back again and again to a question that is socially-relevant and very much needed. But the discussion should take place in scientific circles and only then between scientists and decisionmakers. For scientists, a "comfortable" way out is simply to do the desirable research in those areas in which they are involved. If we gain better knowledge of hydrological relations, in the sense of the interdependence of the elements which shape the water balance, and if we are better able to define the relationships between conditions for biological life in aquatic ecosystems and physical conditions, then this will be our contribution to the decisions taken in the future.

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I think that the area of uncertainty in climatic scenarios will gradually narrow. Such huge resources are being assigned to this by science worldwide that it must eventually lead to improvements in the accuracy of models. When that happens, the results of our research will become needed. Fields of study worth considering are appearing here, especially in the final panel discussion. But which thrusts of research should be developed in pure study, and what as regards adapting the economy to possible climate change, assuming that the degree of uncertainty will be less in future? The key question is how to approach the decisionmaking process. If we are not able to assess the value of the different scenarios then it is difficult to make choices.

Docent J. Żelaziński (Institute of Meteorology and Water Management)

Whether or not the probability of the different scenarios varies, the essence of the problem does not change. The problems of water management can usually be solved in many different ways. It is a truism, but we often fail to recall this as we see the reservoir as a kind of universal panacea. In proceeding on this assumption, we should prepare a certain number of variant solutions for each scenario of climatic change, beginning with the building of reservoirs and going through water conservation, changes in agriculture cultivation and so on, in order to sort out the situation a scenario presents.

In this we come to the most important problem of how to make choices. I think we should proceed sequentially to find the best solution to compiling a ranking of solutions within the framework of each scenario, while taking account of economic, social and ecological criteria. However, the very serious problem of dimension appears. I first propose limiting the number of variants for resolving the implementation-related problems of each scenario, e.g. to two. The next stage will involve the choice of selection criteria. The choice should be a multicriterial one in relation to one scenario. The criteria must vary. For example, the threat to biological diversity cannot be treated equivalently to economic effects or the threat to human life. There are tested techniques for reaching a compromise between experts. If the EIA (Environment Impact Assessments) approach were adopted, the problem would be one of negotiation, rather than one solved by the methods of optimization.

A ranking of possible ways of proceeding, considered within the framework of the different scenarios, would allow for study of the consequences of completing each of the developmental variants under conditions in which the different possible scenarios came to fruition. The basic criterion would then be weighted by probabilities. We would choose solutions for which the criterial function in relation to all possible scenarios of climatic change would be minimal or maximal, as agreed. This criterion would be the basic, but not only, one, because such an analysis would most likely show that certain solutions assumed to be good in the realization of a defined scenario would have very negative consequences if implemented in another scenario.

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Session III: WATER-RESOURCE MANAGEMENT IN CONDITIONS OF UNCERTAINTY

Professor W. Strupczewski (Institute of Geophysics PAS)

Docent Żelaziński's paper aroused a lot of interest. The beginning impressed me because it went beyond a consideration of uncertainty in water management to touch on philosophy and theology. Some truths will always be inaccessible to us, such as the non-deterministic nature of the world from the point of view of the observer, in the light of the possibilities for human understanding. We could refer to the France or England of the early 18th century, to the deists who believed that God created the world and furnished it with certain transformation mechanisms and took no further interest in it. The author says that decisionmaking makes no sense in predetermined situations. It is only when conditions of uncertainty exist that the issue of decisions arises. But this is an unclear approach. In water management, the models applied were of linear programming in deterministic conditions. If do not resolve this model we were not in a position to indicate the optimal decision.

Docent J. Żelaziński (Institute of Meteorlogy and Water Management)

I would like to refer to the opinion of Karl Popper — for me an authority in the sphere of philosophy — for whom the unpredictability of the world is a basic thesis. An important motif is humility in the description of reality and the drawing of conclusions from it. Does a deterministic situation in water management imply a need to make decisions? It is obviously necessary to distinguish between the decisionmaking process and the decision. The task of optimization is resolved in operational studies, or in the theory of steering towards mathematical games involving the search for the extreme function of one or many variables. It is difficult to term an algorithm finding the extreme functions of a pair of variables a decision. For a decision entails the choice of a criterial function that we minimize. The solution of the mathematical problem, denoting the discovery of the extreme function of many variables, is not linked with an essential need to take certain decisions, other than those of a general type like which computer to choose, or which of the 150 optimization methods to use that the theory puts forward.

My view is that the only true remedy for floods is departure from floodplain areas. The risks should simply not be faced in the first place. The whole experience worldwide, what has happened in the Mississippi or Rhine valleys in recent times, all show the idea that we can combat natural disasters to be nothing more than a technocratic illusion. Once I rebelled against such a treatment of the issues as was expressed in the view of Professor Sugawara who stated that natural disasters cannot be prevented. But we are making atonement for the sins of our forebears, who settled in river valleys. Technical means are a very imperfect tool and we should be under no illusion that

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they can solve the problem completely. A system of protection, evacuation and warnings needs to be organized. But how to assign money to the development of the system in the context of last year's floods. The Hydroprojekt study for the World Bank did not find room for my views, for it is written there that the Świnna–Poręba Reservoir protects Kraków from flooding. This is obviously untrue, for it is at most able to reduce the water level in Kraków by 10 cm. And this year Czorsztyn had no effect beyond the confluence points with the Kamienica and the Ochotnica, while the peak high water in Nowy Sącz was lowered by something of the order of 5 cm. Statements to the contrary are fables put about by those interested in funding for the next reservoir. In this context, the flood-prevention system must be effective in organizational terms, with a proper defensive warning system. The legal system must be changed, with limits put on opportunities for infrastructural development in floodplain areas.

