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EXTREME METEOROLOGICAL AND HYDROLOGICAL EVENTS IN POLAND

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CONTENTS

ARTICLES

PREFACE

JACEK A. JANIA and ZBIGNIEW W. KUNDZEWICZ

The present issue of *Geographia Polonica* reviews a sample of results obtained through implementation of the Integrated Project entitled ”Extreme meteorological and hydrological events in Poland (The evaluation of events and forecasting of their effects for the human environment)”. The project, launched by the Ministry of Science and Higher Education of the Republic of Poland in 2004, has as its aim an analysis and spatio-temporal assessment of main extreme meteorological and hydrological events in Poland, using all the available data within an interdisciplinary framework that relates to climatology, hydrology, oceanology, geomorphology, human geography and the economy. In the context of global-scale studies, it is very important that the relationships between extreme events in Poland and trends to ongoing climate changes be determined. The studies presented are devoted to a range of weather-related extremes, such as intense precipitation, floods, and geomorphic hazards like landslides and debris flow, storm surges, droughts and extreme winds, as well as the impacts of all of these on human existence (health and death hazards, economic damage). The major obstacle in conducting these scientific studies has been considerable difficulty with the accessing of basic observational data from the meteorological, hydrological and other stations run by governmental institutions. Recently, a better understanding of the importance of the problem of natural extremes by some governmental bodies in Poland has given cause for hope that the problem of the commercialised delivery of observational data for scientific and educational purposes can be resolved. Despite such major problems with access to complete (gap-free) series of data, especially in digital form, research work within the project framework is being continued with.

A milestone for the Integrated Project was the convening of a conference on “Extreme hydrometeorological events in Poland and their impacts—A European context” in Warsaw on 7–9 December 2006. This provided an opportunity for selected interim results from the project to be presented, and made subject to extensive discussion. The participation at the conference of speakers from other European countries made the forming of a broader perspective possible, allowing the Polish findings to be seen in the context of results from elsewhere, e.g. via projects funded by the European Commission, and global-scale considerations. Information on the subject matter of the conference may be found in Jania and Kundzewicz (2006). The event was organized by the Faculty of Earth Sciences, University of Silesia and the Institute of Geography and Spatial Organisation, Polish Academy of Sciences.

The present volume is a collection of individual contributions rather than a complete review of the project. The issue starts with a stage-setting contribution by Kundzewicz and Jania (2007), reviewing extreme hydrometeorological events and their impacts in a nutshell, on a range of scales (from the global down to the regional). In the next paper, Donker (2007) reviews the vital problem of access to, and the re-use of, environmental data in the public sector in European Union countries. This has been a problem of paramount importance in Poland. Indeed, a lack of affordable access to hydrometeorological data has jeopardized the attainability of the original objectives of the present Integrated Project. Next, Matczak *et al*. (2007) deal with the economic dimension by reviewing valuation of losses caused by extreme weather events, with particular emphasis on flood damages. Approaches based on restoration value and market value, and methods addressing indirect tangible losses and intangible damage are reviewed.

The subsequent ten papers are related to the analysis of observational records. The final three papers then deal with various aspects of mathematical modelling and forecasting.

A very important part of the study of extreme hydrometeorological events relates to the detection of changes in long time-series of observational data. Three papers, by Przybylak *et al.* (2007), Uscka-Kowalkowska *et al.* (2007) and Araźny *et al.* (2007) thus deal with extremes in such long time-series of meteorological variables extending between 1951 and 2005. Przybylak *et al.* (2007) seek changes in the index of climate extremes. Since Polish meteorological data were not available at affordable cost, the following two papers deal with the results of an NCEP/NCAR reanalysis carried out in the USA. The studies cover the region of Central Europe. Uscka-Kowalkowska *et al.* (2007) examine the variability to global solar radiation, while Araźny *et al.* (2007) study mean and extreme wind speeds.

Floods have continued to be a major weather-related hazard in Poland, with several destructive events having occurred even since the truly catastrophic deluge of July 1997. Łajczak (2007) examines the impact of human activity, and river training in particular, on the flood risk in the Upper Vistula River Basin, over a longer time-scale of a few centuries. Absalon *et al.* (2007) study the impacts of the anthropogenic modification of drainage basins on flood patterns. They consider the urbanised and industrialised areas of the Upper Silesia Industrial Region in the 19th and 20th centuries, with particular reference to the Kłodnica River Basin. Marosz (2007) sketches the methodological background to studies of historical floods in Gdansk (including events dating back to the pre-observational period), as well as the usage of GIS in analysing and reconstructing historical floods.

The further two papers examine droughts in parts of Poland. Judging by annual precipitation and the variability thereto, meteorological and hydrological droughts and low flows (streamflow droughts) are to be seen as frequent phenomena during which water availability may achieve extremely low values. Tomaszewski (2007) analyses temporal and spatial patterns to the hydrological droughts and low flows occurring in central Poland (in the basins of the Warta, the Pilica, and the Bzura). Ciepielowski and Kaznowska (2007) deal with recent hydrological droughts (2003–2005) in the Białowieża Primaeval Forest, the largest and most unique National Park in Poland.

The next two contributions deal with geomorphological hazards capable of being triggered by extreme rainfall events. Kotarba (2007) discusses geomorphological instability processes in the Tatra Mountains and compares them with the activity of debris flows in other high European mountains. Smolska (2007) reviews the geomorphological impact of extreme rainfall events in the Suwałki Lakeland (NE Poland), on the basis of soil-erosion measurements.

Two papers are devoted to aspects of mathematical modelling in the analysis of extremes and their impacts. Kundzewicz *et al.* (2007) review alternative approaches to the modelling of the impacts of hydrometeorological extremes, discussing such aspects as: model taxonomy, the trade-off between accuracy and complexity, uncertainty, and barriers relating to data (i.e. existence, accuracy, credibility and availability). Kowalewska-Kalkowska *et al.* (2007) present the application of the M3D_UG numerical model developed at the Institute of Oceanography, University of Gdańsk, to a *post-hoc* analysis of storm surges along the Polish (southern) Baltic coast.

The final paper, by Szwed *et al.* (2007) examines model-based projections of climate (weather) extremes in Poland, in relation to both intense precipitation and hot and dry spells. A comparison of model-based information for the control period (1961–1990) and for the future projection horizon (2070–2099) is made.

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EXTREME HYDRO-METEOROLOGICAL EVENTS AND THEIR IMPACTS. FROM THE GLOBAL DOWN TO THE REGIONAL SCALE

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Abstract: Despite the progress in technology, the risk of weather-related disasters has not been eradicated and never will be. On the global scale, disasters are becoming both more frequent and more destructive, annually causing material losses worth tens of billions of Euros, as well as several thousand fatalities. Furthermore, catastrophic weather events have been the subject of a rapid upward trend, with the value of material damage increasing by an order of magnitude over the last four decades, in inflation-adjusted monetary units. There is now an increasing body of evidence of ongoing planetary climate change (global warming), which has brought about considerable changes where extreme hydro-meteorological events are concerned, and is likely to lead to even more marked changes in the future. Typically, changes in extremes are more pronounced and exert more impact than changes in mean values. Among the extremes on the rise are the number of hot days and tropical nights; the duration and intensity of heatwaves; precipitation intensity (and resulting floods, landslides and mudflows); the frequency, length and severity of droughts; glacier and snow melt; tropical cyclone intensity and sea level and storm surges. In turn, a ubiquitous decrease in cold extremes (number of cool days and nights, and frost days) is projected. Increases in climate extremes associated with climate change are likely to cause physical damage and population displacement, as well as having adverse effects on food production and the availability and quality of fresh water. A discussion of hydro-meteorological extremes and their impacts is therefore provided here in relation to a range of scales, and with the context for adaptation and mitigation also being alluded to.

Key words: extreme events; hydrometeorology; climate variability; climate change; climate change impacts

1. INTRODUCTION

It is normal that, at times, hydro-meteorological variables such as temperature of air, water or the ground; precipitation intensity or total; soil moisture; river flow; wind velocity; etc. attain extreme values. Such a situation may jeopardize people and their settlements.

Despite the fascinating progress in technology, humankind continues to live with the hazards of extreme hydrometeorological events, which may cause severe human and material damage. The risk of weather-related disasters has not been eradicated and never will be. In fact, on the global scale, disasters are becoming more frequent and more destructive, causing material losses of tens of billions of Euros, as well as several thousand fatalities annually. Catastrophic weather events have been exhibiting a rapid upward trend, increasing by an order of magnitude over the last four decades, when expressed in terms of inflation-adjusted monetary units.

There are several categories of factors that may explain changes in hydro-meteorological hazards, and their impacts. The principal categories of this kind are: (1) changes in the climate and atmospheric system; (2) changes in interactions between the atmosphere, the cryosphere and the oceans; (3) changes in terrestrial systems (e.g. land-cover change: urbanization and deforestation); (4) changes in socio-economic systems (e.g. land-use change, increases exposure and damages potential, changing risk perception). The relative importance of the above factors is site- and event-dependent.

The aim of this paper is to provide a short introduction to different aspects of the interrelationships between global climate changes and extreme meteorological and hydrological events and their impacts on the regional and local scales in Europe. Adaptation and mitigation attempts are also considered, with a special emphasis being put on the so-called “short memory syndrome” where severe extremes are concerned.

2. CLIMATE CHANGE AND ITS IMPACTS

There is an increasing body of evidence on the ongoing planetary climate change (global warming) being attributable to human activities and caused by rising emissions of greenhouse gases (carbon dioxide, methane, nitrous oxide, etc) leading to a buildup of the said gases in the atmosphere and consequent enhancement of the greenhouse effect, and causing land-use changes (e.g. deforestation in tropical areas reducing carbon sequestration). The global climate system has been driven out of its stable natural variability mode. As stated in the IPCC Fourth Assessment Report (IPCC, 2007), most of the observed increase in globally averaged temperatures since the mid-20th century is *very likely* (with a probability of over 90%) due to the observed increase in anthropogenic greenhouse gas concentrations.

The 1990s are likely to have been the warmest decade and the 20th century increase in temperature is likely to have been the largest occurring in any century over the second Millennium in the Northern Hemisphere (Watson and Core Writing Team, 2001).

Twelve of the thirteen warmest years globally in the 158-year global instrumental temperature observation period occurred in the recent twelve years (see Table 1).

Only one of the last 13 years (1996) did not make it on to the list of the top twelve hottest years. It was the 19th warmest year, still warmer by 0.137°C than the 1961–1990 mean global temperature (cf. Table 1). The year 2007 also belongs to the short list of globally warmest years (rank 8). Future warming will depend on scenarios of socio-economic development and on the mitigation policy (the curbing of greenhouse gas emissions). Projected temperature changes differ regionally, being scenario- and model-specific, with the range of global mean temperature increase for the 2090s horizon being likely from 1.0 to 6.3°C above the control period 1980–1999 (IPCC, 2007).

Beside the temperature change, there have been ongoing changes in other climate-related variables, such as sea level, precipitation (growth in some areas, decrease in other areas of the globe), river discharge, soil moisture, glacier and snow cover extents. Even more marked changes are projected for the future. Projected precipitation changes differ regionally, but are loaded with a high level of uncertainty, being model- and scenario-specific.

Table 1. Ranking of years with highest global mean annual temperature since 1860.

Ranking of particular years with the highest global mean temperature since 1860	Year	Deviation from the long-term mean temperature (in the reference period 1961–1990)
1	1998	0.546
2	2005	0.482
3	2003	0.473
4	2002	0.464
5	2004	0.447
6	2006	0.422
7	2001	0.409
8	2007	0.403
9	1997	0.351
10	1999	0.296
11	1995	0.275
12	2000	0.270
13	1990	0.254
14	1991	0.212
15	1988	0.180
16	1987	0.179
17	1983	0.177
18	1994	0.171
19	1996	0.137

Data source: Jones (2007).

It is important to note that the Arctic system is very sensitive to climate change. Even when account is taken of the fact that the system is not located close to the territory of Poland, climate-cryosphere interactions play an important role in driving climatic changes on the global and European scales. Moreover, traditionally, Polish scientists have been active in studying the Arctic system, and their achievements are visible in the international context.

There are several important (positive) feedback mechanisms in the Polar/Arctic track in the climate system (ACIA, 2005):

- positive albedo feedback; a decrease in snow-cover area, and sea ice extent and a retreat of glaciers affect albedo on the global scale, hence reducing the reflected part of solar radiation and driving warming;
- positive methane feedback; a thawing of permafrost leads to the release of large volumes of methane (a powerful greenhouse gas), these having been previously immobilized in the frozen ground.

In addition, a dynamic response of tidewater glaciers to climatic (and sea) warming is caused by increased melting of their surface. Faster flow of glaciers induced by greater meltwater supply to their beds results in massive calving and faster transfer of ice resting previously on land into the sea. Such processes are responsible for more distinct sea-level rise. Substantial loss of mass due to melting and ice transfer into the sea from the Svalbard glaciers (Jania, 2002) and other Arctic areas has been noted during the last two decades. While global sea rise 2 mm/yr was reported over the 40 years at the end of the last century (Cabanes *et al*, 2001), the contribution due to glaciers was of the order of 0.2–0.4 mm/yr through the whole 20th century (ACIA, 2005). In this respect a special role has been played by the Greenland Ice Sheet—the largest ice mass in the Northern Hemisphere. Recently published studies

(Dowdeswell, 2006; Rignot and Kanagaratnam, 2006; Stearns and Hamilton, 2006) suggest that the ice sheet responds more rapidly to climate warming than previously thought, particularly by way of accelerated flow of several large outlet glaciers draining the southern part of the ice sheet. Extreme acceleration of Greenland ice-mass loss has been noted by the satellite gravity survey for the period April 2002–April 2006. A transfer of 248±36 km^3/yr of ice to the sea has been detected, and constitutes an equivalent contribution of 0.5±0.1 mm/yr to global sea-level rise (Velicogna and Wahr, 2006). The level of the contribution is ten times greater than that estimated earlier for the whole Arctic. More intense melting and accelerated glacier flow doubled the mass balance deficit of the Greenland Ice Sheet during the last decade, contributing to global sea-level rise and likely to be subject to intensification. In consequence, low-lying seashore zones will be affected more frequently and widely by storm surges.

In the longer term, a slowdown of thermohaline circulation is likely to partly compensate for further warming (ACIA, 2005). These processes operate in the North Atlantic area and influence the climate of Europe, indirectly stimulating extreme events in remote regions. Such linkages (tele-connections) are a good example of interactions between global warming and regional consequences and, in turn, show how the influence of processes observed in the Arctic on a regional scale risks increases the range of extreme events worldwide.

3. EXTREMES AND THEIR IMPACTS——THE GLOBAL SCALE

Ongoing climatic and non-climatic changes have already influenced environmental conditions on a global scale (and more specifically water resources) in a discernible way. Even more marked changes are projected for the future. The most certain impacts of climate change on freshwater systems are due to increases in temperature, sea level and precipitation variability. Where changes in temperature produce changes in the timing of streamflow, climate change effects are generally more marked than in areas in which hydrological regimes are more sensitive to changes in precipitation. There are generally consistent patterns to changes in runoff and water availability, with an increase at higher latitudes and in some wet tropical areas, and a decrease at mid-latitudes and in the dry tropics. Climate change may cause increased summer drying in continental interiors. Semi-arid and arid areas are particularly exposed to the impacts of climate change on freshwater. The area of the Earth's surface with a “very dry” status has been increasing and is projected to increase further. The global water cycle has accelerated, with consequences for extremes. In many areas there has been an increase in intense precipitation which can be translated into an increase in the flood hazard (Kundzewicz *et al.*, 2007).

Global warming has brought about considerable changes in extreme hydro-meteorological events and is likely to lead to even more major changes in the future. As a result, several extremes will become yet more extreme. For instance, many presently dry areas are likely to become drier, while those that are now wet may become wetter. As a rule, changes in extremes are more pronounced and exert more impact than changes in mean levels.

It can be expected that, in the warmer climate of the future, there will be a ubiquitous decrease in cold extremes (number of cool days / nights / frost days). It is projected that many areas will witness increases in extremes as regards the number of hot days and tropical nights; the duration of heat-waves; precipitation intensity; the frequency, length and severity of droughts; glacier and snow melt and tropical cyclone intensity (IPCC, 2007). Non-tropical cyclones and the most intense storms may also increase, while storm tracks may shift more poleward. Impacts on air quality are likely. Stagnation of air masses in the summer may exacerbate air pollution problems (ozone and particulate matter—soot, with cardiac and respiratory hazards), which will accumulate until a cleansing cold front comes.

Any regional increases in climate extremes (storms, floods, cyclones, droughts, etc.) associated with climate change are likely to cause physical damage, population displacement, and adverse effects on the economy of food production, freshwater availability and quality. Growing adverse health effects would include the risks of infectious disease epidemics in developing countries. It is estimated that diarrhoeal diseases attributable to unsafe water and a lack of basic sanitation already cause numerous (nearly 2 million) deaths a year worldwide. The projected increase in the frequency and severity of droughts would exacerbate the situation and exert an adverse impact on human health.

The consequences of globalization should be appreciated. As a result of the global village effect, the number of Swedish citizens (mostly Christmas tourists) killed by the tsunami disaster of December 2004 in the Indian Ocean coasts greatly exceeded the number of fatalities caused by all the natural disasters within Sweden over many decades. Polish citizens were likewise among the fatalities caused by the forest fires during the droughts in France in 2003 and in Greece in 2007.

4. EUROPEAN, REGIONAL AND SUB-REGIONAL SCALES

Europe has warmed up considerably, especially in the last few decades, and further, stronger, warming is projected for the future by climate models. The European Commission's perspective is focused on the juxtaposition of two scenarios: a controlled (around 2°C) warming by 2100 if global mitigation policy becomes effective, and a very much stronger (possibly 5°C) warming, if a business-as-usual approach prevails and atmospheric concentrations of greenhouse gases keep growing without effective mitigation.

Long-term precipitation trends have also been observed, and are projected for the future, in many regions of Europe. Mean annual precipitation is likely to decrease over much of Europe (in particular, over Southern and Central Europe). In much of Southern Europe, a joint effect of temperature rise and a decline in precipitation is foreseen for the summer. Global warming contributes to heat stress and more drying (evaporative demand), exacerbating water stress. The risk of drought increases substantially in summer, along with the risk of wildfires.

Mean annual precipitation is likely to increase in northern Europe. However, the intensity of rainfall events is projected to increase even in regions in which the mean annual precipitation is likely to decrease (cf. Kundzewicz *et al.*, 2006).

Extremely heavy and/or long-lasting rainfall events cause geomorphic hazards such as landslides and mud-debris flows in the mountains. The geological structure and lithological composition of the Polish Carpathians are favorable for development of landslides. More than 95% of all registered landslides in Poland are located in the Flysch Carpathians and, statistically, they are as dense as one form per 1 km^2. While the majority of landslides in the Carpathians occurred during the Pleistocene, the Late Glacial and the early and middle Holocene (Alexandrowicz, 1977; Margielewski, 2001), a reactivation of many of them and a creation of new forms during the last decade have been observed. Deforestation of mountain slopes and their cultivation (in cereal- and potato-growing) created favourable conditions for water infiltration into slope-cover, mantle and bedrock. Due to an increase in the number of extreme rainfall events, a rejuvenation of older forms and occurrence of new landslides has been observed since 1996 (Rączkowski and Mrozek, 2002, Starkel, 2006). Large proportions of the landslide events are associated with regional and local flood events in the area, like those in 1997, 2000, 2001, 2002 and 2005.

One of the most catastrophic landslides affected an area of 15 ha in Lachowice village in the Beskid Makowski range. Rapid displacement of slope-cover masses destroyed 14 buildings and a road during just

15 minutes on 27 July 2001. The eastern part of this landslide was reactivated again a year later and additional 4 buildings were affected then. Damage caused to buildings and roads by landslides in Małopolskie Voivodship had a value in excess of 173 million PLN (43 million Euro) in the years 2000–2001. Extremely heavy rainfall in summer 2002 again activated many landslide forms, though it concentrated its downpour in the town of Muszyna and its surroundings, causing large mud and debris flows. These damaged up to 100 buildings there (Bejgier-Kowalska, 2005).

It is worth stressing here that a large part of the material damage caused by slope mass movements in the Flysch Carpathians is co-induced by the location of new, larger and heavier brick and concrete buildings on old landslide slopes. Excavations on slopes for constructional purposes and their undercutting near the valley floor as the construction or modernization of roads takes place destabilize the slopes. Particular landslides and mudflows are damaging phenomena of relatively limited extent in comparison with floods. Nevertheless, their density in the Carpathians shows the importance of severe local events whose frequency grows with global climate change and the more frequent occurrence of extreme rainfall.

Warming leads to changes in the seasonality of river discharge in catchments in which much winter precipitation falls as snow (e.g. in the Alps). Winter flows increase, while snowmelt occurs faster and earlier (with peak flows coming earlier). There is less snow pack in spring and less soil moisture in summer, and summer and autumn flows decrease. The ongoing reduction of European glaciers will lead to gradual longer-term decreases in the contribution glaciers make to river discharge (with the possibility of a river flow increase in the short term, including flooding due to rapid melt). Similar phenomena have been observed in the majority of glacierized high mountains over the Northern Hemisphere. As decreasing groundwater recharge is projected over many areas, also in already water-stressed regions, the possibility of offsetting declining surface water availability due to increasing precipitation variability may not prove a practical one. Sea-level rise will extend areas of salinization of groundwater and estuaries, resulting in a decrease in the availability of fresh water for both people and ecosystems (Kundzewicz *et al.*, 2007). In many places, winter precipitation is increasingly likely to fall as rain, rather than snow. This may jeopardize winter sports, especially in lower skiing domains.

In much of Europe, occurrences of very wet winters and of intense rainfall events will become more frequent, with likely consequences as regards flood risk. Increasing temperature and variability of runoff are likely to lead to adverse changes in water quality (turbidity increases, algal blooms, mobilizing and washing away of pollutants, favouring of pathogens, and thermal pollution).

Very severe material flood damage (above 20 billion Euros in value) was noted on the European continent in 2002, considerably exceeding records for any single year before. The floods in Central Europe in August 2002 alone (on the rivers Danube, Labe/Elbe and their tributaries) caused damage exceeding 15 billion Euros in value. Only a year later, the summer (June to mid-August period) of 2003 brought a disastrous heatwave and drought across large parts of Europe, with temperatures exceeding the averages even by 3–5°C and annual precipitation deficits of up to 300 mm, with the result being an estimated reduction of 30% over Europe in gross primary production of terrestrial ecosystems (Ciais *et al.*, 2005). The hot and dry conditions led to many very large wildfires. Many major rivers (in particular in southern Europe) were at record low levels, resulting in a disruption of irrigation and a cooling of power plants.

The 2003 European heatwave killed tens of thousands of people (Koppe *et al.*, 2004), showing that even developed countries may not be adequately prepared to cope with extreme heat. Such extreme events are usually amplified in large urban areas due to the heat-island effect (caused by heat absorption in asphalt, concrete and building roof surfaces). Heatwaves in Poland are not yet perceived as a major disaster in the public health perspective, yet one can expect that they will increasingly become a hazard in conditions of a warming climate combined with an ageing society. Systematic studies on the influence of heat waves on the health of the urban dwellers in Poland have been initiated (e.g. Kuchcik, 2003). Summer 2006 in Poland was warmer than that of 2003 (when temperature records were broken in much of Europe) and in much of Poland, July 2006 was the warmest month in the history of observations.

Severe heatwaves in the Mediterranean region and SE Europe, often with temperatures exceeding 40°C, occurred during the summer of 2007. Usually, at least one serious heatwave occurs in Greece each summer (typically in August). However, in 2007, three such heatwaves struck the Balkan area, causing at least 700 additional deaths. Hungarian medical officials reported up to 500 heat-related fatalities across Hungary in the second half of July 2007.

Drought and heat frequently go together with wildfires, and these occurred in many places in south-eastern Europe in the summer of 2007 (Fig. 1). In Greece alone, over 3,000 wildfires were registered, causing damage to forests, pastures and farmland, and producing a loss of up to 80 lives. At least 10,000 farms were destroyed or seriously damaged. Thousands of villagers were left homeless. Fire and smoke endangered settlements and summer holiday resorts in Greece, Bulgaria, Albania and even France. Greek citizens and foreign visitors questioned the state's ability to cope with extremes. Summer months—usually a time for leisure for tourists—became a period of horror and traumatic experience.

Severe summer droughts have occurred a number of times in Poland in the last decades (e.g. in 1992 and 2006), often accompanied by violent wildfires claiming human lives.

The occurrence of a heatwave as extreme as that of summer 2003 over much of Europe would be unlikely in the absence of anthropogenic climate change (IPCC, 2007). However, an individual extreme event, such as an extreme flood or a heatwave, can never be directly attributed to climate change. What it is fair to state is that the probability of such an extreme event of a given intensity (magnitude) is likely to increase in the future. Hence, the excess deaths caused by a heatwave can be linked indirectly with climate change. An increase in the frequency or intensity of heatwaves in the future warming climate will increase the risk of mortality and morbidity, particularly in older age groups (sick people, lonely people), and among the urban poor.

Gales, the disasters causing the largest insured material damage, play havoc with northern and western Europe, at times combining with coastal flooding. The storm of 8 January 2005 blew down 75 million m^3 of trees in southern Sweden, breaking the all-time record. In Sweden, nearly 350,000 homes lost power and the problems persisted over a longer time, as about 10,000 homes were still without power after three weeks (Wikipedia, 2006). The death toll in Scandinavia was at least 17. Only a few days later, there was another gale across the north of the British Isles, with windspeeds of up to nearly 200 km/h, attendant fatalities and major socio-economic disruption (disrupted power supply, paralysed transport).

Gales in Poland are less frequent. However, gradual sea-level rise with superimposed storm surges is projected to cause more frequent inundations in the area of the Baltic mouths of Polish rivers. Following the beginning of the verified observation series in 1950/51, the probability of storm-surge flooding about doubled towards the end of the 20th century (Sztobryn *et al.*, 2005).

Sea-level rise and storminess are very important for the erosion of coasts and potential damage to the near-shore infrastructure. Displacements of the Polish shoreline measured in the period 1875–1979 show erosion along almost the complete length, except in the Gulf of Gdańsk segment. More intense erosion is predicted for the entire Polish

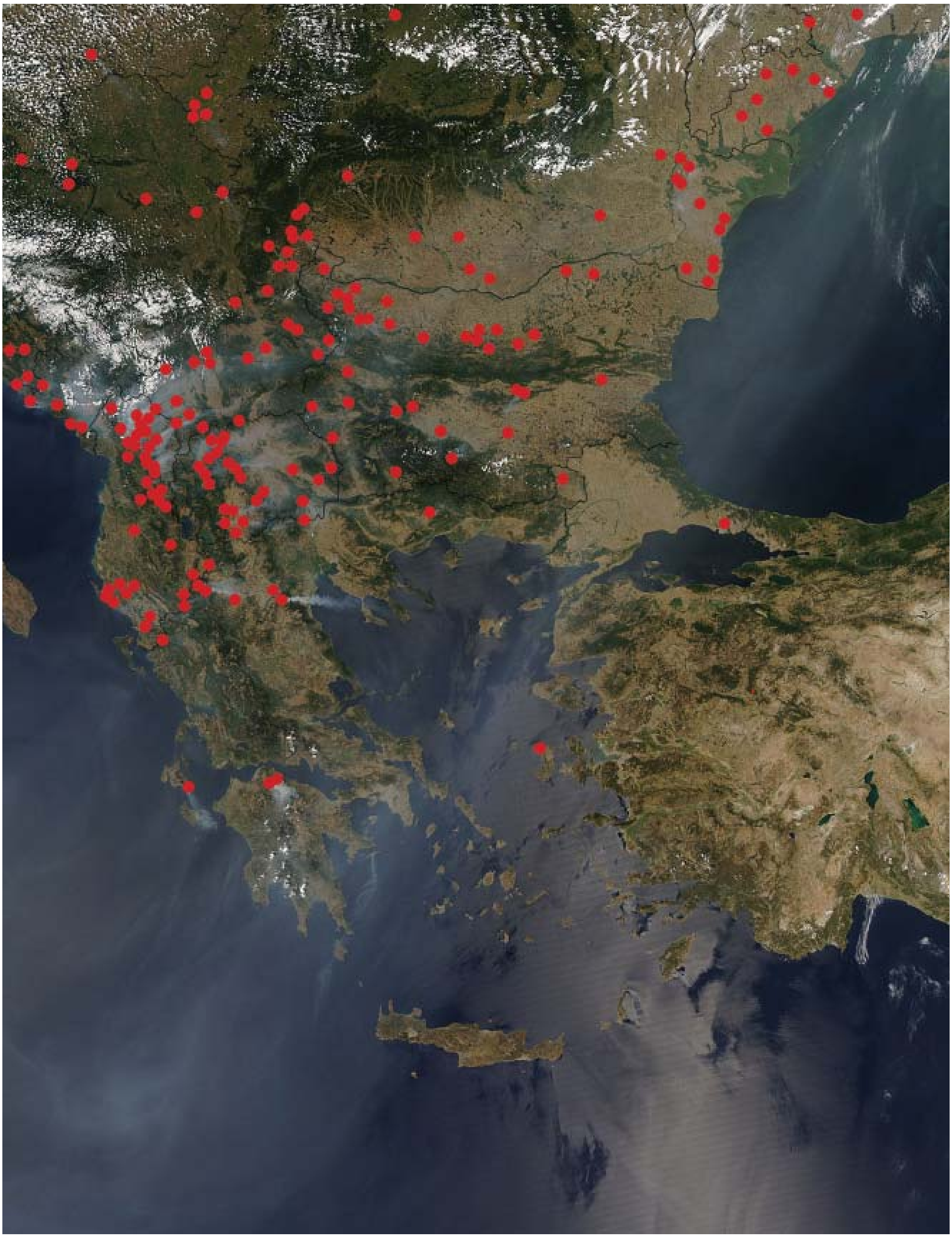

Figure 1. Wildfires (red dots) in the Southern Balkan region recorded on the MODIS satellite image taken on 25 July 2007 (© NASA, Visible Earth).

Table 2. Erosion risk on the Baltic coast of Poland and its prediction to 2050

	Distance along the coast[1]	Erosion rate in the period 1875–1979 (sea level rise by 2 mm/yr)		Prediction to 2050 (expected sea level rise by 6 mm/yr)	
Regions and sub-regions of the coast	(km)	Rate of shoreline position change[2] m/yr	Erosion vulnerability classes	Rate of shoreline position change m/yr	Erosion vulnerability classes
Gulf of Gdańsk					
Vistula Lagoon bar	0.0–29.0	+0.15	low	-0.12	low
Wisła Przekop–Władysławowo	48.5–124.0	+0.11	low	-0.08	low
Hel Peninsula					
Gulfward shore	H36.0–71.5	-0.21	low	-0.30	medium
Open sea shore	H0.0–36.0	-0.46	medium	-0.64	medium
Open sea					
Karwieńska bar	134–144	-0.42	medium	-0.59	medium
Piaśnica–Sarbsko Lake bar	149–181.5	-0.66	medium	-0.93	medium
Sarbsko Lake bar–Gardno Lake bar	181.5–216	-0.91	medium	-1.27	high
Rowy–Ustka	217–233	-1.33	high	-1.86	high
Ustka W–Wicko Lake bar–Kopań Lake bar–Darłowo	233–270	-0.37	medium	-0.52	medium
Bukowo Lake bar–Jamno Lake bar	278–300	-0.42	medium	-0.59	medium
Ustronie Morskie–Dźwirzyno	319–345	-0.45	medium	-0.63	medium
Mrzeżyno–Dziwnów	352–386	-0.38	medium	-0.53	medium
Wolin cliff–Pomorska Bay	401–424	-0.47	medium	-0.66	medium

[1] beginning at the Polish-Russian border (except for the Hel Peninsula)

[2] max. values for shoreline length segments ≥ 2 km

(after Dubrawski and Zawadzka-Kahlau, 2006)

coast in future (Table 2), as a consequence of more rapid further sea-level rise.

Shore erosion, as a consequence of more frequent winter storm surges along the Polish coast, results in the shrinking of the beautiful sandy beaches available for tourists. Therefore, this process could slowly affect the attractiveness of the Baltic beaches in Poland, counteracting the positive effect of increasing temperature.

Despite the warming climate, the main killer among hydro-meteorological events in Poland remains the cold snap in winter, during which many people (some of them homeless and drunk) freeze to death. According to data assembled by CRED (2006), the 2005/6 winter killed 233, while the 2001/2 winter killed 270 people in Poland.

Fewer fatalities but far greater material damage in Poland have resulted from floods. The 1997 flood was indeed an extreme event. Four issues of the principal and most influential weekly magazine POLITYKA had flood-related cover stories (Fig. 2). Such media attention has been without precedent in Polish history. This illustrates the severity of impact of the 1997 flood (55 fatalities, 162,500 affected people and over $ 4 billion in material damage). The floods in 1998, 2001, 2002 and 2005 also caused fatalities and affected thousands of people.

5. WHAT CAN BE DONE? ADAPTATION AND MITIGATION

A working definition of adaptation based on the one accepted in the IPCC process is: adjustment in natural or human systems in response to actual or expected changes,

Figure 2. The July 1997 flood attracted massive media interest.

which moderates harm or exploits beneficial opportunities. The taxonomy of adaptation distinguishes classification into adaptation types (dichotomies), such as: anticipatory (proactive; adaptation to ongoing changes) or reactive (to projected changes); autonomous (spontaneous) or planned; private / public, etc.

The capacity to adapt varies greatly across regions, societies and gender and income groups (differences reflecting a number of factors, such as wealth, housing quality and location, level of education, mobility etc.). Enhanced adaptability is needed, i.e. an increase in the system's coping capacity and coping range (cf. Kundzewicz, 2007).

There can be limits to adaptation (physical, economic, socio-political, or institutional). Barriers to adaptation to floods via relocation can be external, reflecting e.g. a lack of land for relocation, as in Bangladesh; or internal, including an unwillingness on the part of people to relocate (Kundzewicz *et al.*, 2007).

Both mitigation of (the causes of) climate change and adaptation to (the effects of) climate change are needed to avert or reduce adverse impacts. Adaptation strategies can reduce vulnerability to changes in climate at the local and regional levels. Mitigation acts at a global level over longer time scales due to the inertia of the climate system, slowing the rate of climate change and thus delaying the occurrence of impact and its magnitude. Most of the benefits of mitigation will not be obtained until several decades later, thus adaptation is needed to address near-future impacts. However, without mitigation, the increasing magnitude of climate change will significantly diminish the effectiveness of adaptation.

Mitigation of climate change and adaptation to climate change and its impacts are sometimes in conflict. For instance, desalination serves adaptation, but requires a high energy input, hence adversely affecting mitigation—it drives the atmospheric greenhouse gas concentration and warming. Afforestation serves mitigation (carbon sequestration) but may play an adverse role where adaptation in some regions is concerned (due to transpiration of large amounts of increasingly precious water). Enhancing water storage in reservoirs brings co-benefits, being advantageous for both mitigation (hydropower without fossil-fuel burning) and adaptation (weakening hydrological extremes—floods and droughts), cf. Kundzewicz *et al.* (2007). Yet it may also have considerable disadvantages (barriers to fish migration, resettlement, etc).