Professor L. Starkel (Institute of Geography and Spatial Organization PAS)

I think that the introduction of a philosophical theme is very much needed to freshen things up. In general, we in the earth sciences very rarely either return to, or reach for, this subject, and so there is a great gap between those involved in the philosophy of nature and those in earth sciences. I would like to draw attention to the fact that our different scenarios based on models relate back to the reality of 30 or 50 years of observation. It is necessary to look at events in the longer time perspective, but I would see a certain danger here — namely that alongside the models, which give either a rise or fall in precipitation, excesses or shortages of water, there is no consideration of situations in which the system will be more or less stable in its average values, but with an increased frequency of extreme events. Climate models indicate increases or shortfalls in precipitation corresponding to mean values, which means to say that they allow the stability of systems to be defined. But they do not allow for any determination of the frequency of the extreme events which ought to be brought into the scenarios of global changes in climate. How long is the system's memory? Or, to put it another way, what is the period of relaxation or for a return to some previous more or less permanent, or short-term, equilibrium? Against the background of docent Żelaziński's paper, we might inquire about the way in which melioration policy reacts to floods. Will it not be necessary to irrigate certain areas in a few years' time? While even in the next year, a limited drought may force us to introduce irrigation.

Professor Z. Kaczmarek (Institute of Geophysics PAS)

Our discussion is working towards proposals that can be used to delimit directions of study. I believe that, in matters connected with water for agriculture, including irrigation, it is this issue of variability that is more important than assessment of the influence of climate scenarios on average water relations in agriculture. We had neither the time nor the resources

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to involve ourselves properly in this issue within the framework of the Country Study for Adaptation of the Economy to Climate Change, but I do think that this should be one of the directions of future study In reference to what Professor Starkel said, I would like to express my view that it is precisely as a result of these water deficits in agriculture that very serious losses in the economic sense may arise.

Professor Cz. Somorowski (Agriculture Academy, Warsaw)
The issue of the variability of different hydrological phenomena and the role of extremes is characterized by losses in production where agriculture is concerned. In the hierarchy of needs, agriculture is always at the bottom of the pile — when we think about safeguarding water supplies for crop production, municipal and industrial requirements always take priority in satisfying demand. Variability must be taken into account, not only in long-term forecasts, but also in operational steering by melioration objects. The need to consider variants, and uncertainties in decisionmaking, must be considered at various levels of administration. This is also an educational problem of importance in decisionmaking circles from the level of the gmina [unit of local government administration] to that of the ministry.

Docent E. Radwański (Warsaw Technical University)
The issues of education in the fields of nature and the environment would seem to be the most important. It is not only decisionmakers, but also students, who are waiting to have the one best solution pointed out to them. In relation to training we encounter a multiplicity of variants for different situations in nature, to which we have to apply a defined type of device and preventative or regulatory system. The choice should be made using common sense. The ecological approach should involve a change in strategy from the restrictive to the creative. There is thus a need for an understanding that man must coexist with nature, and teachers are there to prompt students in how to do this in a way that prevents the exceeding of limits beyond which there is nothing but degradation and an irreversible loss of equilibrium in the environment.

The reduction of uncertainty is a necessary condition in all analyses. Skill in assessing the probability that a defined situation will arise is perhaps most important. However, it seems that the function of teaching has changed. In the past it was skills, but a certain length of time ago a capacity for ongoing thinking and discussion became the most important function. In the technical sciences, confinement to a single full-time post has very much impaired opportunities for practical training. A higher education establishment had a basic core of professors but very often cooperated with different specialists who came in for quarter-time work and brought the teaching process closer to reality.

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Professor W. Strupczewski (Institute of Geophysics PAS)

The paper from Professor Somorowski took into account predictions of agricultural needs where irrigation of the soil is concerned. I think that demographic forecasts may also create a demand for water for people and agriculture. There would appear to be a high degree of predictability in agriculture, but the fundamental elements of uncertainty are probably not inherent to the assumptions of the scenarios, but rather to a wrong assessment of demand.

Docent Napiórkowski assumed increased demand in relation to the demographic forecast in the area of the Upper Vistula. He pointed to the relevant use of water "per capita" and the consumption of water in industry, with account taken of rationalization due to new technologies. The increase in the demand for water extended to between 40 and 50% over the next 80 years. Flows into reservoirs were modelled on the basis of global models. How to introduce a decisionmaking mechanism? The answer is very problematical.

According to Professor Zalewski, the majority of biological processes which determine water quality in the critical period, i.e. in summer, are initiated in May. Are deficits in May serious, or minimal? The answer is that they are minimal, because at that time there is an opportunity to steer the level of water in a reservoir — at the end of winter we make every effort to ensure that reservoirs are full. If the water level is lowered in May, and a deficit threatens, then there will be difficulties in filling a reservoir. Is there such a threat with those scenarios that are most probable?

Docent J. Napiórkowski (Institute of Geophysics PAS)

I assumed a variant in which I knew the prediction very precisely, so that I might compare the influence exerted by the climate scenarios, and not by possible strategies or decisionmaking models. It is on this basis that I state that certain scenarios will have a significant influence on the appearance of deficits. The introduction of the decisionmaking mechanism is quite a separate problem when we do not know what the future flows into reservoirs will be.

PANEL DISCUSSION ON THE DIRECTIONS OF FURTHER STUDIES

Professor Z. Kaczmarek (Institute of Geophysics PAS)

We are approaching the end of what I believe to be a Conference of interest to everyone. I would like to ask those chairing the different sessions to give their impressions and to provide a summing-up of the papers and dicussions. I would also ask that we consider the directions that future research should take.