In general, Europe has a high adaptation potential in socio-economic terms, due to its strong economies, high GDPs, stable growth, moderate changes in numbers of inhabitants, well-trained population with a capacity to migrate within the supranational organism of the European Union, and well-developed political, institutional and technological support systems. However, adaptation is generally limited in the cases of the natural systems. Equity issues also arise, since the more marginal and less wealthy areas (and groups of people within them) are less able to adapt (Kundzewicz *et al.*, 2007).

Many adaptation options address water-related problems exacerbated by climate change, in particular the increasing variability of water resources, i.e. increased frequency of occurrence of situations in which there is too little or too much water. Adaptation options for the former situation (too little water—water stress or drought) address (enhance) water supply by way of such measures as:

- the conjunctive use of surface water and groundwater;
- increased storage capacity for surface water, groundwater, and rain water;
- water transfer;
- the desalination of sea water;
- the removing of invasive non-native vegetation,

In turn, water demand may be addressed (reduced) by:

- improving the efficiency of agricultural water use (e.g. "more crop per drop"); in particular—irrigation;
- soil moisture conservation, e.g. through mulching;
- recycling water (e.g. the re-use of waste water after treatment);
- water-demand management through metering;
- promoting water-saving technologies;
- leak reduction;
- market-based instruments, e.g. water pricing;
- the re-allocation of water to high-value uses;
- awareness raising.

Adaptation to the latter situation (too much water; intense precipitation, flooding, landslides, erosion) addresses options aimed at reducing the load:

- enhanced implementation of structural/technical protection measures, such as dikes, relief channels, enhanced water storage;
- watershed management ("keeping water where it falls" and reducing surface runoff and erosion).

Resistance may in turn be increased by:

- flood forecasting and warning;
- regulation through planning, legislation, and zoning;
- flood insurance;
- the relocation of populations living in flood-risk areas;
- flood proofing on location;
- flood plain protection measures.

There are several adaptation strategies when it comes to coping with floods, these being labeled as: protect, accommodate, or retreat (relocate), cf. Kundzewicz (2007). Strategies for flood protection and management may modify either flood waters, or susceptibility to flood damage and the impact of flooding. The EU Floods Directive (Commission of European Communities, 2006) obliges EU Member Countries to prepare preliminary flood risk assessment ("taking into account long-term development including climate change"), and to develop flood risk maps and flood management plans. In some countries, such as the Netherlands and the UK, flood design values have been increased, based on early climate-change impact scenarios. In The Netherlands, measures to cope with an increase in design discharge from the Rhine from 15,000 to 16,000 m^3/s must be implemented by 2015, and it is planned that design discharge be increased to 18,000 m^3/s in the longer term, in order to maintain a high level of protection, including under conditions of climate change.

However, dedicated and consequent long-term disaster preparedness efforts are jeopardized by a prolonged absence of disaster. This effect can be called a short-memory syndrome. In hydrology, the vicious circle illustrated in Fig. 3 is sometimes called a hydro-illogical cycle. In many countries, the average time to the next large disaster is much longer than the duration of terms of office of elected authorities. Since a large hydrometeorological emergency is not very likely to happen during the short terms of office, the attention of decisionmakers is focused on more immediate, more burning (and more certain) needs.

Many potential current adaptations are consistent with the principle of sustainable development; that is, they can protect against both climate variability now and future climate change (this refers in particular to "no-regret" strategies—doing things that make sense anyway. It is always good to save energy and water). Improved adaptation to current climate variability would render societies better prepared to future climate change.

6. CONCLUDING REMARKS

Extreme meteorological and hydrological events affect human life and the environment on different spatial scales. As demonstrated in the paper, a majority of the extreme events have a direct effect locally (e.g. gales, storm surges, rain-induced local flooding, landslides and mudflows). Some extremes like heatwaves, droughts and major floods have impacts on a regional scale. Only ocean level rise and its consequences can be directly observed globally. Our knowledge of climate and environmental change on the global scale is based on millions of measurements made at particular locations, and observations of extreme events and their consequences on local and regional scales (Fig. 4). Extreme meteorological and hydrological

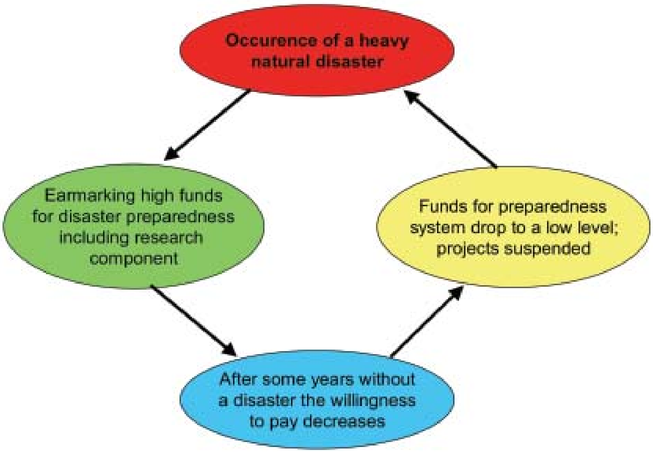

Figure 3. Illustration of the short memory syndrome related to natural disasters.

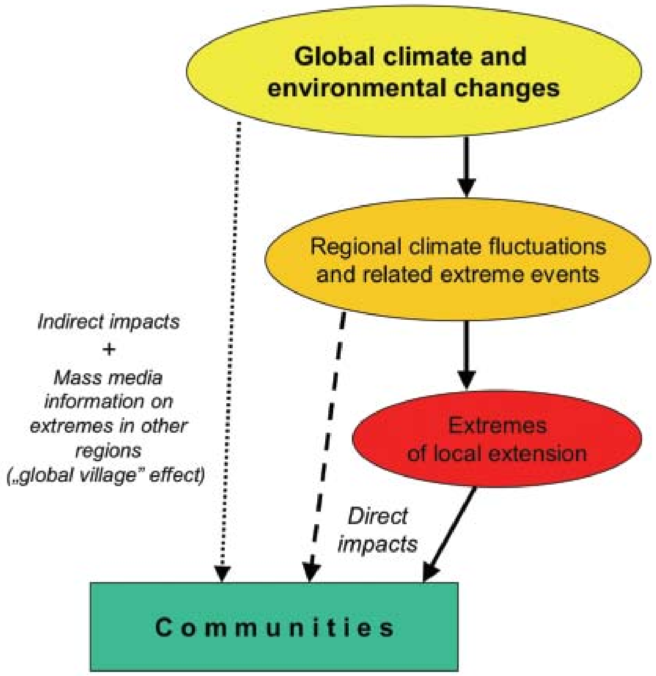

Figure 4. Mechanism of reduction of the short memory syndrome by direct and indirect impulses of impacts of the extreme events on communities with the importance of the mass media spreading information.

events with their impacts on human life conditions in public perceptions are considered a direct local experience.

The short memory syndrome influences the perspectives of local authorities and communities in particular areas. However, the media coverage of global and regional climate change enhances the awareness of threats caused by related extreme events. Timely dissemination of information on environmental disasters at different locations worldwide amplifies the societal effect of scientific reports on climate warming and its environmental consequences (e.g. IPCC, 2007).

The existence of short memory syndrome can also be observed among politicians and policymakers at the parliamentary and governmental levels. The theme of threats related to climate change and extreme events had not been not present in public political debates prior to elections in Poland.

Scientific evidence for global warming and associated extreme events has been built up as the ensemble of ground observations on a local and regional scale, combined with remote-sensing methods usually applied to supraregional areas. Positive and negative feedbacks of differing intensity and scale have been detected. Improved social awareness and understanding of such processes governing global-scale environmental changes—with a special emphasis on local and regional impacts—can help overcome short memory syndrome. In this context, the permanent care and attention of politicians, authorities at different levels and especially the mass media, devoted to information on the risk of hydrometeorological extremes is of special importance. This would create enhancing conditions for the adaptation of societies to ongoing and future climatic variability and change, preparing them to deal with extremes and to reduce their consequences.

ACKNOWLEDGEMENTS

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ACCESS TO AND RE-USE OF PUBLIC-SECTOR ENVIRONMENTAL DATA AND INFORMATION. POLICY DEVELOPMENTS WITH A FOCUS ON THE EUROPEAN HYDRO-METEOROLOGICAL SCENE

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Abstract: Thus far, the process of obtaining basic data and information from governmental agencies with a view to its being used in the information industry has seemingly been a troublesome and sometimes discouraging operation in most European countries. Re-users in both the public and private sectors are faced with extensive barriers reflecting increasing commercialization in the operations of government agencies, data protection, high license fees and a short-sighted appeal to profitability principles. However, a trend towards the provision of "free data" at delivery cost only now appears to be gaining currency both in society and with governments. It can be argued that "free data provision", unlike short-term cost recovery policies, will generate optimal socio-economic benefits. But "free data" in our digital era is one side of the picture. The other is that national governments will be forced to re-think their role in the information society, and last but not least in their relationship with the private information industry. Neither full public dominance nor a private monopoly seem optimal solutions from the societal viewpoint.

Key words: data re-use policy drivers, data protection, government commercialization, information society, digital era, creation of derived and new data sets, knowledge-based economies, socio-economic benefits, information industries, value-added information services, decline of cost recovery policies, European Commission Directives

INTRODUCTION

Weather, climate and water cycles know no national boundaries. Inevitably, international cooperation on a global scale is crucial to the development of meteorology and operational hydrology, and to any reaping of benefits from their applications there may be. Under the auspices of the World Meteorological Organization (WMO), established in 1950, as well as its predecessor, the International Meteorological Organization (IMO), established in 1873, member nations enjoyed worldwide unrestricted exchange of nationally collected data and information for over a century. This international collaboration survived World War II, the Cold War and many other conflicts, demonstrating that the WMO, as a specialized agency of the United Nations, is also an outstanding example of sustainable global cooperation. However, in line with various drivers, the tide has turned (mainly in the European Community) since the mid 1980s. Following the US example, the first EU-based private weather services have entered the European market. Almost all National (Hydro) Meteorological Services (N(H)MSs) responded by introducing competitive activity via their commercial arms, for reasons of protection. This was (and remains) in line with current political finding and views to the effect that "Public sector bodies must be required to utilize their own resources and operate in a way that ensures that they are not a burden to the tax-payer". The consequence is that most European N(H)MSs nowadays operate under the dual disciplines of the market and the budget. Such a hybrid foundation is not a stable one, lacks transparency, and puts (inter)national relationships under pressure.

By virtue of their national WMO Memberships, all European N(H)MSs exercise a monopoly on actual national and international data and information which are continuously exchanged through WMO telecommunications channels. This means that private entrepreneurs and other (semi) public entities depend fully on operational data provision through their N(H)MSs. For this reason a regulatory framework was created through ECOMET, established in 1995, a joint Economic Interest Grouping of European N(H)MSs.

Moreover all European nations are members of the European Centre for Medium Range Weather Forecasts (ECMWF, Reading, UK) and of the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT, Darmstadt, Germany) which produce very valuable data and information. The Member States are represented by their N(H)MSs and jointly settle the terms for data provisions to third parties. All this demonstrates the dominant position of the N(H)MSs.

National policies very much focused on cost recovery and the application of profitability principles are now putting severe pressure on re-users of data. As in the cases of many other kinds of public data assets (e.g. the spatial and geographical), government-commercialization raises significant obstacles. Thus far this has been a source of ongoing conflict between the public and private sectors, and in some countries even amongst public agencies themselves.

Last but not least, protective data policies regularly hamper the process of the creation of new knowledge unnecessarily. In this way, the further development of knowledge-based economies is discouraged. Overall, it can be concluded that most taxpayer-funded data in the EU have become underexploited, something that cannot be said to be beneficial for our societies as a whole.

Now, however—some 25 years later—we await radical policy changes in the near future. There is growing awareness at national and European administrative levels that publicly-funded data and information (e.g. statistics, land surveys, data on health, the environment, weather and climate) represent valuable public goods and resources. The socio-economic benefits to society are maximized when such data and information are made available freely, or at least inexpensively and as widely as possible. This "macro-approach" appears to be gaining currency among both the public and the policymakers, and one can observe that the cost recovery policies present in some countries are now in decline.

THE IMPORTANCE OF ACCESS TO AND THE RE-USE OF DATA FOR RESEARCH AND DEVELOPMENT

The atmospheric and hydrological sciences have progressed in the twentieth century towards a world-wide enterprise providing considerable benefits to individuals, business and governments. Through research and applications, these sciences provide information that contributes to the protection of life and property, economic and industrial vitality, management of air and water quantity and quality, national policies concerning energy and the environment, and so on. In our developed industrialized societies we count increasingly on reliable, factual information about the environment and many other issues. This is the lifeblood of all progress. A continuum of processing and interpretation is needed if goals are to be achieved, and we might distinguish the following consecutive phases and definitions (Resolving..., 2001)**:**

1) data—numerical quantities or other factual attributes derived from measurement, observation, experiment or calculation that lay the foundation of all research activities;

2) information—collected data assets and associated explanations, interpretations or other textual material (i.e. meta-data) concerning a particular object, event or process; (*Note from the author*: Both data and information are generally denoted in this paper as PSI: Public Sector Information)

3) knowledge—information, which is organized, synthesized or summarized to enhance comprehension, awareness or understanding;

4) understanding—possession of a clear and complete idea of the nature, significance or explanation of something. It is the power to render experience intelligible by ordering particulars under broad concepts

It is self-evident that obstacles and conflicts at the PSI foundation may have harmful impacts. This can be demonstrated by many examples like the discovery of the Antarctic Ozone Hole. Carver (1998) wrote:

“A dramatic loss of ozone in the lower stratosphere over Antarctica was first noticed in the 1980s by a research group from the British Antarctic Survey (BAS) that was monitoring the atmosphere using a network of ground-based instruments. The drop in ozone levels was so large that at first the meteorologists thought their instruments were faulty, although careful checks subsequently confirmed their measurements. Meanwhile, data from NASA’s Total Ozone Mapping Spectrometer (TOMS) satellite failed to show a similar decline. The BAS results spurred NASA scientists to re-examine the TOMS data, and they found that their algorithms had been set to eliminate data with extreme low ozone levels. NASA had been disregarding valid evidence for years. The reanalyzed TOMS data confirmed that the ozone loss first observed by the BAS was real and occurred over most of the Antarctic continent”

This lesson learned here is that discoveries in environmental science may go undetected, sometimes for many years, simply because they are unexpected. The only safeguard is constant vigilance and scrutiny of data and methods with a view to their being analyzed by as many scientists as possible. This is a particularly important reason for environmental scientists to anticipate full and open access to all environmental data upon which scientific interferences are based.

A free PSI policy for scientific researchers in both the public and private domains would have many benefits of kinds that may not always be valued in purely monetary terms, but which are surely helpful as we strive for socio-economic sustainability (*OECD*, 2006):

- interdisciplinary, inter-sector, inter-institutional and international research for the creation of new knowledge is promoted;
- expensive duplication of research is avoided, and new research and types thereof promoted;
- open scientific enquiry is reinforced and diversity of analysis and opinion encouraged;
- the verification of previous results is provided for;
- new or alternative hypotheses and methods of analysis can be tested for;
- studies on methods of data collection, measurement and calibration are supported;
- the education of new researchers is facilitated;
- the exploration of topics not envisioned by the initial investigators is provided for;
- the creation of new and derived datasets is permitted when multiple sources are combined;

- the building of research capacity in developing countries is promoted;
- a maximising of the research potential of new digital technologies and networks is facilitated, thereby providing greater returns from the public investment in research and education.

REGULATIONS AND RECENT POLICY INITIATIVES

WMO RESOLUTION 40 CG XII (1995)

WMO Resolution 40 was adopted in response to the onset of commerce in meteorology in Europe.

The resolution enshrines an understanding among WMO Member States that they will endorse the free and unrestricted exchange of data and products (*in situ* observations, data from satellites and models) for the official public duties of N(H)MSs, the legal tasks of other national public bodies (e.g. in defence) and (non-commercial) research. However, it includes a provision to the effect that an individual Member State may place restraints on the commercial re-use of data and products by thirds parties, unlike the application for public duties (cf. www.wmo.ch).

A two-tier classification of data and products was introduced:

- WMO Essential Data and Products: no conditions as regards use and re-use,
- WMO Additional Data and Products: conditions for commercial re-use generally expressed (apart from a recouping of delivery costs) in retribution for the creation of data, in other words a licence charge. Additional conditions and licence fees may also apply to e.g. broadcasting of derived value added services through TV and the internet.

Resolution 40 was initiated factually by the hybrid and "commercial" N(H)MSs in Europe. Outside the EU, criticism came from the USA and Japan, academia and the private sector all over the world. One fear is that Resolution 40 will not prevent cross-subsidies within the commercial N(H)MSs, the abuse of their dominant position and unequal treatment of the private sector. A major further deficit is that valuable data and products may be transferred from the free Essential Data Set to the Additional Set in order that revenues from PSI sales be boosted.

WMO RESOLUTION 25 CG XIII (1999)

A similar resolution was adopted for hydrological data to monitor and allocate water resources and assessments of the risks of floods and droughts. Under Resolution 25, a core set of data are freely available without conditions to use, while the remainder can be sold or restricted by the Member State that collected the data (cf. www.wmo.ch).

Some of the core data, such as river flow records, are available through the WMO Global Runoff Data Centre (Koblenz, Germany). However the Centre imposes three restrictions:

- the amount of data that can be requested is limited;
- users are not permitted to share the data with third parties;
- users must inform the Centre how data will be used.

It is generally understood by experts that the limiting of access to and re-use of all available hydrological data severely hampers scientists' ability to construct or validate global or regional models of the hydrological cycle, land-atmosphere interactions and biochemical cycles. Restricted PSI cannot be shared amongst colleagues, and this undermines the scientific practices upon which the research enterprise depends. Restrictions also create major inefficiencies in the PSI systems, because the same data and information must be collected by multiple organizations.