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Professor L. Starkel (Institute of Geography and Spatial Organization PAS)

The papers and discussion show that hydrological processes have been approximated to global changes in climate. As different models, methods and examples were presented, we came to a view that the non-stationarity of the processes is one of the main issues. It is exceedingly difficult to move from models of global scenarios to scenarios on a more-detailed scale. I see the need to integrate scientific teams working on modelling and local and global climate scenarios with parties interested in water resources and their management. Sometimes our approaches appear to diverge. From this point of view, I consider that the very idea of the subject matter for the Conference and the linking of these issues was an excellent one. The circle interested in the Conference was a relatively small one, a fact which points to the undervaluing of changes happening on the global scale. The publication of materials from this Conference, and the dissemination of the results, will represent a significant contribution to the discussion and should go on to offer insights into the mechanisms and feedback processes which connect climate change and all that goes with it with the exchange of energy and the cycling of matter at the very surface of the continents. I think that the discussion points to the need for verification of the methods applied to date, as well as for that certain care and circumspection in the drawing of conclusions and in the inspection of the various alternatives that was called for by docent Żelaziński. But in the main decisionmakers are looking for concrete and decisive assessments.

Professor Z. Kaczmarek (Institute of Geophysics PAS)

Even before the Conference began I pondered over the main directions of study in relation to the three sessions into which the Conference was divided. In the part concerning scenarios for climate change I would propose three main directions. First, the development of methods by which to adapt scenarios to different regions. Second, better use of the available information for analysis of the possible changes in climatic parameters other than air temperature and atmospheric precipitation. These two issues are in my view key ones, and the most important in future research. Finally, the third direction — over which I now have certain doubts — should work towards test assessments of the reliability of the different scenarios for climate change.

Professor W. Czernuszenko (Institute of Geophysics PAS)

It would seem that if we were well acquainted with the action of global models, and the ways in which they differ, the majority of the studies into their influence on water management might not be required. But such an assessment of the models does not exist and so we cannot explain the way in which they influence certain hydrological parameters. To gain a precise understanding of the scenarios of climate, their reliability and the physical principles and assumptions underpinning them is to be able to assess whether

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they are more or less probable, and whether their assumptions are acceptable or not.

This is an ambitious idea, but I would like to draw attention to the fact that research teams working in different centres and preparing the theoretical foundations of particular models do not always share information openly when it comes to the detailed theoretical assumptions. Furthermore, there is a certain competition between the teams. If the accessible published materials or reports provide us with a chance to assess the assumptions behind the models, then this should be done. The element of reliability is also included here. However, I fear, purely and simply, that this will not always be possible. I think that we all have an interest in the emergence of a framework National Climate Programme, within which it will be possible to build up particular, more-specialized elements.

Docent Zelaziński dealt with the conjecture that global changes will enhance the frequency of extreme events. There is a great deal of interest in whether this issue is thus being resolved in existing programmes and taken into consideration in the scenarios. The possibility that the frequency of extreme phenomena will increase in the next century is the subject of much speculation and forecasting.

Professor W. Strupczewski (Institute of Geophysics PAS)

My past, negative, experience teaches me that even explanation of the assumptions behind a model will not make it reliable and allow one model to be placed ahead of another. I believe that the technology of the models is the preserve of those outstanding number-crunchers, and that the "devil" is in the detail of those numbers. We are not in a position to uncover it and so study of the assumptions will not resolve the matter. Study of the past for extrapolation into the future remains an open issue. The period of climate change linked with warming is not a stationary period. More attention needs to paid to the temporal and spatial variability of climatic processes and to detection associated with the use of information from the past, along with the area of interest resulting from palaeoclimatic and palaeohydrological data. I think it would be interesting to include last year's peak high water, and also that from 1934, for example, in an analysis of variability of flows.

Docent J. Pruchnicki (Institute of Meteorology and Water Management)

The second session was concerned with the influence of climate change on hydrological processes and water resources. We had 6 papers, of which some concerned phenomena described on the macroscale, some those on the regional scale and some those on the microscale of reservoirs. It has been shown in all cases that the potential climate changes will undoubtedly influence hydrological processes and water resources, albeit with the size, scope and intensity of this influence being subject to a high degree of uncertainty. This uncertainty depends on the scenario of climate change applied. The assessment and forecasting of demand for water in different sectors of

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the economy are also burdened by a high level of uncertainty as Professor Somorowski, amongst others, has shown. The uncertainty of the results obtained in water management depends on the uncertainty of climatic models and there is really not much that can be done here except for interpretation of results or attempts to transfer the results of global models to the regional or local scale. We here are condemned to observing the development of research worldwide and to attempting to improve the methods by which we assess the processes going on in the hydrosphere.

I would like to share the following reflection with you. In 1974, I wrote an article on *Energy and climate*, which was published in the periodical entitled "Basic Problems of Contemporary Technology". In the article I presented the results of global climate models, then quite simple, involving the study of processes by which energy, mass and momentum were transported in the meridional direction. The results of these models provided a basis for concluding that the driving factor was the amount of energy emitted to the atmosphere as a result of the combustion of a defined amount of fuel. This was linked up with discussions following the 1972 Energy Crisis, when attention was paid to alternatives to fossil fuels, i.e. coal and oil. The result of this relatively simple model, which did not require large outlays or computer capacity, was an estimate for the rise in average global air temperature of the order of 1.5°C with a rise in energy emissions of 50%. The distribution between the Equator and the Pole was more or less like thus: from 0.5°C at the former to 7°C at the latter. The subsequent 25 years — for that is how much time has passed since 1972 — have seen enormous intellectual and financial resources put into the development of complicated dynamic models (Global Circulation Models and other models of the atmosphere are examples), but the results that have emerged are virtually identical. The only benefit to have come from these dynamic models is that they have allowed for better spatial differentiation of elements of the climate.

Anyone who had the occasion and patience to read through the fat volume on the work of the First IPCC Working Group knows that the reservations and limitations are so huge as to make one doubt the reliability of the results obtained when it comes to the spatial distribution of anticipated changes in air temperature. Two months ago, there was an international Conference in Geneva devoted to assessment of the achievements of the international programe investigating the climate and to plans for the future. In spite of the high degree of complexity of the equations, no significant improvements in the results have been obtained. Various numerical tricks which are to achieve this aim have been developed, but we are unable to parametrize the basic processes which need to be built into the models. Professor Morell has criticized this approach, and — in referring to his statement — I would like to shed light on the need for a reorientation of our views and indications regarding the direction of further study. Professor Morell claims that the Earth's climate is often determined by processes on the microscale, e.g. those being played out in clouds. Only in the wake of

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a good understanding of the mechanisms, and their devising and mathematical description, can we be in a position to attempt to integrate them with measurement techniques. Problems of the scale on which the processes continue are particularly important. Professor Morell has a unique ability in the incisive diagnosis of climatological processes and is an unquestioned authority in climatology. For 12 years he headed the department within WMO for the world programme of climate study, which is to say that he was responsible for everything that has gone on in this field to date. In the light of this, his self- censure may certainly be regarded as reliable, and should give us all a great deal to think about.

Professor Z. Kaczmarek (Institute of Geophysics PAS)

As follows from Docent Pruchnicki's statement, the rational way of proceeding should entail improved familiarity with physical, biological and chemical processes in the natural environment. It is to be hoped that, as time passes, we will be in possession of ever-better and more reliable information from meteorologists.

Professor M. Zalewski (Department of Applied Ecology, University of Łódź)

Docent Pruchnicki has said that he feels global climate scenarios are now developed optimally. This is thus a typical moment in science when a certain paradigm has been exhausted and a new one must emerge. I therefore think that this is not an issue of new methods of measurement technique, but rather of a new concept from which a revolution can develop. The new situation may then lead to the emergence of new technology.

Lovelock's "Gaia Hypothesis" has brought about a revolution in biology. It seeks to explain the action of the biogeosystem as a system which functions, and has arisen, as a result of biotic evolution impacting also on the present state of the atmosphere. The dynamics of biological processes, including the assimilation of CO_2 in a state of equilibrium and disturbance, induced not only by emission but also by assimilation, may have a modifying influence on the state of the atmosphere. From the global point of view, the accumulated layer of biomass is very large, but it has a mosaic-like unevenness when it comes to the intensity of biological processes in the epigeosphere, and this factor is capable of significantly influencing climatic processes and their predictability.

Docent J. Napiórkowski (Institute of Geophysics PAS)

My dream is that a climatic model used in forecasting might offer the chance of predicting the weather 5 days ahead. At the time of the 1997 flood, we in Poland came to realize that we may only forecast for the next 2 days. Nothing more than that can be achieved. However, we may make a more certain forecast once rain is already falling. Unfortunately, the forecasting model applied to flows of the Vistula in Warsaw was only able to offer a rather imprecise simulation of the situation (with an error of 1.5 m).

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I know a few people who are better able to simulate the flows of the Vistula and Oder (from source to mouth). We should be prepared to devise an operational and simulatory version of such a model and then introduce climate change at the outset.

I think that the search for analogies between the forecasts for 2, 5 or 7 days, and models of the climate type is a misunderstanding. Nobody intends to forecast climate in the short-term sense of the word, i.e. by defining what the air temperature in July 2003 will be. Climate modellers claim that their models do not offer forecasts, because the establishment of the statistical characteristics defining the state of the climate is something different to an attempt to set a value for a variable at a given moment in time. I agree that, until we have proper parametrization of models, e.g. of the atmosphere–oceanosphere and biosphere–atmosphere subsystems, we cannot expect any reduction in the degree of uncertainty.

Professor Z. Kaczmarek (Institute of Geophysics PAS)

Hydrologists do not engage in the modelling of atmospheric processes. Our most important task is to study processes ongoing in drainage basins, in a lake, in a river, in groundwater — in connection with climatic conditions. However, there is no great sense in repeating hydrological calculations in the future using one new climate scenario or another, if we are not convinced as to the high reliability of the input data resulting from meteorological models.

Professor Z. Czernuszenko (Institute of Geophysics PAS)

The most important issue is the stability of the model, not its exactitude. A mathematical model cannot react suddenly, e.g. give rise to some far-reaching global change if we introduce a small change into it. I do not know if Professor Morell's statement is justified. Processes on the small scale cannot lead to significant changes in an aquatic system. I have noticed that a typical study entails our use of, for example, a sequence of river flows, with statistical apparatus being used to define trends, periodicity or variability, or climate change. It is extremely difficult to use such data as a basis for assessing the influence of the structure of drainage basins (ecosystems undergoing continuous transformation over the last 100 years), as opposed to the influence of climate change. Research in a basin needs to focus on physical processes based on natural laws and described with the aid of the equations of mathematical physics. This is the proper direction. A better understanding of the processes in drainage basins will be valuable, and the drawing of conclusions on the basis of series of data may be illusory. Anticipating more reliable information from climatologists, it would be better to concentrate at present on the study of physical, chemical and biological processes in a basin.