THE EC DATABASE DIRECTIVE 96/9/EC (1996)

It is common for N(H)MSs to claim a protective policy in their capacity as PSI holders. This is achieved via a doubtful and contestable appeal against the Database Directive of the European Parliament and of the Council of 11 March 1996 on the Legal Protection of Databases (cf.http://ec.europa.eu.prelex).

Indeed, this Directive was barely needed for private work though the growing understanding now is that it should not or even cannot apply to PSI, funded by the tax-payers. The key elements of the Directive are open to conflicting interpretations and controversy across the board (Hugenholz, 2001).

For example Article 10, Term of Protection, Para. 1 states: “The right provided for in Article 7 shall run from the date of the completion of the making of the database. It shall expire fifteen years from the first of January of the year following the date of completion”.

Following Para. 3 of this Article 10, any compiler who makes a database available to the public may continually renew the right for additional 15-year terms with every additional investment in or extension of the database. This renewal covers the content of the entire database, and not just the new matter.

All meteorological and hydrological data and *in situ* observations are collected in near real-time, and by consequence their archives are of a very dynamic nature with high refreshment rates. Compliance with this Directive would mean that meteorological and hydrological data never can or will be disseminated widely for free. Moreover, such compliance is in contradiction with more recent EC Directives which, on the contrary, encourage public access to, and the re-use of PSI.

THE EC GREEN PAPER (1999)

The Green Paper issued by the Commission of the European Communities in January 1999 comes to the conclusion that PSI is a key resource for Europe, and suggests that EU nations should more closely follow the model of US Federal Government policies with regard to promoting broader access to government databases (EC, 1998).

A few years after the Green Paper’s publication, additional developments took place, i.e. the transposition of more compelling EC Directives into the domestic legislation of EU Member States. Deadlines have been set for the review of implementation and evaluation.

DIRECTIVE 2003/4/EC ON THE PUBLIC ACCESS TO ENVIRONMENTAL INFORMATION

EC Directive 2003/4/EC (cf. http://ec.europa.eu.prelex) prescribes free public access without discrimination to public-sector environmental data and information, in order to increase public awareness as regards environmental matters. The Directive states that any natural and legal person has a right of access to updated information held by or for public authorities, without his having to state an interest. Explicitly, reference is made to the state of the elements of the environment such as air and atmosphere, water, soil and land, including environmental impact studies and risk assessments. Dissemination is recommended in particular through “electronic means” like the internet.

The Member States were expected to comply with the Directive by 15 February 2005, and not later than 14 February 2009, the Member States will report on the experiences gained in the application of the Directive.

An important “spin off” of this Directive for European citizens is the current proposal (COM 2006/15 final) of the European Parliament and of the Council on the assessment and management of floods in Europe.

DIRECTIVE 2003/98/EC ON THE RE-USE OF PUBLIC SECTOR INFORMATION

The PSI Directive (cf. http://ec.europa.eu.prelex) provides a general framework for re-use, i.e. use for commercial or non-commercial purposes other than the initial purpose within the public task for which the data or information were produced. However, the exchange of data and information between public sector bodies purely in pursuit of their public task does not constitute re-use within in the meaning of the Directive.

“Re-use of” includes more than “access to”. Thus the Directive provides for a minimum harmonization, imposes non-discrimination and equal treatment (especially regarding exclusive arrangements), seeks to prevent abuse of a dominant position (pricing) and cross-subsidies, and lays down transparency requirements. With regard to fair trading, it is emphasized in Article 10 that "if data and information are re-used by a public sector body as input for its commercial activities which fall outside the scope of its public tasks, the same charges and other conditions shall apply to the supply of the data and information for those activities as apply to other users".

An important aim is to remove the existing barriers for private entrepreneurs: "wider possibilities of re-using public sector information should inter alia allow European companies to exploit their potentials and contribute to economic growth and job creation." (Excerpt from Article 5).

The PSI holder may charge for creation, reproduction and dissemination, but the Directive recommends that public-sector bodies be encouraged to make PSI available at charges that do not exceed the marginal or incremental costs for reproduction and distribution (preamble 14). The Member States were expected to comply by 1 July 2005. The EC shall execute a review of the application before 1 July 2008 and shall communicate the results of this review, together with any proposals for modification to the European Parliament and the Council.

THE FORTHCOMING INSPIRE DIRECTIVE

The general situation on spatial information in Europe is one of fragmentation of datasets and sources, gaps in availability, lack of harmonization between datasets and formats at different geographical scales, and duplications of information collection. These problems make it difficult to identify and re-use the data that are available. Fortunately, awareness is growing at all levels of the need for quality geo-referenced information to support understanding of the complexity and interactions between human activities and environmental pressures and impacts. This ambitious Directive (cf. http://inspire.jrc.int) intends to trigger the creation of a European spatial information infrastructure that delivers integrated spatial information services to the users, in an inter-operable way and for a variety of applications. Possible services are the visualization of information layers, overlay of information from different sources, spatial and temporal analyses, etc. for the benefit of policy-makers, planners and managers at EU, national, and local levels, citizens and applicants in the private information industry.

While the international (hydro) meteorological community already meets many INSIPRE requirements by virtue of technical WMO regulations, new technologies can enhance exchange and representations of data and information in a different format for comprehensive operations and research. The Directive is still in the stage of conciliation. The Conciliation Committee accomplished its joint text (PE-CONS 3685/2006) on 17 January 2007. Currently implementation teams are commencing with their tasks.

SOCIO-ECONOMIC ASPECTS OF PSI

The vast economic potential of PSI has only recently begun to be recognized in the economic and public policy literature. With respect to the growing challenge from economists, the European Commission's Directorate General for the Information Society commissioned two studies.

THE PIRA STUDY (2000)

The PIRA Study (Lit. 12) attempted to quantify the economical potential of PSI in Europe, and the extent to which it is being exploited commercially, as well as to suggest policy initiatives and good practices. The study observed that the European PSI market would not even have to double in size for governments to more than recoup (in additional VAT receipts) what they would lose by ceasing to charge for (or license) PSI.

The amounts of money involved are significant. *PIRA* distinguished between government investment in PSI ("Investment Value") and the value added by users in the economy as a whole ("Economic Value"). Economic Value could not be obtained directly, so aggregated data were used. *PIRA* estimated the Investment Value for the entire European Union at 9.5 billion EURO/year. The Economic Value was estimated at 68 billion EURO/year. By comparison, the Investment Value for the USA is 19 and the Economic Value is 750 billion EURO/year.

Other *PIRA* conclusions are that:

- the pursuit and monitoring of protective PSI policies is expensive. Charging for PSI (in some countries even between public sector bodies and without any revenue for the Treasury) may be counter-productive, even from the short-term perspective of the raising of direct revenue from government agencies;
- Government should make PSI available in digital form at no more than the costs of dissemination or direct delivery to individual users;
- Governments experience two kinds of financial gain when they drop license charges:

(i) higher indirect tax revenue from higher sales of value-added products for which PSI served as "raw materials" and (ii) higher income tax revenue and lower social welfare payments form net gains in employment in information industries.

Due to the circumstances at that time, *PIRA* had to confine its estimates to a limited number of individual and promising in-depth studies (land survey, meteorology, publishers, patent & trade marks, business services). Consequently, the individual values of *PIRA* might be more robust, but the subsequent aggregated value is less so.

Nevertheless, the study should be sufficient to persuade policymakers of the need for a serious rethink of European PSI policy and its high priority.

THE *MEPSIR* STUDY (2006)

In the context of the preparations for the PSI Directive (2003/98/EC) an extensive study on Measuring European Public Sector Information Resources (*MEPSIR*, 2006) was undertaken by an international research consortium from November 2004 through April 2006. The main objectives were:

- to develop, document and test a repeatable methodology for measurement of PSI re-use;
- to perform a baseline measurement of PSI re-use in the EU Member States and Norway, including a comparison with the United States.

MEPSIR conducted the measurement in 25 Member States of the European Union and in Norway, and investigated the conditions of availability, accessibility, transparency, accountability, non-discrimination, actual demand and economic results in six main information domains, i.e. business, geographical, legal, social, transport, and meteorological/hydrological.

The economic results will eventually translate into direct results (more turnover and employment for PSI re-users) and indirect results (increasing commercial activity based on the re-use of PSI). Demand and economic performance were measured by directly asking both PSI-holders and re-users for key economic data under the current regimes.

This allows for the generating of estimates in billions of EUROs of:

- the overall European PSI markets based on estimates from respondents; the market size estimated between 26 (median) and 48 billion (upper limit) EUROs,
- the overall European PSI markets based on estimates of turnover (minus the data license charges) from Public Sector Information; the market seize was estimated between 12 (median) and 45 billion (upper limit) EUROs.

MEPSIR found an inverse correlation between the charges for PSI and the number of re-users: decreases in licence charges were more than offset by increases in the number of users seeing additional business opportunities.

A repeat of *MEPSIR* within a few years will most likely show a substantially increased overall PSI market potential, but with large spreading over market segments.

OBSERVATIONS

There are different practices among the European countries and a still imperfect understanding of the costs and benefits of making PSI freely available. Indeed, the issues are complex and are of a different nature in different fields: economic/financial, social/cultural, organisational/institutional, management, legal/regulatory and technological, although some are cross-cutting. This is still preventing the full exploitation of the potentials behind PSI.

Nevertheless, at the national and international levels, there are initiatives and new practices removing obstacles towards unhindered application of (hydro)meteorological data and information by users unlike the N(H)MSs.

- In most of the EU countries the initial licence charges have not risen over the past 10 years, or have been reduced in some cases;
- A growing number of N(H)MSs are transferring chargeable data assets to the free WMO Essential Data Set on a step by step basis (e.g. the United Kingdom, The Netherlands, Austria and Spain);
- The Norwegian Met. Service recently designated all data (in-situ observations, radar, models) as WMO Essential;
- Most newcomers to the EU doubt whether they should pursue a protective data policy;
- After much deliberation, the first licences for Internet dissemination of a "commercial sensitive" West-European Weather Radar Composite could be concluded (cf www.meteox.com).
- The ECMWF Council decided to simplify the licence conditions and reduced licence tariffs for the commercial re-use of global and regional atmospheric and oceanographic model output. It appeared in 2003 that more than 95% of the numerical weather prediction data used by the private sector in Europe originated from free sources in the USA (NOAA) and Japan. Meanwhile the visibility of ECMWF, a Centre of Excellence, improved remarkably and the number of licencees in and outside the EU has been growing.
- EUMETSAT is in the process of reducing license tariffs for Meteosat image data. Regulations and conditions will be simplified, and broadcasting of Meteosat image products through TV and the Internet will be encouraged.

Other observations indicate that PSI policy issues and private-public settings are beginning to move advantageously.

- PSI surely has value, but its pricing is precarious and seldom clearly explicable. Perhaps this clarifies the striking difference of N(H)Ms licence tariffs for the same data asset (e.g. the price of an WMO standardized in-situ observation).

The pricing and "selling" of publicly-funded data and information are more and more criticized from an economic point of view. Economic analyses show that not all goods can be transacted through markets readily. PSI, a public good, is created for collective consumption or production, rather than private consumption or production. Moreover, a public good is characterized by two attributes: non-depletability and non-excludability. Non-depletability means that the product in question cannot be used up and is available to additional persons. If (hydro)meteorological data are provided, the same data remain just as available as before for other users. Non-depletability is the main reason that free use of PSI can be justified: there is no additional social cost when another person uses it, and there is no justification for the disincentive to its use that is constituted by a substantial fee for that use. Non-excludabilty refers to the supplier side of the problem. It means that the goods in question produce benefits from which others cannot be excluded and which cannot be easily constrained only to those who pay (e.g. police services).

- Debate in the public-private arena is gradually shifting from data costs to competition issues. Several cases have been brought forward to National Competition Authorities and deal with unfair competition by commercial arms of some N(H)MSs which are believed not to pay in real money to the core for the re-use of data.

- Some N(H)MSs are willing to reduce their licence fees as far as possible, or even to zero. But they fear non-compensation by their National Treasury for the loss of revenue.
- Some N(H)MSs are in a process of formal separation of their public duties and commercial functions. One NMS achieved that in 1999 through full privatization.

CONCLUDING REFLECTIONS

There are indications that, in the near future, data policies and public private relationships in the European (hydro)meteorological arena will gain momentum, due to internal and external drivers. Ongoing policy considerations are likely to show that the benefits on the national and European scales due to open access and re-use far outweigh revenue that might be generated through cost-recovery policies.

Next developments in information and communications technologies will endure in a spectacular manner. It is difficult to imagine that, in this revolution, either N(H)MSs or the private sector can fully meet all the fast-growing demand present in society for information related to weather and climate. It is also difficult to imagine that restrictive data policies and all national conditions imposed on data re-use can be preserved or maintained through an unavoidable "digital dilemma". On the other hand, ICT will enable us to produce, disseminate or individually distribute data and information on a scale and with an efficiency unimaginable before.

The following statements related to the chain of data – information – knowledge – understanding, are proposed:

- Mixed public and private functions on one working floor and the "selling" of publicly funded data is not a sustainable solution for a government funding and a marketing problem;
- N(H)MSs should remain the (hydro) meteorological "conscience of the nation", the upright national centre and holder of authentic data and information and primary provider;
- Treasuries should not simply regard N(H)MSs as traditional budgetary "items of costs". In the emerging information era, N(H)MSs can seamlessly participate in the information industry, and generate benefits in an indirect way (e.g. tax revenues from value-adding information services);
- The Public-private relationship or perhaps duality must be fostered, but an understandable and sustainable balance will not be easy to achieve. However, the private sector or other applicants should not "pay twice" for the use of data from the N(H)MSs, while the public should not "pay twice" for the provision of all essential news and information related to weather and climate;
- Not the delusions of the day but the long term interest should prevail for all parties.

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ESTIMATION OF DAMAGE CAUSED BY EXTREME WEATHER EVENTS, WITH AN EMPHASIS ON FLOODS

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Abstract: Damage caused by extreme weather events is projected to increase on account of climate change. However, the assessment of losses is a weak point of the systems concerning preparedness for and management of weather extremes. Methods of *ex post* loss assessment are discussed here, with particular emphasis on floods. Approaches based on restoration value and market value are presented. Methods addressing indirect tangible losses and intangible damage are also reviewed. Restrictions and ambiguities connected with the methods are presented, and difficulties with data collection discussed.

Key words: Loss estimation, extreme weather events, floods, intangible damage, tangible damage

INTRODUCTION

Data provided by the insurance industry reveal that losses caused by weather-related catastrophes represent several tens of billions of USD per year on average, and have been increasing rapidly in recent years. The number of major flood disasters in the 1990s was greater than in the three and a half decades 1950–1985 taken together (Berz, 2001). Annual global economic losses brought about by major events have increased in value by an order of magnitude in four decades; from USD 4 billion in the 1950s to USD 40 billion per year in the 1990s (all in inflation-adjusted 1999 USD), cf. Vellinga *et al.* (2001). The insured portion of these losses rose even more strongly, from a negligible level to USD 9.2 billion annually between the 1950s and 1990s, with a significantly higher insured fraction in industrialized countries, while the ratio of premiums to catastrophe losses fell by two-thirds (Mills *et al.*, 2001). Inflation-adjusted economic losses due to catastrophic events increased 8-fold between the 1960s and 1990s, while insured losses increased 17-fold (Mills, 2005). Insured and total property losses (USD 45 billion and 107 billion in 2004, respectively) are rising faster than population growth, or economic growth. Between 1970 and 1999, weather-related losses (adjusted for inflation) grew at a rate nine times faster than the population. Over the 15 years at the end of the 20th century (Mills *et al.*, 2001), natural disasters caused damage worth about 1 trillion USD, three quarters of which was weather-related and a fifth—insured.

It is likely that such trends in the late 20th century were related to the frequency and / or intensity of several types of extreme weather event in the warming climate (IPCC, 2007). Among extremes on the rise have been heatwaves and large-area droughts. The frequency of heavy precipitation events (or the proportion of total rainfall accounted for by heavy falls) is likely to have increased over most areas, and is very likely to increase likewise in the future. Tropical cyclone activity is likely to have increased in some regions since the 1990s and is also likely to increase further in the 21st century. An increase in intense precipitation leads to a greater risk of rain-induced flooding. The latter effect will be exacerbated by increasing damage potential.

If the public policies by which disasters are to be coped with are to be planned, the measurement of losses is an important issue, since it helps in the evaluation of public expenditure within the cost-benefit framework. Implementation of any adaptation or mitigation measures involves a policy process, and requires economic analysis of costs and benefits.

Notwithstanding their importance, assessments of the impacts of climate change are only poorly developed (Feyen *et al.*, 2006). Insurers have developed methods of loss assessment, but they are reluctant to make the data available (e.g. for scientific research), because they are a part of their business know-how (Genovese, 2006). Yet, even within the insurance industry systematic data collection is done in certain sectors only (Changnon, 2003). A range of problems relate to data available in the public domain:

1) Data on extreme events are very scarce—uncertainties in short time series are enormous;

2) Even the most-advanced countries lack a commonly-agreed system of data collection. Information is gathered using a variety of methods and sources, and this renders their comparability very complex.

3) Estimation of losses requires special staff. Changnon (2003) argues that people who estimate losses do not have adequate skills and experience.

4) Some losses are delayed, and indirect, which makes assessments even more difficult and less precise.

5) The loss itself (e.g. a destroyed bridge) should be expressed in economic terms (monetary values). This is typically a difficult task. Moreover, for some losses (e.g. cultural and environmental values) the very possibility of assessment in monetary terms is problematic.