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Professor J. Cyberski (Institute of Oceanography, University of Gdańsk)

Changes in the hydrology of rivers will undoubtedly be reflected in the marine environment of the Baltic Sea. Research in Scandinavia is proceeding in a similar direction to that in Poland. Inflows of water from Poland to the Baltic account for c. 10% of the total mass of water coming in, and future changes to this as a result of global warming may be of great significance. It is already possible for us to draw up a certain scheme for changes in the marine environment. In Scandinavia, certain hydrotechnical beginnings have already brought repercussions in the marine environment, at the very least a reduced influx of SiO_2 as a result of its accumulation in reservoirs in Sweden and in natural and artificial bodies of water in Finland. Such processes are observed in the northern part of the Baltic Sea, in the Gulf of Bothnia. A certain shift in phases may occur in relation to the inflow of freshwater, inducing changes of great significance in the marine environment. At present, after all, the highest water in the Baltic is observed in September or October, and not in July.

Professor L. Starkel (Institute of Geography and Spatial Organization PAS)

I think that one of the problems connected with the modelling of changes over the longer time perspective is the fact that the models are concerned with the functioning and exchange of mass and energy between the atmosphere, the oceans and the land, while they are not set to seek out the causes of long-term changes. When we look at the "Global Change" Programme we see an outline of the role played by certain theories in the natural sciences. Among these are Darwin's theory of evolution by natural selection, or the theory of Wegener, which was later transformed into the theory of continental drift or plate tectonics. A similar history characterizes the history of knowledge on climate change, its mechanisms and causes. We are living in a period in which the theory is being hatched and created. Study of the water cycle constitutes a very important integrational element in the whole system.

Docent H.T. Mitosek (Institute of Geophysics PAS)

In speaking of models from mathematical physics, and in bringing into relief their role, we cannot forget that when theoretical models are constructed without exact knowledge of boundary conditions or of the real empirical world resulting from measurement, then we are not able to verify the results introduced from the very well-ordered equations of mathematical physics. Unfortunately, we are still not in possession of the reliable data that would allow us to say that we have observed such and such a trend in such and such a time. On what am I basing my statement? The very well-ordered meteorological station for Puławy has an air-temperature series dating back to 1870. However, I already know of a third version of the series for mean monthly values. This attests to the fact that our data are simply very bad. A similar situation applies to the air-temperature series for Warsaw on the basis of various stations. If I perform statistical calculations, I come to the

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end of the possibilities in 1988 — there are no newer data. If we are not going to be able to verify the physical models then just what is the value of our research?

Professor Z. Kaczmarek (Institute of Geophysics PAS)

I do not think anyone here has proposed doing theoretical research in the field of geophysics without measurements. The study of physical or biological processes takes in both experiment and theory and it is perhaps necessary to understand this. Another matter is the methodology by which to re-create long series. This is really a very complex problem, but not one linked with the issue of research into processes.

Docent J. Pruchnicki (Institute of Meteorology and Water Management)

My statement links up with the subject matter of the first group of papers, and only partly with the course of the discussion. I want to draw attention to terminological matters. In climatologists' circles and within governmental teams involved in "climate change" there is an ongoing discussion as to the appropriacy of using this term. There is after all no precise definition here, just a colloquial usage. If we emit a defined amount of CO_2 up to the year 2020 then a defined climatic effect will follow up to the year 2100. I am convinced that such a definition of climate is inadequate. At the moment we reach this situation (2100) we come to a new reference state and everything starts again from the beginning. During the deliberations of the WMO climatology commission in Geneva (July 1997), voices were heard to the effect that the terms climatic evolution or climatic stability should rather be used. If we are speaking of climate change we have no certainty that they will really occur, because too much uncertainty in research remains.

A second problem concerns verification of results from physical models. The last 10–20 years have seen a marked worsening of the state of the measurement and observation network worldwide, and not merely in developing countries. This results from the need to make savings and limit the funding of state services. Where Poland's meteorological service is concerned there is a current total of 60 synoptic stations, which should work every hour, or every three hours, 24 hours a day, and send appropriate dispatches to weather centres. However, it turns out that one-third of these only make observations and measurements in the daytime. This is completely useless for the purposes of climatological research. The quality of observations and measurements is also deteriorating constantly. While the introduction of automation and new measuring techniques undoubtedly represents a move to greater accuracy with less servicing, it leads at the same time to the non-homogeneity of data series in relation to those deriving from measurements made in the traditional way. The meteorological services often do not heed the procedures recommended by the WMO in the event of the uncovering of some lack of homogenity in a series as a result of changed measuring techniques. This is an element reducing the reliability of data and it is also

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true for measurements on the global scale. It has been found that there may be errors in assessments of the trends in air temperature worldwide made on the basis of measurements from meteorological stations. There are around 16,000 such posts spread around the globe which may be put to such use, while a group of experts working for the WMO have stated that assessments of the state of, and changes in, the climate require only about 1000 representative stations that are reliable and have long, homogeneous series. I hope that these will not be moved of liquidated in the future, but will be maintained with a stable working regime. These stations are to be the core of the so-called global system of climate observation, in which Poland is a participant.

Professor M. Zalewski (Department of Applied Ecology, University of Łódź). The first of the papers from Session III concerned the range of uncertainty in water management and identified problems of strategic rank. The Hippocratic Principle — "above all do no harm" — seems to me important because, in managing the resources of the aquatic ecosystem and real drainage basins we are dealing with a superorganism possessed of a certain capacity for homeostasis, resistance and flexible reaction. As docent Żelaziński has said, resistance is the basic criterion in the functioning of the system. It can be measured easily by reference to biological diversity or the load of biogenic compounds assimilated or entering or leaving the ecosystem. Parameters describing resistance must be specific to each ecosystem.

A question has also been raised as to whether we should share our uncertainty with those making the decisions. Here I would pick up on the polemic. On the first day, docent Żelaziński suggested that I overestimate the perceptive abilities of decisionmakers. Today I would like to say the same: you simply overestimate perceptive ability, and for this reason we cannot fully share our doubts with decisionmakers in every case. I would support this statement with a concrete example. Now at some time a consultancy proposed biofilters for the Sulejowski Reservoir at a cost of half a million dollars. I expressed my view that biofilters would not work because the reservoir was at too advanced a stage of eutrophication, and in addition because the biofilters would have been put in an inappropriate place. When questioned as to how I would propose to resolve the problem I replied that control over the biological processes in the reservoir was essential. The decisionmaker did not agree because I informed him about the scope of the necessary research. The money was spent, the biofilters were installed, but to this day they do not work and have not brought improvements in water quality.

A second example is also linked with attempts to improve the situation at the Sulejowski Reservoir. Those taking the decisions wanted to build 10–20 wastewater treatment plants. Each little village wanted its own plant. At the same time, the only solution for the effective reclamation of the reservoir was to reduce the influx of phosphorous compounds. The introduction

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of wastewaters from additional plants would have degraded the system entirely. The only way out was to construct sewerage and treatment plants below the Reservoir. This time there was no grey area of uncertainty and the decisionmakers were swayed by the arguments. Our uncertainty as to the course or processes is usually equal to something like 10 or 20%, while among the decisionmakers it often reaches 99%. Hence the negative effects of decisions may be multiplied.

The paper from docent Radwański brought into sharp relief the significant role of humankind in steering the macroscale processes responsible for climate change. It can be seen clearly that there are possibilities for positive action to limit the processes by which CO_2 is emitted. I think that one aspect of our role is to disseminate information in such a form that it indicates to society that the ones deciding the extent to which the people are to create their own future are the people themselves.

The next paper from professor Somorowski showed the extent to which demands for water may change in relation to the kind of strategy for the development of agriculture which Poland adopts. This is a very important factor which requires further study. The paper from docent Napiórkowski indicated precisely the extent to which scenarios for climatic change and demand for water may influence the functioning of reservoirs. Each definition of processes and phenomena — on the micro-, meso- and macroscales — brings us closer to the most effective advice that we can give decisionmakers and to the more efficient steering of water management.

Professor Z. Kaczmarek (Institute of Geophysics PAS)

I was co-creater of successive plans for water management which appeared in Poland in the 1960s, 1970s and 1980s. Before the end of the 1970s, the estimated demand for water in Poland in the year 2000 was at a level more or less twice as high as it will be in reality. This is also an element of uncertainty. I speak of this because Hydroprojekt, which prepared its plans for water management on this basis, did not treat these figures as uncertain, but took them as a starting point for its planning and decisionmaking. Well the effects are such that, for example, the Siemianówka and Jeziorsko Reservoirs were built unnecessarily. We have had to deal with the problem of uncertainty in water management for a long time, in fact for a lot longer than we have been discussing climate change and its influence on water resources and demand. It results from this discussion that water systems should be planned in such a way that they are resistant to disturbance. This would seem to be the most rational approach. However, as we do not know what conditions will be like in the future, then each solution less vulnerable to the assumptions adopted is more valuable.

Professor Cz. Somorowski (Agriculture Academy, Warsaw)

Water systems in agriculture have differing levels of immunity depending on whether changes are evolutionary or temporary. For example, in the

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development strategy we are to launch there will be a greater amount of permanent grassland and areas under grass than cultivated areas. Drought never occurs throughout the country but is shaped regionally and may be of differing duration. Uncertainty as to the effectiveness of our technical solutions in relation to the need for adaptation to the demand may be small, accounting for the specific features of the given user.

T. Rudzińska-Zapaśnik, M.Sc. (Polish Geological Institute)

The threats to the resources of surface and groundwater should be treated together with the intensification of pollution. How to prevent this is a challenge to water management in Poland. In addition, the safeguarding of the Baltic shore is a very important problem on account of the threat. The development of the natural retention of water and the building of reservoirs are among the most urgent problems, along with drastic limitations on the use of groundwaters in supply. At present about 50% of river and lake water is used. In the face of anticipated global changes in climate and the possible limitation of resources. groundwaters will be a fundamental source of supply, despite their limited renewability.

We are making excessive use of groundwaters and ever-deepening depression funnels are being created. As a result, some of the resources will be taken out of use. It will be necessary to move in the direction of the treatment and maximal utilization of surface waters, with groundwater resources being left for that time in which they will be the main source of supply to the populace. At present, Poland's deficit in water resources is of the order of 15%. Regionally, however, it may reach 75%. The areas of deficit need to be limited, because the deficit will only worsen in conditions of climatic change. One of the important conclusions to be drawn from the Conference concerns the need for society and decisionmakers to be made aware of the possible influence of global climatic change and of the different forms the uncertainties take.

Docent J. Żelaziński (Institute of Meteorology and Water Management)

The most recent amendment of the Water Law Statute confirmed the need for conditions for the use of water in a drainage basin to be drawn up. These are defined as a system of restrictions on the use of water in a given area, including permissible discharges, abstractions etc., as well as a strategy for investment programmes linked with the development or exploitation of the water resources in a basin. In legal terms, the conditions for the utilization of waters are treated as the basic instrument in the steering of water management. In seeking out research areas for scientific teams, it will be necessary to stress the need for the methods by which these conditions are set to be devised on the basis of the latest knowledge in the field, with account also being taken of scenarios for climatic change. The starting point should be the integration of meteorological and hydrological models on the mesoscale, e.g. for the Pilica basin.