6) Alongside the losses, extreme events also bring positive effects (opportunities), e.g. prosperity for the construction industry dealing with massive orders. This aspect should also be taken into account.

As a result, existing data are fragmented and there are substantial uncertainties in the assessments. For example, in the US, 20-year losses due to tornados could only be assessed with a margin of an order of magnitude, with estimates ranging from 5.8 to 58 billion USD (Changnon, 2003). Attempts to assess losses are based on the data which are available, even if their validity is at times doubtful. Detailed damage surveys are uncommon and data are often therefore based on relief payments, insurance pay-outs or even newspaper news. This process can lead to large inaccuracies and a biased view. For instance, the insurance industry started to cover weather extreme events in the 1980s, and in 1990–94 the insured losses reached 40 billion USD. As a result, however, both insurance and reinsurance sectors have suffered, and many institutions have withdrawn coverage in some areas. Thus, a reliance on insured losses as the source of information representing total damage has its limitations.

This paper discusses the basic approaches to the estimation of damage caused by extreme events. Problems with data collection are reviewed, and possibilities for the assessment of intangible damage presented. The analysis is referred to a particular example of floods, but it is sufficiently generic to also be applicable to damage caused by other weather-related extremes.

BASIC METHODS OF LOSS ESTIMATION

Losses caused by extreme weather events can be assigned to many categories, including different aspects of the economy and social life. The scheme presented below (Fig. 1) offers a typology of damage. The primary division can be placed between tangible and intangible losses, the former being easier to express in monetary terms than the latter. The evaluation of intangible losses can be very difficult, if not impossible.

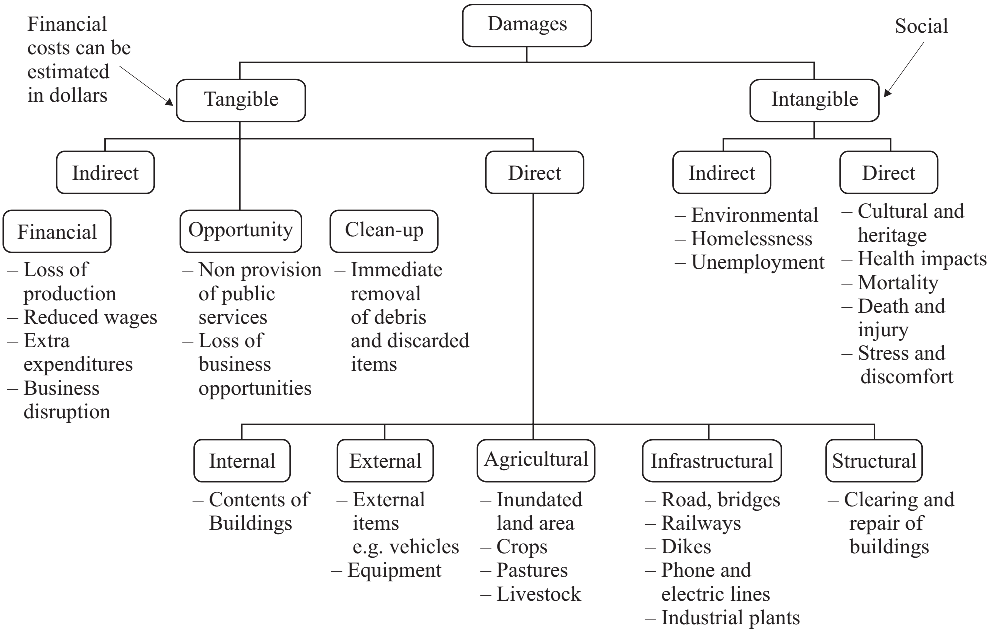

Figure 1. Types of loss which can be caused by extreme weather events (*after*: *Guidance on the Assessment of Tangible Flood Damage*, Queensland Government, Natural Resources and Mines, 2002).

The losses classified in Fig. 1 can be estimated using two basic procedural approaches: *ex ante* and *ex post*. In the former case, the model prepared allows for an assessment of potential losses, assuming certain conditions. In the latter case, losses are assessed by reference to estimates of real damage. This is related, in one way or another, to the field collection of data. The division between the two approaches is not sharp. According to Smith (1994), the synthetic methodology combines data from actual flood events, but also relies on some hypothetical analysis. As a result, it is possible to assess both actual flood loss and potential damage (Gissing and Blong, 2004). Nevertheless, in this paper it is basically *ex post* assessments that are considered.

There are two typical methods of asset valuation derived from accounting. Both use real market prices, but only one is directly connected with the utility of an asset. The methods are based on:

1) restoration value (reconstruction/reproduction);

2) market value.

The merits and weaknesses of these two methods are presented in what follows.

VALUATION BASED ON RESTORATION VALUE

The restoration method is usually used in asset valuation, when there is no functioning market for valuing a good, or at least a close substitute thereof. The concept of reproduction value is that an asset or good is worth as much as a the sum of values of its parts (components), and of the work necessary to restore usefulness and its ability to fulfil its function to the level existing before the damage. Restoration value is the price of obtaining exactly the same asset (including the case in which there is no possibility of it being bought in a normal market).

Every asset has its book value. This expresses nominal value on a balance sheet from the date of introduction into accountancy reporting. Usage of the restoration method in *ex post* flood loss estimation has one important advantage as compared to book value. The book value does not necessarily stand for the amount of money that is enough to restore an asset to its former state, while restoration value directly quantifies this.

In terms of flood loss assessment, restoration value is broadly used in practice in *ex post* damage estimation. It is obvious that lost value of a particular asset is the cost of restoring it to its prior condition. Such a sum of costs provides good proxy value. In order to estimate its value, one has to proceed in line with the following steps:

1) assessment of the restoration cost of an asset;

2) assessment of the rate of depreciation of an asset due to normal usage, technical and economic ageing and other factors;

3) assessment of the net restoration cost as the difference between gross restoration cost and depreciation of an asset.

Damaged assets have usually been worn out, to some degree, in the course of normal activity by the date of occurrence of a flood. Restoration is provided in excess to a former value, because material used cannot be worn out in the same proportion. Moreover, restoration is usually connected with modernization, even if this is not the intention, but there is no other opportunity to bring them back into usage. Reconstruction value then represents an inaccurate value of loss. However, acceptance of restoration value in flood damage assessment is supported by the fact that the present value of an asset is not well reflected in book value. Moreover, there is sometimes no book value for individual farms, households and some important components of technical infrastructure (e.g. public roads). This problem of difference between the gross book value and the restoration value is well presented for assessment in the case of the flood damage in Poland in 1997 (cf. Table 1).

Table 1. Damage caused by the 1997 flood in Poland.

Voivodship (province)	Total damage	
	According to gross book value	According to restoration value
	in million PLN (1997)	
Total	1469.0	1947.8
Bielskie	23.0	25.2
Częstochowskie	224.8	241.6
Gorzowskie	2.4	22.9
Jeleniogórskie	14.4	36.8
Katowickie	178.5	173.3
Krakowskie	19.9	19.7
Nowosądeckie	22.5	22.7
Opolskie	356.4	409.9
Tarnowskie	12.1	16.9
Wałbrzyskie	33.0	133.0
Wrocławskie	554.9	817.7
Zielonogórskie	11.1	9.1
Other provinces	16.9	19.0

after Centrum Informacyjne Rządu [Government Information Center], 1998.

As can be seen from the table above, for the reasons mentioned above, the restoration value is greater than the book value. Restoration of an asset to its former state is obviously impossible. Evaluation of some assets is not up-to-date and sometimes their replacement requires considerably greater expenses then their book value (e.g. when there are no spare parts). Simultaneously, any restoration is usually conducted with modernization, which is understandable from the economic point of view, especially for entrepreneurs. Therefore, *ex post* damage assessment may face distortion, as may *ex ante*, which takes into account potential losses in terms of book value. Nonetheless, such a gap between these two values (book and restoration) may show how modern a structure is.

Restoration value is based on a simple concept of the amount of money necessary to reinstate an asset to its former features. It is a well-defined market measure, in contrast to the book value that is devoid of real depreciation (book depreciation does not provide a market decrease of value). However, the restoration value defined above is a measure which does not represent the utility of an entire asset. Further disadvantages are connected with the following issues:

1) What prices of work and spare parts are most appropriate in calculating restoration value?

2) Should average market prices, or minima and maxima on the market be taken into consideration?

3) Should restoration value include transaction and other costs (e.g. taxes)?

Minimum prices are usually difficult to obtain, and taking different levels for different assets leaves assessment distorted.

Assessment of losses via restoration value is a widely-used method. It is relatively simple and effective. For instance, losses caused by the 1997 flood in Wrocław were estimated for categories of loss for the public sector, taking into account particular buildings. For private households and companies assessments were based on questionnaires from Poland's Central Statistical Office. For each case, the assessment was done mainly using restoration value and the incorporated cost of lost benefits, as defined in comparison with the business activity in the year before the occurrence of the damage caused by the extreme event.

DATA COLLECTION

Valuation based on restoration data requires input data for analysis. Within the synthetic method, Smith (1994) differentiates between:

1) existing data; and

2) data based on surveys by valuers and loss adjusters.

The former method is based on classification of residential buildings depending on the number of floors, building age, and content (furniture etc.). Similarly, types of land use are classified as commercial, industrial etc. (Lugeri *et al.*, 2006). The approach is based on maps combining data on land cover type, and the exposure (dependent on the value at risk—Lavalle *et al.*, 2005). If such a map is available, the estimation of losses is an easy procedure, providing that data on a geographical scale are known for an event. The crucial issue is the level of map resolution. The smaller the territorial unit and the more detailed the classification, the more precise can be the assessment. Due to the substantial input needed, this approach is more important for *ex ante* than for *ex post* assessment.

The latter method, based on surveys, has to be used if no earlier data on the affected territory and assets are available. This approach is based on valuation of actual flood damage in a dwelling, as done by a qualified loss adjuster or valuer. This is a basic *ex post* method used in the insurance industry, but also in the collection of public data. Two basic classes of losses are dealt with: structural (building and non-movable components thereof) and contents (the movable content of buildings). In both cases, more precise classifications are often made. Table 2 presents an example of the classification and distribution of losses among the classes for a flood case.

Data collection based on surveys offers better results when valuers are experienced and unbiased, which is not always the actual case. Sometimes valuations are based on valuations by the victims. This method is very susceptible, and overvaluation is typical. Despite difficulties, there are databases which already serve as a source for analysis and modeling. There are also databases in Britain and other countries, such as Germany, where the HAWAS database contains data on around 4000 buildings destroyed by floods between 1978 and 1994. Kreibisch *et al.* (2005) undertook a questionnaire survey among the victims of the 2002 Elbe River flood. As a result, information on the scale of damage was gathered, allowing for the valuation of content per one m^2 of living area. However, as the authors admit, the accuracy of data is not perfect due to a lack of data for about half of the examined cases.

Table 2. Distribution of losses reported for 113 residential damage claims for the Grand River flood of May 1974

Categories of loss	Percentage of total losses
Food	5.7
Fuel oil	0.1
Furniture	13.9
Appliances	
Large	11.4
Small	1.9
Clothing	10.3
Television/radios	3.3
Recreational equipment	1.4
Floor coverings	5.9
Structural repairs	
Floors	5.5
Walls	6.6
Furnace	7.9
Other	17.1
Cleaning	2.2
Miscellaneous items	6.8

(based on McBean *et al.*, 1986).

VALUATION BASED ON MARKET VALUE

Although restoration value may seem good, and provide quite appropriate results, it has one major disadvantage. It does not include assessment of the utility of an asset to its owner. The utility concept introduces the personal relationship of an owner to the value of an asset. The issue of the subjective character of personal utility is resolved by the observation of market value. A market value conveys the most adequate price, keeping the assumptions of independence and rationality on the part of parties to an agreement. A market value should reflect the market situation on the date of valuation. The market provides a price of an asset that is neither under- nor overvalued, in terms of its economic value to market participants.

Market value reflects the real price as an effect of the demand and supply balance. It is based on the microeconomic assumption that no one will pay more than an asset is worth to him, and no one will sell for a lower price than something has a value to him/her. In a dynamic formulation, the rational expectations theory constitutes a fundamental in considering market value as a best price (Muth, 1961). One of the applications of the concept of rational expectations is the efficient markets theory of asset prices (Sargent, 2002).

In fact, this approach to valuation includes utility as well. Some may argue that the price resulting from the market may be set inappropriately due to temporary disequilibrium. However, any market that complies with the conditions listed before eliminates such disequilibrium almost as soon as it appears.

Assessment of loss to any asset due to an extreme event that uses market value is based on two valuations:

1) the market price of an asset before the occurrence of the extreme;

2) the market value of a damaged asset.

The difference between these two valuations is the market-oriented loss assessment.

One disadvantage of market valuation is the necessity that perfect market conditions should exist. This is not observed for many goods, so such markets would be barely observed for assets damaged by a flood. Another disadvantage of this approach is connected with the possibility of a supply surplus after a flood that lowers the equilibrium price and results in undervaluation of assets. A simple explanation may release that disadvantage. If some vendors put off their offer for some time, they will obtain a higher price later (than those vendors who do not postpone). Taking into account the discounting factor (inflation, liquidity cost etc.) at the time after a flood (when a market is already functioning), the higher price (plus possible extra costs, e.g. warehousing costs) would be much lowered—it is highly probable that the price could be even lower after discounting. This means that the equilibrium price seems proper from the economic point of view.

When considering the ratio of market value of damaged asset to value before damage, we should observe the same ratio as is presented by the stage-damage curve in particular conditions in relative terms (actual to potential losses). It may be written in the following relationship for asset *i*:

$$D_i(C) = P_i(C) + \varepsilon_i(C)$$

where:

$P_i(C)$ is the ratio of an asset's price before a flood to its price after having been damaged in certain flood conditions (C—reflects water depth, velocity etc., and indirectly the scale of damages to an asset)

$D_i(C)$ is the ratio of actual damage to potential damage

$\varepsilon_i(C)$ is a stochastic component

It is obvious that $D(C)$ and $P(C) \in [0,1]$, by definition. The stochastic component should be heteroscedastic. This results from a high level of certainty in the evaluation of fully and merely damaged by market participants. Moreover, for C which generates complete damage var(ε_i) tends to 0, and the same holds for an intact asset. If a market is efficient, the distribution of ε_i is symmetrical, which means that participants' misassessments offset each other to equilibrium. Such an assumption helps to provide $D(C), P(C) \in [0,1]$ and is consistent with rational expectations of market participants. The presented concept is obviously connected to stage-damage functions ($D(C)$ actually refers to a relative stage-damage function), but includes utility into the valuation. The main disadvantage is the necessity, not only for a market for a particular asset to exist, but also for it to be of liquid form and for there to be effective collection of information about the transaction. Moreover, more complex assets e.g. buildings, do not form a cohesive set of similar goods and constitute rather one distinguishable tradeable object. In such a case, any price acquired from a market only goes unbiased if there are a large number of potential buyers (this generates an appropriate valuation that includes utility).

ESTIMATION OF INDIRECT TANGIBLE DAMAGE

Estimation methods based on the restoration value and on the market are generally easily applicable to tangible, direct damage. However, losses caused by extreme events not only include direct costs (physical damage, valued restoration costs, possessions, production means); but also indirect costs (economic interruption, environmental damage, cleaning, evacuation), and relief costs (food aid, heath care; sanitation) (Genovese, 2006). In such cases assumptions have to be made. Clean-up costs can serve as an example. They are assessed in terms of hours or days per household. In practice, there is a variety of suggestions: 15–20 hours per house; 50–60 hours, or 5 person-days (McBean *et al.*, 1986). The differences can be attributed to local conditions of a particular flood, but also to imprecise assessment.

On the macro level, indirect losses (disruptions caused by extreme events) are often estimated as a fixed proportion of the direct ones. The study by Parker *et al.* (1987) shows that indirect costs are overestimated due to insurance payments for business interruptions.

Smith (1994) recommends assessment of indirect losses on the regional or national levels. In this way a loss of e.g. a retailer is "compensated" for by the increased sales of the business outside the flooded area. This gives no net loss on the regional and national level.

ESTIMATION OF INTANGIBLE DAMAGE

Assessment of intangible damage poses more problems than in the case of tangible losses. Losses in terms of cultural heritage, biodiversity, human health etc, caused by extreme weather events can be severe and unquestionable, but expressing them in monetary terms is difficult. The issue of whether intangible goods can be treated in economic terms has been discussed widely in the environmental protection context. Some authors argue that at least some features of nature are of an intrinsic character, and are not possible to measure. Others disagree, and propose methods by which to measure the value of the environment, e.g. the value of environmental services, cf. Costanza *et al.* (1997). The same discussion also applies to the assessment of intangible damage caused by extremes. First of all, the very definition of tangibility appears problematical. For instance, Smith (1994) poses the question of how to treat gardens. Gardening equipment is possible to value, but the loss of plants and lawns is more difficult and these can be treated as intangible. The issue here is whether a garden can be treated as a tangible or an intangible.

Natural resources are more of an intangible characteristic. Since extreme events have effects on biological systems, they can disturb the robustness of ecological systems: provoking the extinction of populations, a decrease in biodiversity, etc. The assessment of ecological (natural) values in monetary terms is of great importance, but is the subject of discussion (e.g. Pearce and Turner, 1990). Methods of assessment are based on:

1) questionnaires measuring Willingness-To-Pay for improvement of the quality of the environment or Willingness-To-Accept the compensation for the decrease in quality of the environment;

2) the quasi-market, where the prices on the real-estate market are indirect indicators of environmental quality;

3) the hedonic price based on costs of travel to a national park for "consumption" of the recreational values of nature.

Assessment of the value of the environment is applied in various contexts: to measure the value of a particular species (includingt those endangered by extinction); particular examples of pristine nature (e.g. the Grand Canyon), etc. Despite several drawbacks the methodology is well-developed and can be used for the assessment of losses caused by extremes.

Another area of intangible damages is human health. Hajat *et al.* (2003) point to several effects of floods on human health. These are:

1) physical health effects (mortality; injuries; illnesses from flood-induced contamination of water supply; other flood-induced illnesses—respiratory problems and chronic health effects); (b) mental effects—especially post-traumatic stress disorder.

Numerous suicides linked with floods (Czabański, 2005) constituted a special category of problems during and after the 1997 flood in Poland. However, the health effects are not obvious and evidence from different countries is contradictory. A study on the 1997 flood in the Czech Republic reveals fewer hospital admissions and no suicide attempts, something which is attributed to an increase in social cohesion in flood circumstances.

Nevertheless, in many cases, human health losses caused by extreme events are tremendous. They can be presented in quantitative terms, as the number of casualties (Jonkman and Kelman, 2005; Jonkman, 2005), morbidity rate, etc. In this case also, however, there are attempts to quantify the effects in monetary terms. Like with measurement of the impact of environmental pollution on human health, losses caused by extreme events can be measured via the human capital concept. The health costs are

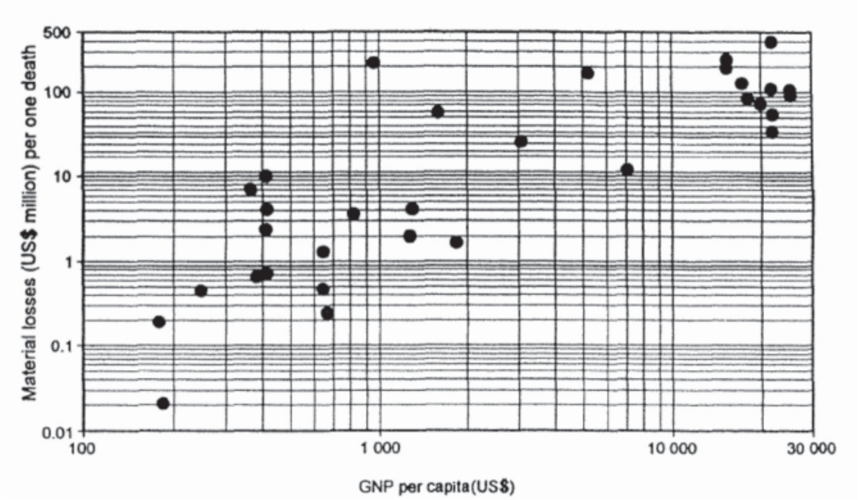

Figure 2. Relationship between the ratio of material losses in million USD to number of deaths and GNP per capita, in USD
Source: Kundzewicz, Takeuchi, 1999.

quantified as loss of quantity and quality of labour force. The inability to work brings costs of treatment and costs of absence from work. It can be measured in terms of costs of person-days in a specific sector and location. The approach focuses on the impact of the deterioration in human health on the economy, emphasizing decreased productivity at the macroeconomic level. There are also attempts to assess the costs of human life in monetary terms (insurance compensation), but obviously this provokes ethical discussion.

There are other attempts at the scalarization of flood-related indicators. Since the number of fatalities and level of material damage are the most meaningful indices, one may use the ratio of material losses (in million USD) to the number of deaths. In simple words, the indicator measures material losses per death. Fig. 2 illustrates how this indicator varies for extreme floods, as a function of GNP per capita (in USD). As expected, there is a general pattern to this relationship (Kundzewicz, Takeuchi, 1997) in that the indicator attains higher values for wealthy countries and lower ones for less wealthy countries. For catastrophic floods in developing countries, material losses per fatality can be as low as USD 21 000, while in developed countries they can be up to USD 400 million, i.e. by four orders of magnitude higher. If floods strike developed countries, they may cause major material damage, but the death toll in developed countries is far lower than in the developing ones, because the former typically have in place an efficient flood preparedness system (including a forecast and warning system).

CONCLUSIONS

The estimation of losses caused by extreme weather events, such as floods, is difficult. In economic terms, extreme events disturb the market prices system. Services offered during the event can be priced above the market process at the normal time. A distorted market is not the only problem. In many cases the damaged goods are not pure market exchangeable goods. This poses additional difficulties with assessment. Even in the case of tangible and direct losses, assessment is normally difficult. However, the scale of damage and the probable increase in the number of extreme events call for data allowing for the preparation and application of mitigation and adaptation measures. Notwithstanding their weaknesses, the presented approaches to the costing of losses on the basis of market value or restoration (replacement) value allow assessments in economic terms to be made. An open question remains related to the defining of the efficiency of data collection, i.e. how to collect the most useful data in given circumstances.

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POLAND'S CLIMATE EXTREMES INDEX, 1951–2005

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Abstract: The paper seeks to synthesise contemporary (1951–2005) trends regarding the occurrence of extreme meteorological events in Poland using the complex Climate Extremes Index (CEI) proposed by Karl *et al.* (1996). Poland's CEI Was the greatest in the 1990s. The trend noted for it in the period from 1951 to 2005 is an upward one, but does not achieve statistical significance. Similar tendencies for the index have been observed in the 20th century for the USA (1910–90), the Russian Federation (1950–96), and Central Europe (1951–2000).

Key words: climate extremes index (CEI), temperature, precipitation, moisture index, Poland.

INTRODUCTION

A common practice in describing the climate of a given area is to present characteristics for the main meteorological variables (e.g. air temperature, precipitation, cloudiness, humidity) on the basis of their average values. Consequently, climate change estimates are also mainly given in terms of such statistical characteristics. Climate extremes and the changes occurring therein in recent years have been investigated more rarely (e.g. in the reports of the Intergovernmental Panel on Climate Change (IPCC): Houghton *et al.* 1990, 1995 and 2001 or Heino *et al.* 1999).

The history of mean climate characteristics for Poland and the changes that have characterized them in recent decades are quite well known (Dubicki *et al.* 1999; Fortuniak *et al.* 2001; Żmudzka 2003; Degirmendžić *et al.* 2004; Kożuchowski 2004). On the other hand, our knowledge of extreme climatic events and relevant contemporary changes resembles our knowledge of such events and trends in other parts of the world in still being limited, notwithstanding significant progress in recent years (e.g. Dubicki *et al.* 1999; Bogdanowicz *et al.* 2005). The reasons for this lack of research are complex, though the main reason seemingly delaying research in this direction (not only in Poland) is the significantly more limited availability (or even absence) of homogeneous data with daily resolution in comparison with monthly or annual mean data. A second, also very important reason relates to the lack of a consensus as regards the definition of extreme events (Easterling *et al.* 2000). Moreover, the large number of existing extreme phenomena, which sometimes show different trends in recent time series, do not allow us to state unequivocally whether an overall change has characterized the extreme events in the given area in the observed record. As a result, reliable spatial averaging of the results obtained over larger areas (e.g. continents and especially the globe as a whole) is very difficult and may even be impossible. Nonetheless, since model outputs simulate more extreme events for future climates (Meehl *et al*. 2000) and suggest that they will lead to greater environmental and societal vulnerability, we should concentrate our efforts on learning more about climate extremes, frequencies and intensities. A greater awareness of these research needs among Polish scientists has led to projects involving interdisciplinary cooperation within an integrated framework called "Extreme Hydrological and Meteorological Events in Poland (Estimation of Events and Impact Forecasting for the Human Environment" supported financially by the State Committee for Scientific Research, Grant No. PBZ-KBN-086/P04/2003. We hope that implementation of this project will significantly improve our knowledge of changes affecting different extreme meteorological, hydrological and geomorphological events in Poland in the 20th century.

The main task of the present paper is to examine whether any increased incidence of climatic extremes is to be observed for Poland over recent decades. This issue is problematic because, as we mentioned earlier, there are a myriad different extreme phenomena (including a large number of different indicators and indices of climate extremes). Analysis of all of them is simply impossible, but the idea of a comprehensive and synthetic index, proposed by Karl *et al*. (1996) to describe climate extremity would seem to be a good solution, permitting us to estimate the existing tendencies more reliably. To this end, we decided to calculate such an index for the area of Poland. Thus far this index (or modifications thereof) has been calculated for the USA (Karl *et al*. 1996), the Russian Federation (Gruza *et al*. 1999), and Central Europe (Przybylak *et al*. 2006). It will thus be possible to compare results.

DATA, AREA AND METHODS

The construction of the index requires meteorological data of a daily resolution. The variables taken account of are: maximum (T_{max}) and minimum (T_{min}) temperatures, amount of precipitation (P), and potential evaporation (EP). In addition, the number of days with precipitation $\geq$ 0.1 mm has also been referred to. Due to the limited availability of such data for Polish meteorological stations, NCEP/NCAR Reanalysis data from 20 grid points have been used (Kalnay *et al*. 1996; Kistler *et al*. 2001; http://www.cdc.noaa.gov/cdc/reanalysis/) (Fig. 1). Throughout the area of Poland the grid points occur at almost every two degrees of longitude (1°52'5") and two degrees of latitude (1°54'3"). As a result, each grid point represents an equal surface area. These surface areas are reduced in line with the proportion lying inside the Polish border. Similar reductions were made for each indicator used to calculate the Climate Extremes Index (CEI). Because EP values are not available in the NCEP/NCAR Reanalysis, they were calculated using the formula from Ivanov (1958):

$$EP= 0.0018\ (25+T)^2\ (100–f)$$

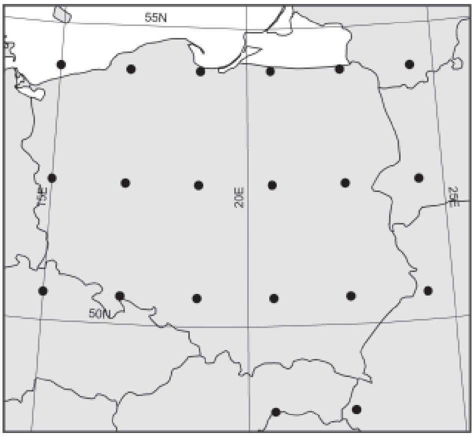

Figure 1. Study area and location of grid points from which data have been taken

To calculate relative humidity (f), the variable which is needed to obtain the EP, we used the daily mean values for specific humidity available in the NCEP/NCAR Reanalysis data set.

As was mentioned earlier, the construction of the Climate Extremes Index is based on the proposal by Karl *et al.* (1996), but we introduced certain minor modifications to it. To calculate the third indicator, the variable P-EP was used for the long-term estimation of moisture anomalies, instead of the Palmer Drought Severe Index (PDSI). In turn, in the fourth indicator, the threshold of extreme high precipitation was reduced from 50.8 mm (two inches) to 15 mm, which is more appropriate for Polish conditions and for the kind of data used. Moreover, to calculate first and second indicators, daily data have been used, instead of the monthly data used by Karl *et al.* (1996).

The Climate Extremes Index is the annual arithmetic average of the following five indicators of the percentage of the study area:

1. The sum of the percentage area of Poland with (a) T_{max} considerably below normal and (b) T_{max} considerably above normal,
2. The sum of the percentage area of Poland with (a) T_{min} considerably below normal and (b) T_{min} considerably above normal,
3. The sum of the percentage area of Poland with (a) P-EP considerably below normal and (b) P-EP considerably above normal,
4. Twice the value of the percentage area of Poland with a considerably greater than normal proportion of P derived from extreme (≥15 mm) 1-day P events,
5. The sum of the percentage area of Poland with (a) a considerably greater than normal number of days with precipitation and (b) a considerably greater than normal number of days without precipitation.

The extreme conditions were defined as the upper (considerably above normal) and lower (considerably below normal) tenth percentile of the local 50-year (1951–2000) period of records. In the case of indicators 1, 2 and 3, thresholds were determined for each month separately, while for indicators 4 and 5, yearly sums were used. A particular year at a given grid point was considered extreme if the number of extreme events was greater than 10%.

RESULTS AND DISCUSSION

To begin by describing the behaviour of particular indicators in the study period, a marked rise in T_{max} is to be observed from the beginning of the 1990s. This is very clear in terms of both average yearly values and the number of days exceeding commonly used threshold values, i.e. 25°C (hot days), 30°C (very hot days), and 35°C (extremely hot days). The last kind of days occurred very rarely prior to 1985. In two years (1992 and 1994) their areally averaged number for Poland oscillated between 4 and 6. In the remaining years the number of these extremely hot days never exceed 2.

Cold T_{max} (areally averaged annual mean number of days with $T_{max} < 1\%$ and $T_{max} < 10\%$) in Poland show downward (if not statistically significant) trends (not shown). On the other hand, the trends for the areally averaged annual mean number of days with $T_{max} > 90\%$ and $T_{max} > 99\%$ (warm T_{max}) are positive and statistically significant (Fig. 2). The last decade of the 20th century was very exceptional in this regard. In many years in this time span the number of days exceeding these two thresholds were greater than 50 and 6, respectively. Similar results for data taken from stations in Pomerania (north-west Poland) have been noted by Filipiak (2004).

Generally, similar results can be seen in Fig. 3, which presents the percentage changes for the area of Poland with T_{max} below the 10th percentile and above the 90th percentile from 1951 to 2005. The latter shows a statistically significant increase for this characteristic (Fig. 3b) while the former shows a non-significant downward trend (Fig. 3a). It is evident that, since the beginning of the 1990s, the warm T_{max} values, if they occur in a given year, are quite widespread and mostly extend over the whole territory of Poland (100%). On the other hand, cold T_{max} values in this time span relate only to isolated parts of Poland, even though they

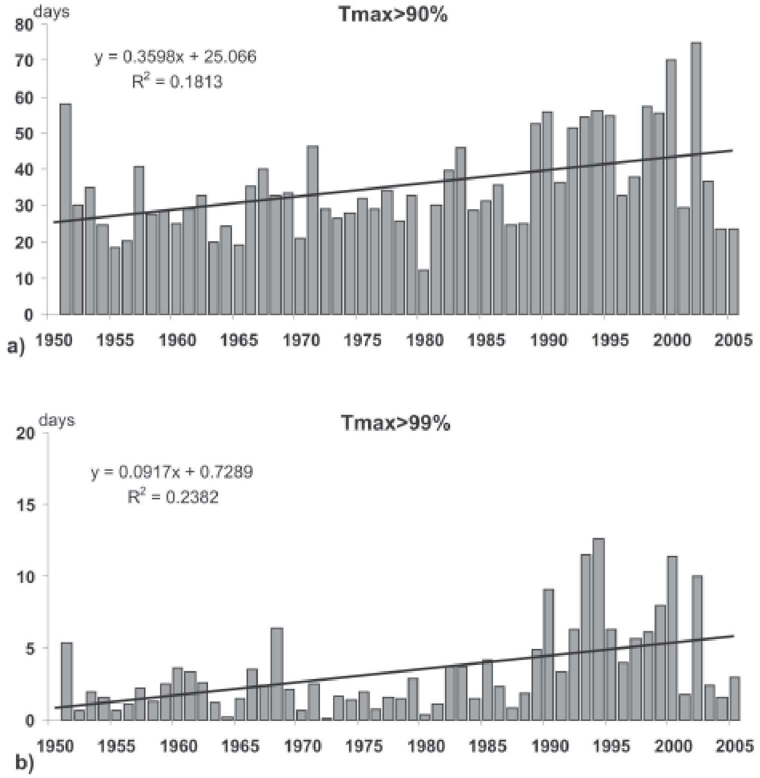

Figure 2. Areally averaged annual mean number of days for Poland with T_{max} above the 90th percentile (a) and above the 99th percentile (b) from 1951–2005.

frequently covered the whole area of the country in the 1950s and 1960s.

In the study period, T_{min} shows significantly more limited changes in Poland than T_{max}. Non-significant changes in both areally averaged T_{min} (upward trend) and the number of frosty ($T_{min}<0°C$), cold ($T_{min}<-10°C$) and very cold ($T_{min}<-20°C$) days (not shown) have been noted. Statistically significant changes were observed only for the areally averaged annual number of days with $T_{min} > 90\%$ and $T_{min} > 99\%$ in Poland. The marked rise in the number of such days has occurred mainly in the last 10 years, in which counts frequently exceeded 50 and 8, respectively (Fig. 4). The percentage changes in the area of Poland with cold T_{min} (< 10th percentile) show a downward trend, but are not statistically significant (Fig. 5a). The opposite behaviour (i.e. upward trend) is seen for warm T_{min} (> 90th percentile). Like cold T_{min}, warm T_{min} also shows non-significant changes. In recent years, however, these are widespread, if they occur in a particular year covering the whole, or almost the whole, area of Poland (Fig. 5b).