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This is a basin with defined and definite problems which has been quite well-studied.

Up to now we have worked as if separated. Hydrology has expected data on precipitation, and sometimes on air temperature or other parameters, from meteorologists, but the interaction is a two-way one characterized by, for example, feedback during the recent floods. This reflects the fact that the majority of precipitation derives from the local water cycle and not from moisture coming in from over the sea. Pilot drainage basins, which would be verified with the aid of a hydrological model, would be a research tool. In using scenarios for global changes in climate and for socioeconomic development, we may generate sequences of programmes meeting future challenges and leading to the rational use of the waters in a drainage basin, i.e. a system of limitations on use and a certain vision of the way in which the system is to develop. If such a programme could be brought in and gain funding from the Committee for Scientific Research this would perhaps serve to integrate this scientific environment.

Professor Z. Kaczmarek (Institute of Geophysics PAS)

The central research planning of the past is well remembered by scientists, and it is a pity that it was abandoned. The present search for alternative forms has had better or worse consequences. I propose that the discussion be wound up and that we move to assumptions in regard to the National Climate Programme.

Docent J. Pruchnicki (Institute of Meteorology and Water Management)

In the last six years, several proposals for the establishment of a National Climate Programme have appeared. These became stuck in the Ministry of Environmental Protection at the opinion-giving stage. The main reason for the failure to implement these programmes was the accusation that proposals only took account of the nature-related aspects of climate change. It was suggested in successive proposals that the scope should not be confined to the study of the climate, its variability and its influence on different socioeconomic sectors, but should also include strategies by which to limit the consequences, i.e. adapt the economy to the changes. This complicated the construction of the programme because it entailed teams of an interdisciplinary nature, a high degree of coordination and results that might prove difficult to proceed with. A change in the position taken by the Ministry came in December last year, during consultations concerning a study on the adaptation of the economy in the face of climate change that had been prepared by the Institute of Environmental Protection, in cooperation with other national institutions.

It was established at that point that work should get underway on the preparation of a National Climate Programme as conceived at the aforementioned meeting. Professor Starkel undertook negotiations and discussions on the assumptions of the NCP at meetings of the "Global Change" Committee.

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These gave a positive reception to the NCP concept and comments in regard to directions of modification were made. A proposal as to the scope of the subject matter was forwarded to the Ministry where it for now remains stuck, as a result of changes in parliament and government, as well as in the Ministry itself. This signifies a postponement, but probably not a sidelining or shelving.

The new assumptions anticipate that the NCP will be effected at two levels: the first would include a strategic programme with a c. 30-year time frame, while the second would consider only the nearest 2–3 years. There would be a set of postulates and tasks to be implemented by various government departments and institutions as part of their statutory tasks and on the basis of their statutory resources. The National Climate Programme will take in 4 spheres. The first would coincide with the subject matter of the first day of the Conference, including as it would the construction of mesoscale models of climate change, the building and interpretation of scenarios, etc. The second sphere would involve assessment of the climate's influence on different socioeconomic sectors and ecosystems. The third would take in methods by which to adapt to climate change and the last would entail the application of climate-related information for the needs of the different socioeconomic sectors. The assumptions would be completed by the beginning of the coming year, and passed on to the Ministry of Environmental Protection, Natural Resources and Forestry and the Global Change Committee. Taking into account the time required to complete the procedures necessary to set up the Programme, it would seem that the coming year will be devoted to preparatory and programme-related discussions. In practice, it is likely to be in 1999 that we will be able to welcome the National Climate Programme into existence.

Professor Z. Kaczmarek (Institute of Geophysics PAS)

The Conference had two assumed aims. First, to present the results of the many scientific teams dealing with the issue of the influence of climate on water resources. In this we sought to facilitate contact between the teams working in this field and the exchange of information on the results of this research. The second aim was to define a programme of work for the future. The organizing committee assumed that this would be an internal discussion within the given scientific circle. We did not foresee its direct use for the needs of decisionmaking bodies. Resulting from the papers and discussion are a series of important proposals concerning the future, especially of further research, education and methods and ways of proceeding in practice. The main proposals concerning research come down to two elements:

I. The search for such solutions in water management that would be useful and optimal irrespective of the climatic situation. The system for water management should be seen in the context of its resistance, especially to extreme situations. For water management mainly reveals its possibilities, or its weaknesses, in extreme situations — in the course of floods or droughts.

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If we are dealing with average conditions then we do not in general face more significant problems, other than the need to improve water quality.

II. Research into the processes ongoing in drainage basins should be undertaken. Study of the relationships between water resources and climatic conditions may be done irrespective of scenarios. Also, if we analyze the methodology of assessing agricultural demand for water, this may be done independently of the scenario of climate change, with variant climatic situations being studied in the particular situations.

I would like to express my heartfelt gratitude to all the authors who agreed to present work at the Conference, by preparing the papers that provided the basic content. I would also like to thank those taking part in the discussion. I consider it my very pleasant duty to thank professor M. Gutry-Korycka and Ms. M. Liszewska, who took the considerable organizational responsibilities upon themselves. Finally, many thanks go to all those present or absent, both authors and participants, for their participation.