The observed trends in selected areally averaged mean annual characteristics for daily T_{max} and T_{min} for 1951–2005, as shown and described above, are in line with the results presented by Niedźwiedź and Ustrnul (1994) and Brázdil *et al.* (1996), who analysed monthly mean data from meteorological stations for Poland (1951–1992) and for central and south-eastern Europe

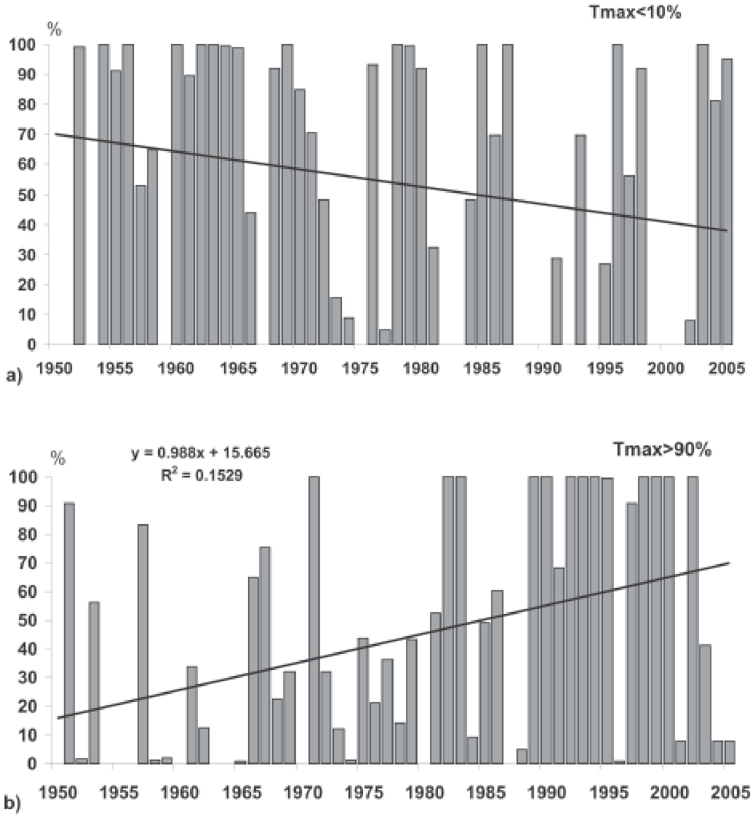

Figure 3. Percentage changes in the area of Poland with T_{max} below the 10th percentile (a) and above the 90th percentile (b) from 1951–2005.

(1951–1990), respectively. On the other hand, opposite tendencies (i.e. greater rises for T_{min} than T_{max}) have been found by Wibig and Głowicki (2002) for Poland for the period 1951–1998. The results in these papers may have been influenced by the different periods analysed and the different kinds of data used (reanalysis or station data); in the case of papers using station data, different sets of data could also have influenced the results. Thus, more research is needed to resolve this discrepancy.

The extreme moisture conditions in Poland changed significantly from the 1950s to the turn of the 20th/21st centuries. There was a marked increase in the last 15 years in the areally averaged annual mean number of days with a moisture index (P-EP) < 1st percentile and 10th percentile (extremely dry and very dry days, respectively). As a result, a statistically significant downward trend is observed. For example, prior to 1990 the areally averaged number of extremely dry days oscillated mainly between 1 and 2, while from 1990 on their number was very often greater than 5. On the other hand, the areally averaged number of extremely wet days and very wet days (P-EP above 99% and 90% respectively) show a statistically significant downward trend during the study period. In the period 1951–1980 the number of extremely wet days oscillated mainly between 3 and 6, while during the last 25 years the figure was generally from 1 to 3 days.

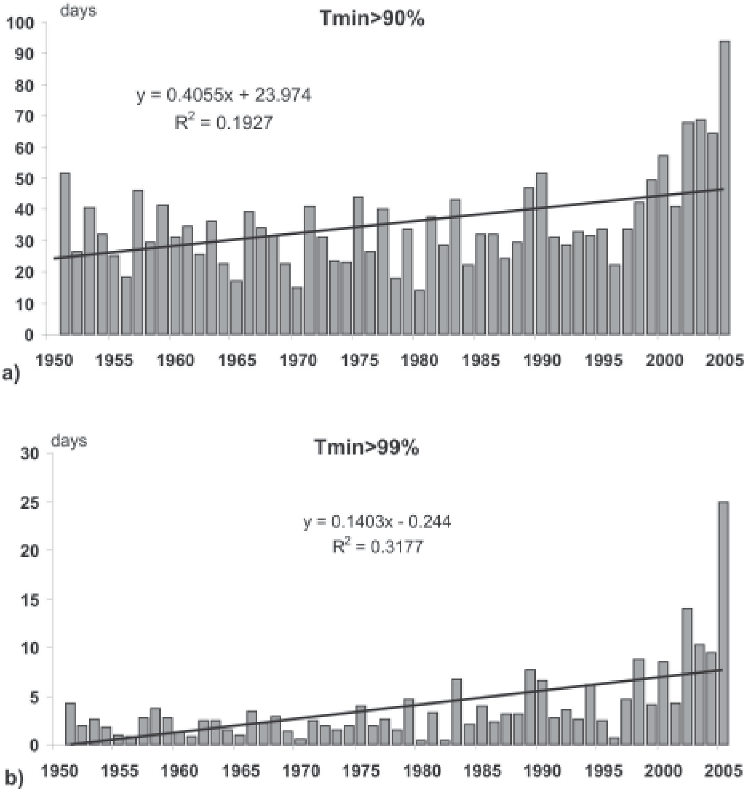

Figure 4. Areally averaged annual mean number of days for Poland with T_{min} above the 90th percentile (a) and above the 99th percentile (b) from 1951–2005.

The percentage changes in the area of Poland with P-EP >90th percentile (Fig. 6b) and P-EP > 99th percentile show large statistically significant downward trends. The opposite behaviour is seen for extremely dry and very dry days (Fig. 6a), which reveal statistically significant upward trends. In recent years, if those kind of days occur in a particular year, they are widespread and cover the whole, or almost the whole, area of Poland

The areally averaged annual mean number of days with extreme 1-day P totals (≥15 mm) shows a significant downward trend in Poland from 1951 to 2005 (Fig. 7a). Similar results (i.e. downward trends, though not statistically significant) were found by Frich *et al*. (2002, see their Fig. 6a) analysing the number of days with P ≥10 mm from 1951 to 1996 based on station data, and also by Heino *et al*. (1999) for the period 1951–1995 (see their Fig. 6 –Potsdam and Łódź stations). Mean counts of days with extreme 1-day P totals (≥15 mm) in the period 1951–2005 oscillated from 8.74 days in 1980 to 1.23 days in 1993. However, in a particular grid box (20°37'30''E, 52°22'48''N) the extreme 1-day P totals varied from 20 days (1952) to 1 day (in many years). On the other hand, the percentage changes in the area of Poland with a considerably greater than normal proportion of P derived from extreme 1-day P events are not characterized by any significant trends (see Fig. 7b). However, it is clear that greater than normal percentage values oc-

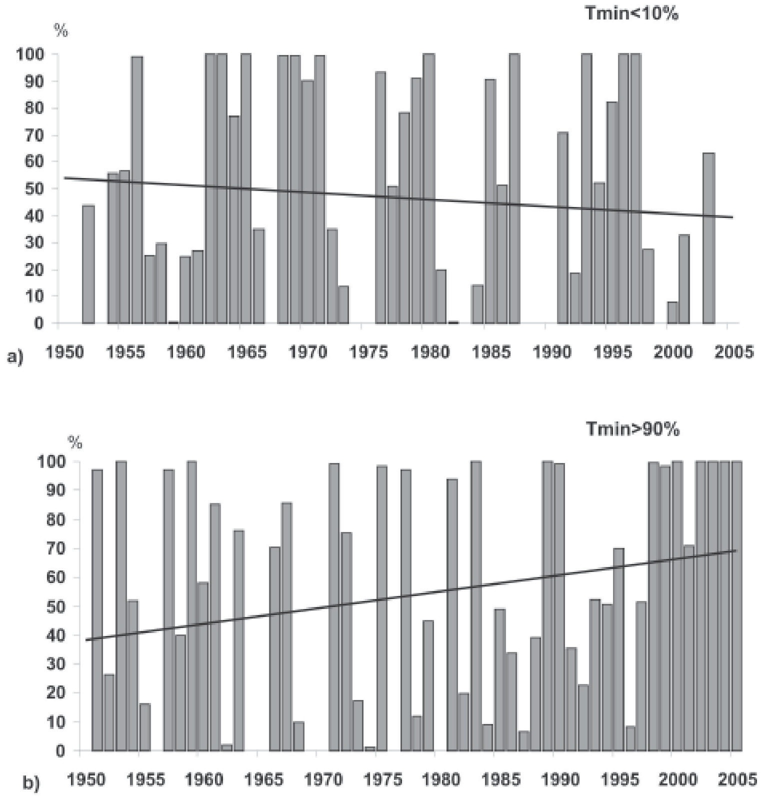

Figure 5. Percentage changes in the area of Poland with T_{min} below the 10th percentile (a) and above the 90th percentile (b) from 1951– 2005.

curred in the 1950s, the 1970s, and the last 10 years. In four years (1952, 1956, 1975 and 1995) about half of Poland received a greater than normal proportion of P in extreme (≥ 15 mm) 1-day P events.

The areally averaged annual mean numbers of days with precipitation (≥0.1 mm) and without precipitation in Poland show statistically significant changes from 1951 to 2005 (not shown). The former show a downward trend, the latter an upward one. In both cases, the changes in the number of days between the 1950s and the period 1991–2005 amounted to 50.

The percentage changes in the area of Poland with a considerably greater than normal number of days without precipitation show a statistically significant increase (Fig. 8a). Such situations did not occur at all in the 1950s, while they were very common at the turn of the 1960s and the 1970s, the 1970s and 1980s and during the 1990s. This means, of course, that in these last three time spans dry conditions were often observed over more than half of Poland. In two years (1972, 1997) such conditions even covered more than 80% of the area. On the other hand, the percentage changes in the area of Poland with a considerably greater than normal number of days with precipitation (P≥0.1 mm) do not show a statistically significant downward trend (Fig. 8b). Such days were observed over quite a large area of Poland (mainly from 10% to 40%) before

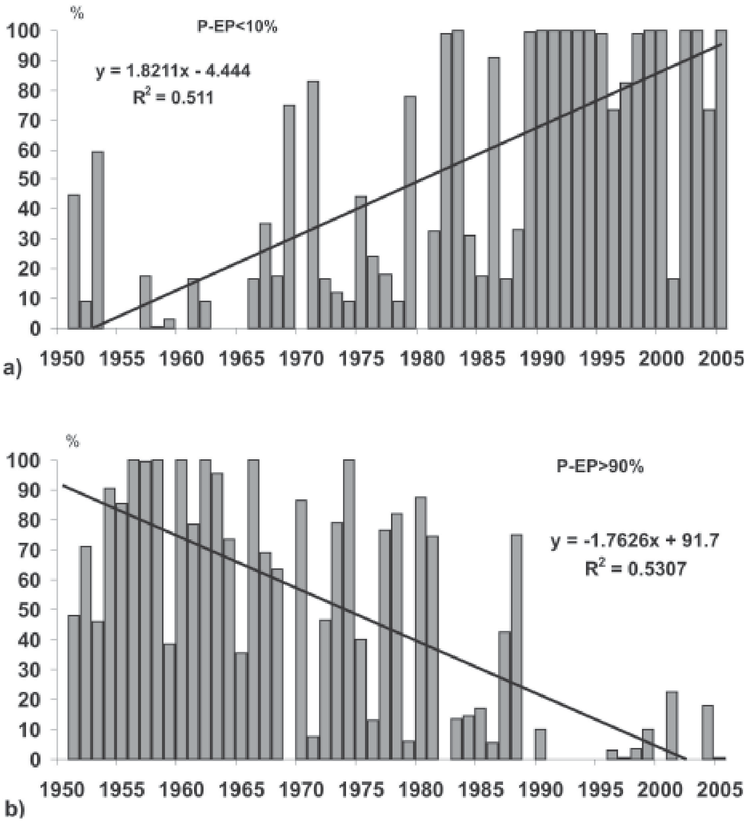

Figure 6. Percentage changes in the area of Poland with P-EP below the 10th percentile (a) and above the 90th percentile (b) from 1951–2005.

1985, while such days only occurred subsequently in 2000 and 2003. Particularly exceptional was 1983, during which a considerably greater than normal number of days with precipitation were noted over 89.37% of the area of Poland.

Poland's CEI does not show any statistically significant rise from 1951 to 2005 (Fig. 9). The greatest extremity of climate was observed during the 1990s and at the turn of the 1960s and 1970s. The 10 most extreme years in descending order were: 1971, 1997, 1998, 1995, 2003, 1993, 1957, 1980, 1963 and 1956. On the other hand, the 10 years with the most limited climate extremes (i.e. the most stable climatic conditions) in Poland occurred (in ascending order of extremity) in 1984, 1974, 1973, 2001, 1988, 1982, 1959, 1964, 1958 and 1967.

Similar results for the USA have been obtained by Karl *et al.* (1996) for the period 1910–1990, for the Russian Federation by Gruza *et al.* (1999) for the period from the 1950s to 1996, and for central Europe by Przybylak *et al.* (2006) for the period 1951–2000.

CONCLUSIONS

1. In the 1990s, a frequency of occurrence of daily T_{max} considerably above normal was evident. As a result, its frequency

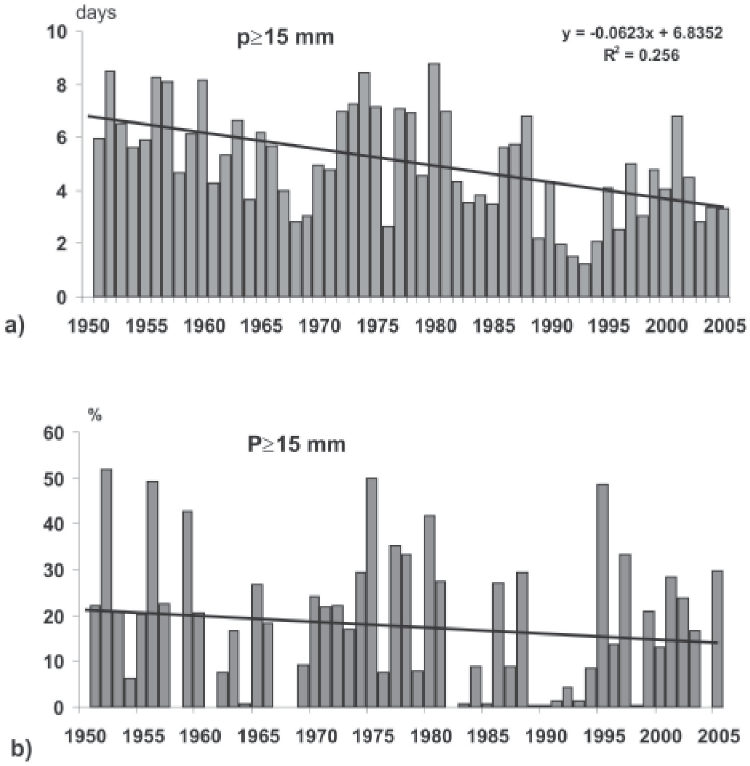

Figure 7. (a) Areally averaged annual mean number of days with extreme 1-day P totals (≥15 mm) and (b) percentage changes in the area of Poland with a considerably greater than normal proportion of P derived from extreme 1-day P totals (≥15 mm) from 1951–2005.

during the period 1951–2005 shows a statistically significant upward trend. Similar changes were also noted for daily T_{min}. The percentage changes in the area of Poland with T_{max} below the 10th percentile and above the 90th percentile show downward and upward trends, respectively. Statistically significant changes only occurred in the case of T_{max} exceeding the 90% threshold. In turn, T_{min} reveals non-significant changes.

2. The indicator of moisture (precipitation minus evaporation, P-EP) shows markedly lower values in the last two decades of the study period. As a result, the study period is characterized by a downward statistically significant trend. Trends for the percentage changes in the area of Poland with P-EP considerably below normal / considerably above normal show strong increases and decreases respectively, then achieving statistical significance in both cases.

3. The areally averaged frequency of occurrence of extreme 1-day P totals (≥15 mm) in Poland shows a statistically significant downward trend. On the other hand, the decreasing percentage of Poland with a considerably greater than normal proportion of P derived from extreme 1-day P events is non-significant.

4. A considerably greater than normal areally averaged mean number of days with precipitation has shown a clear decrease in Poland in the last two decades. In the

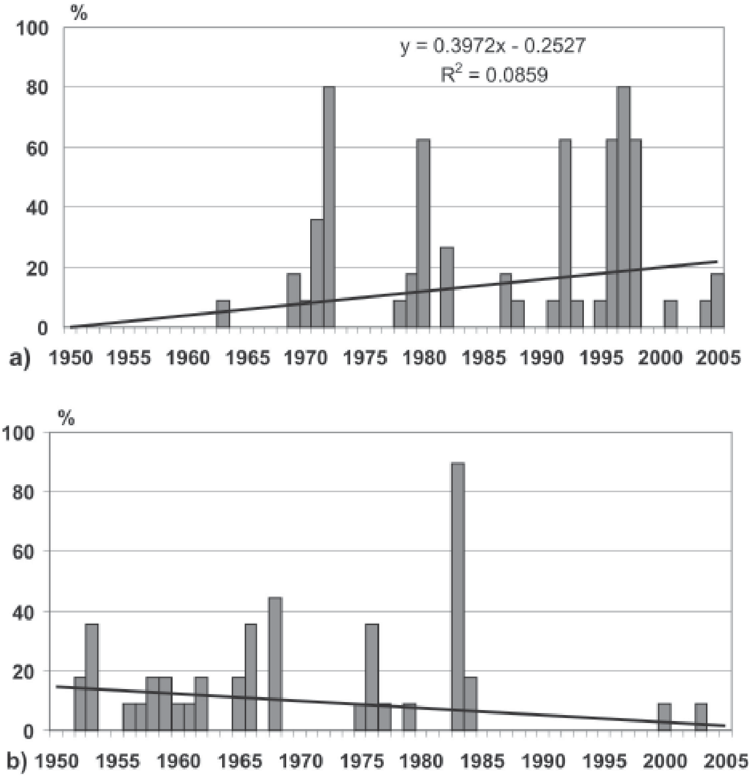

Figure 8. Percentage changes in the area of Poland with a number of days without precipitation (a) and with precipitation ($P \geq 0.1$ mm) (b) having a frequency above the 90th percentile from 1951–2005.