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Conference Organizing Committee
Z. Kaczmarek, Chairman

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LIST OF PARTICIPANTS

CYBERSKI Jerzy, Prof., Institute of Oceanography, Gdańsk University

CZERNUSZENKO Włodzimierz, Prof., Institute of Geophysics PAS, Warsaw

DRUET Czesław, Prof., Institute of Oceanology PAS, Sopot

GRELA Jerzy, D.Eng., Institute of Meteorology and Water Management, Cracow

GUTRY-KORYCKA Małgorzata, Prof, Department of Hydrology, Faculty of Geography and Regional Studies, University of Warsaw

JAKUBIAK Bogumił, D. Eng., Interdisciplines Centrum of Mathematical and Computer Modelling, University of Warsaw

JANKOWSKI Jerzy, Prof., Institute of Geophysics PAS, Warsaw

JOKIEL Paweł, Docent, University of Łódź

JURAK Danuta, Docent, Institute of Meteorlogy and Water Management, Warsaw

KACZMAREK Zdzisław, Prof., Institute of Geophysics PAS, Warsaw

KIRWIEL Jan, Docent, Pedagogical Institute, Mińsk, Belarus; temporarily Faculty of Geography and Regional Studies, University of Warsaw

KOZŁOWSKI Antoni, M.Eng., Institute of Geophysics PAS, Warsaw

LISZEWSKA Małgorzata, M.Eng., Institute of Geophysics PAS, Warsaw

ŁOPATA Katarzyna, M.Sc., Faculty of Geography and Regional Studies, University of Warsaw

MIKULSKI Zdzisław, Prof., Faculty of Geography and Regional Studies, University of Warsaw

MITOSEK Henryk, Docent, Institute of Geophysics PAS, Warsaw

NAPIÓRKOWSKI Jarosław, Docent, Institute of Geophysics PAS, Warsaw

OLECKA Anna, M.Sc., Institute of Environmental Protection, Warsaw

OSUCH Marzena, M.Eng, Institute of Geophysics PAS, Warsaw

PIANKO-KLUCZYŃSKA Krystyna, M.Eng., Institute of Meteorology and Water Management, Warsaw

PRUCHNICKI Jerzy, Docent, Institute of Meteorology and Water Management, Warsaw

RADWAŃSKI Edward, Docent, Polish Foundation for Energy Efficiency, Warsaw

ROTNICKA Jadwiga, Docent, Department of Hydrology and Water Management, Institute of Physical Geography, Adam Mickiewicz University in Poznań

ROWIŃSKI Paweł, Doctor, Institute of Geophysics PAS, Warsaw

RUDZIŃSKA-ZAPAŚNIK Teresa, M.Sc., Polish Geological Institute, Warsaw

RUTKOWSKI Zbigniew, Msc.Eng., Institute of Meteorology and Water Management, Warsaw

RYLOV Alexei, Doctor, Institute of Environmental and Water Problems, Russian Academy of Sciences

SŁOTA Henryk, Prof., Institute of Meteorology and Water Management, Warsaw

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SADURSKI Andrzej, Docent, Polish Geological Institute, Warsaw
SOCZYŃSKA Urszula, Prof., Faculty of Geography and Regional Studies, University of Warsaw
SOMOROWSKI Czesław, Prof., Warsaw Agricultural University
STARKEL Leszek, Prof., Institute of Geography and Spatial Organization PAS, Cracow
STAROSTA Katarzyna, Doctor, Institute of Meteorology and Water Management, Warsaw
STRUPCZEWSKI Witold, Prof., Institute of Geophysics PAS, Warsaw
SZYMCZAK Tomasz, Doctor, Institute of Melioration and Grasslands in Falenty
TERLIKOWSKI Tomasz, Doctor, Institute of Geophysics PAS, Warsaw
WAGNER Iwona, M.Sc., Department of Applied Ecology, University of Łódź
ZALEWSKI Maciej, Prof., Department of Applied Ecology, University of Łódź
ZAWADZKA Jolanta, M.Eng., Institute of Geophysics PAS, Warsaw
ZIELIŃSKI Jan, Prof., Institute of Meteorology and Water Management, Warsaw
ŻELAZIŃSKI Janusz, Docent, Institute of Meteorology and Water Management, Warsaw

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All articles are reviewed and they are expected to be original and not yet published elsewhere unless in other languages than those stated above. Authors are responsible for submitting accurately-typed manuscripts.

Along with the two printed copies of the text please also submit on a computer disk in ASCII Code with possible export to ASCII Code with the name extension TXT, i.e. Data Base TXT. Enclose the Disk Specification Form.

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Presentation. The manuscript should be arranged in the following order of presentation. First sheet: title, name of author (authors), affiliation, full postal address, telephone, fax numbers. The same refers to all co-authors, if appropriate. Second sheet: Abstract of 100 words, Key words, 3–10. Subsequent sheets: Introduction, the text, conclusion (conclusions). Then on separate sheets: number one — acknowledgement (if desired); number two — notes; number three — references.

Appendices, tables, figures and captions to illustrations should also be given on separate sheets. Words or text passages should not be underlined.

Do not use indents. For paragraphs enter a line space. The main text may be organized in sections under appropriate headings without numerals.

All measurements should be given in metric units. Authors are expected to write as concisely as possible and avoid footnotes wherever possible.

References should be listed triple-spaced in one alphabetical sequence at the end of the text. Write name of author (authors), initials, date of publication, title, publisher and place of publication. If applicable, indicate pages reffered to. Names of journals should be abbreviated in accordance with the International List of Abbreviations.

References should be indicated in the text by giving, in parenthesis, the author's name followed by the data of the paper, publication or book, as (Smith 1992).

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