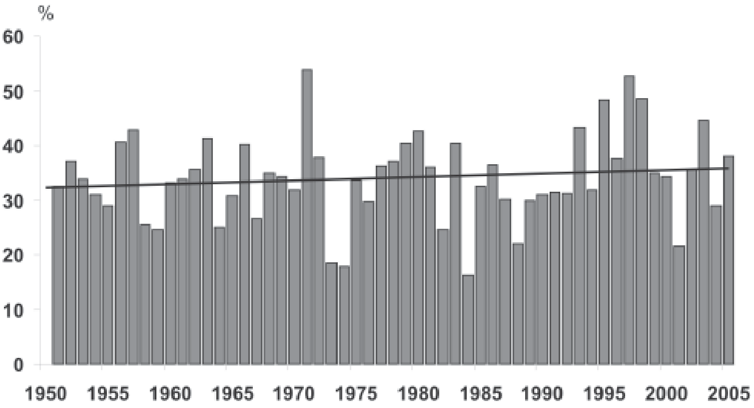

Figure 9. Year-to-year course of the CEI for Poland from 1951–2005.

study period, a strong negative, statistically significant trend for such days was noted. On the other hand, the percentage changes in the area of Poland with this kind of data do not show a statistically significant downward tendency.

5. Poland's CEI was greatest in the 1990s. Its trend in the period from 1951 to 2005 is upward, though not significantly so. Similar results for the USA have been obtained by Karl *et al*. (1996) for the period 1910–1990, for the Russian Federation by Gruza *et al*. (1999) for the period from 1950s to 1996, and for central Europe by Przybylak *et al*. (2006) for the period 1951–2000.

ACKNOWLEDGEMENTS

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VARIABILITY TO GLOBAL SOLAR RADIATION IN CENTRAL EUROPE DURING THE PERIOD 1951–2005 (ON THE BASIS OF DATA FROM NCEP/NCAR REANALYSIS PROJECT)

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Abstract: The paper presents the variability to Global Solar Radiation (GSR) in Central Europe in the period 1951–2005. The basic material comprises the data from the NCEP/NCAR reanalysis of 35 grid points. The research shows a statistically significant increase in GSR income in the entire study period in the research area. This increase, which started in the late 1980s, was also observed across Europe as a whole. One of the reasons for this change might be the decrease in pollutant emissions to the atmosphere. Moreover, an upward trend in the numbers of days with GSR over the 90th percentile is to be observed in the study period, while the number of days with GSR lower than the 10th percentile shows a negative trend. In both cases, the recorded trends are statistically significant at the 0.05 level.

Key Words: global solar radiation, Central Europe, NCEP/NCAR reanalysis data

INTRODUCTION

Since solar radiation is the main source of energy for both weather and climatic processes, changes to it in terms of either size or spatial and temporal distribution, may result in significant changes in weather and climate patterns, which, in turn, influence human life and activity. The most significant changes involve both the scale and frequency of extreme meteorological phenomena. As extreme weather conditions exert a negative influence over ecosystems and human activity, it is essential to find out why they occur and, most importantly, why their frequency is on the increase, especially in recent years (Przybylak *et al*. 2006).

AIM OF THE RESEARCH, STUDY AREA AND SOURCE MATERIALS

The aim of this paper is to present the changes in the level of Global Solar Radiation (GSR) in Central Europe in the period 1951–2005. This has been done on the basis of data from the NCEP/NCAR reanalysis (Kalnay *et al*. 1996) provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their website at http://www.cdc.noaa.gov/. Mean daily values for the GSR, expressed in W·m^{-2}, were recorded for 35 grid points within the study area. The grid points were located at almost every two degrees of longitude and latitude.

Monthly and annual totals for the GSR (MJ·m^{-2}) were calculated for every grid point for both individual years and the entire observation period. The trends to the changes were studied in terms of annual sums as well as for the individual months. Moreover, studied for every grid point was the number of times mean daily values for the GSR (W·m^{-2}) were lower than the threshold value of the 10th percentile, and how many times they were higher than that of the 90th percentile.

RESULTS

Within the study period, the lowest annual totals for the GSR were recorded in the 1950s and 1960s; in as many as 22 grid points the lowest sums were recorded in 1960. The largest input of solar energy was recorded at the end of the research period, especially in the 1990s, with 1992 and 1994 being the most significant. Thus, between 1951 and 2005 a statistically significant increase in annual global solar radiation within the entire study area was observed ($p = 0.05$) (Fig. 1).

According to studies undertaken in Europe on the basis of data directly from actinometric measurements, in the first part of the study period a decrease in GSR was recorded. The examples include the results of the measurements at stations located in the Baltic Sea area (Russak 1990). Between 1969 and 1986, the stations Toravere (Estonia), Helsinki, Stockholm, Kołobrzeg, Taastrup and Saint Petersburg reported a lowering of the value of GSR by 6.4% to 16.0%. At Toravere, a negative trend of -6.8% was also recorded over a longer research period (1955–1986). Russak (1990) argued that the decrease in the value of GSR at Toravere throughout the 32-year study period may be connected with an increase in the amount of low level cloud by 11% (1964–1986) and a decrease in transparency of the atmosphere of 3.7%. A decrease in GSR of 7.1%

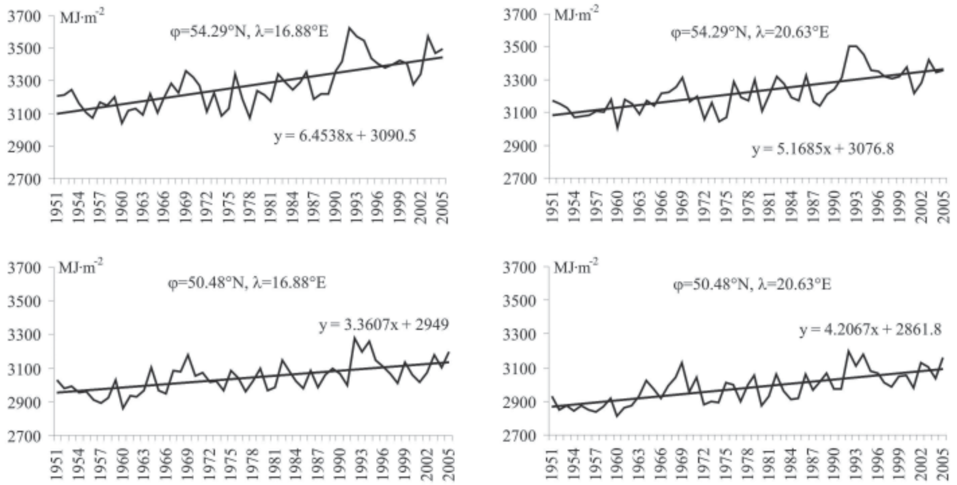

Figure 1. Long-term course for sums of global solar radiation for selected grid points in Central Europe in the period 1951–2005

was also recorded for Moscow, between 1958 and 1993. This phenomenon is also connected with greater cloudiness and lower transparency of the atmosphere (Abakumova *et al*. 1996). Abakumova *et al*. (1996) also show that the GSR in the European part of Russia, the Baltic States, Belarus and Ukraine from 1960 to 1987 point to a downward trend equal to more than 2% per decade.

Data gathered for Europe as a whole attest to a negative trend for GSR to the surface between 1950 and 1985. Later this trend was reversed, an increase in GSR even being observed (Wild *et al*. 2005). The reversed trend for changes in GSR was in line with the trend towards changes in the transparency of the atmosphere. The latter has been growing since the mid-1980s, something that might be connected with decreasing pollutant emissions due to the introduction of stricter rules on environmental protection and changes of manufacturing technologies. It was followed by later economic transformation in the countries of Central and Eastern Europe, which often meant closedowns or changes in technologies for the factories most burdensome to the environment (Wild *et al*. 2005).

The reverse trend for the GSR data was also noted for Sweden in the period 1983–1997 (Persson 1999). Stations located in various parts of the country recorded an upward trend (equal to 7.2 per decade) for the GSR. This increase was predominantly the result of reduced cloudiness, mainly in the summer months (Persson 1999).

Variability to GSR for the years 1961–1995 was also studied for the area of Poland (Bogdańska and Podogrocki 2000). The research was based on measurements from an actinometric network of 7 stations of the Institute of Meteorology and Water Management (IMGW) located across Poland. Increased GSR input was recorded for 5 of the stations; though for only one of them (Warsaw) was the trend statistically significant. The two remaining stations (Suwałki and Zakopane) recorded decreasing values for GSR, though this tendency did not achieve statistical significance (Bogdańska and Podogrocki 2000).

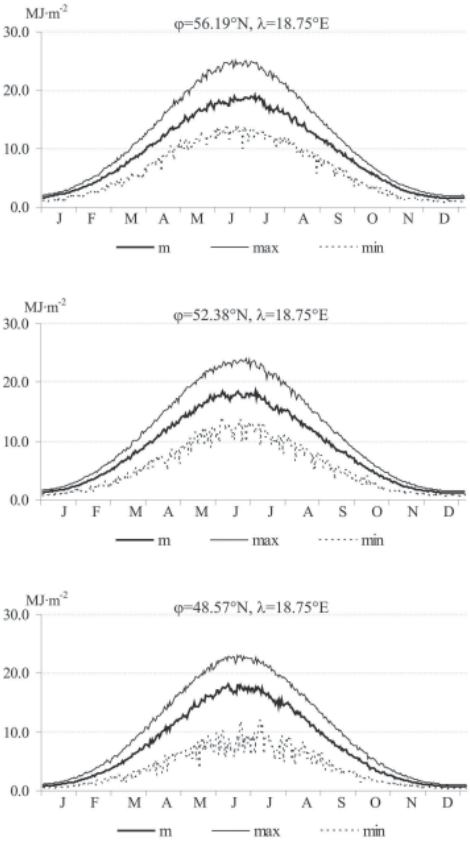

Figure 2. Annual course for daily sums of global solar radiation (mean—m, highest —max and lowest—min) for the selected grid points in the period 1951–2005

An upward trend for total GSR was recorded for both annual values and for individual months (Table 1). A negative slope to the linear trend for monthly GSR totals was only recorded for one grid point in March, six grid points in June and one grid point in September. This means that the magnitude of incoming GSR in these months decreased over the 55-year study period. In none of the above cases, however, was the decrease statistically significant. In all other cases an increase in incoming GSR was observed, mostly statistically significant. The most

Table 1. Trend coefficients (MJ·m^{-2} per month or year) for monthly and annual totals of global solar radiation for individual grids in Central Europe in the period 1951–2005[1]

Grid points[2]	Months												Year
	J	F	M	A	M	J	J	A	S	O	N	D	
1	**0.144**	**0.215**	**0.422**	**0.855**	**1.550**	**1.612**	**1.122**	**0.795**	**0.329**	0.061	**0.119**	**0.089**	**7.315**
2	**0.082**	**0.158**	**0.213**	**0.749**	**1.314**	**1.605**	**1.046**	**1.078**	**0.369**	0.089	**0.093**	**0.053**	**6.850**
3	0.039	0.103	0.083	**0.429**	**0.661**	**0.532**	**0.539**	**0.660**	0.175	0.060	**0.088**	**0.053**	**3.421**
4	0.025	0.076	0.068	**0.297**	**0.374**	-0.006	0.378	**0.427**	0.113	0.072	**0.076**	**0.043**	**1.945**
5	**0.040**	0.077	0.156	**0.326**	**0.405**	-0.094	**0.507**	**0.358**	0.169	**0.122**	**0.057**	**0.024**	**2.146**
6	**0.149**	**0.206**	**0.355**	**0.665**	**1.437**	**1.644**	**1.185**	**0.757**	**0.295**	0.045	**0.115**	**0.087**	**6.940**
7	**0.091**	**0.155**	**0.226**	**0.736**	**1.296**	**1.603**	**1.027**	**0.971**	**0.337**	0.097	**0.106**	**0.072**	**6.717**
8	0.042	0.114	0.107	**0.525**	**0.725**	**0.619**	**0.583**	**0.650**	0.203	0.068	**0.100**	**0.071**	**3.809**
9	0.023	0.081	0.083	**0.439**	**0.482**	0.089	0.446	**0.453**	0.151	0.083	**0.084**	**0.055**	**2.470**
10	0.034	0.058	0.142	**0.458**	**0.517**	-0.054	**0.562**	**0.362**	0.174	**0.140**	**0.060**	**0.026**	**2.477**
11	**0.142**	**0.182**	**0.282**	**0.482**	**1.305**	**1.695**	**1.173**	**0.647**	0.235	0.039	**0.128**	**0.083**	**6.391**
12	**0.100**	**0.158**	**0.233**	**0.714**	**1.275**	**1.474**	**1.005**	**0.853**	**0.293**	0.111	**0.139**	**0.097**	**6.454**
13	0.051	**0.123**	0.126	**0.631**	**0.823**	**0.753**	**0.679**	**0.673**	**0.281**	0.097	**0.124**	**0.092**	**4.453**
14	0.028	0.094	0.146	**0.617**	**0.608**	0.252	**0.588**	**0.509**	**0.233**	0.121	**0.097**	**0.068**	**3.361**
15	0.027	**0.071**	**0.279**	**0.661**	**0.590**	-0.054	**0.691**	**0.363**	**0.153**	**0.176**	**0.060**	**0.026**	**3.043**
16	**0.153**	**0.250**	**0.314**	**0.431**	**1.184**	**1.588**	**0.953**	0.468	0.111	0.039	**0.167**	**0.112**	**5.770**
17	**0.118**	**0.171**	0.190	**0.624**	**1.166**	**1.380**	**0.844**	**0.696**	0.238	0.112	**0.166**	**0.114**	**5.819**
18	**0.070**	**0.130**	0.135	**0.676**	**1.018**	**0.733**	**0.752**	**0.685**	**0.278**	0.127	**0.150**	**0.093**	**4.848**
19	0.037	0.094	**0.164**	**0.699**	**0.838**	0.312	**0.678**	**0.576**	**0.248**	**0.134**	**0.113**	**0.063**	**3.955**
20	0.017	0.062	**0.268**	**0.695**	**0.633**	0.085	**0.616**	**0.387**	**0.157**	**0.134**	**0.054**	**0.024**	**3.133**
21	**0.163**	**0.325**	**0.338**	**0.364**	**1.041**	**1.411**	**0.718**	0.360	0.028	0.042	**0.184**	**0.136**	**5.111**
22	**0.130**	**0.204**	0.189	**0.522**	**1.048**	**1.212**	**0.668**	**0.599**	0.185	0.109	**0.171**	**0.131**	**5.169**
23	**0.090**	**0.147**	0.156	**0.651**	**1.094**	**0.674**	**0.723**	**0.677**	**0.270**	0.153	**0.159**	**0.098**	**4.891**
24	**0.055**	0.102	0.167	**0.692**	**0.948**	0.313	**0.693**	**0.612**	**0.284**	**0.151**	**0.123**	**0.067**	**4.207**
25	0.026	0.068	**0.218**	**0.655**	**0.643**	0.102	**0.590**	**0.426**	**0.234**	**0.108**	**0.066**	**0.040**	**3.175**
26	**0.172**	**0.408**	**0.356**	**0.281**	**0.880**	**1.166**	0.469	0.321	-0.014	0.049	**0.179**	**0.155**	**4.422**
27	**0.137**	**0.256**	**0.230**	**0.407**	**0.919**	**0.973**	0.474	**0.562**	0.134	0.101	**0.154**	**0.147**	**4.494**
28	**0.109**	**0.175**	0.190	**0.556**	**1.053**	**0.579**	0.589	**0.650**	**0.257**	**0.175**	**0.149**	**0.106**	**4.589**
29	**0.082**	0.119	0.156	**0.595**	**0.939**	0.255	**0.633**	**0.617**	**0.339**	**0.170**	**0.129**	**0.081**	**4.115**
30	0.054	0.087	0.131	**0.540**	**0.620**	-0.004	0.613	**0.483**	**0.383**	0.094	**0.095**	**0.073**	**3.169**
31	**0.163**	**0.363**	**0.355**	**0.262**	**0.948**	**1.092**	0.394	**0.400**	0.033	0.074	**0.179**	**0.162**	**4.425**
32	**0.136**	**0.260**	**0.269**	0.241	**0.896**	**1.035**	0.456	**0.672**	0.177	0.102	**0.150**	**0.132**	**4.525**
33	**0.093**	**0.157**	0.156	**0.437**	**0.984**	**0.600**	0.592	**0.712**	0.240	0.161	**0.139**	**0.094**	**4.366**
34	**0.055**	0.082	0.063	**0.494**	**0.924**	0.236	**0.635**	**0.610**	**0.314**	**0.173**	**0.122**	**0.074**	**3.781**
35	0.021	0.034	-0.007	**0.431**	**0.739**	-0.059	**0.600**	0.390	**0.392**	0.145	**0.097**	**0.074**	**2.857**

[1] values statistically significant at the 0.05 level are given in bold

[2] grid points (numbering was made by columns from N to S, begining at the westernmost column, see also Figs. 5–10)

distinguished were the months at the turn of autumn and winter (November and December) and in spring (April and May). At that time, an increase in GSR input significant at the 0.05 level was recorded at all, or nearly all, grid points. The smallest number of grid points in which the increase in GSR input to the Earth's surface was significant characterised October and March.

The mean course for annual GSR at every grid point reveals the highest values in June, and the lowest in December. Of course, this is mainly connected to the height of the Sun above the horizon and the values obtained for cloudiness in these months. For all the grid points mean monthly values for GSR ranged from 38.8 MJ·m^{-2} in December to 534.1 MJ·m^{-2} in June (Table 2). On average, over the entire research period it was spring that showed the lowest variability for GSR, the highest being noted in winter. Considering individual months, the lowest value for the variability coefficient was recorded in August (3.9%), the highest in the winter months—December and February (5.8%).

Greater diversification in the course for annual GSR was visible when daily totals were taken into consideration. The annual course for GSR by daily totals (mean, highest and lowest) for three selected grids is presented in Fig. 2. The greatest variability over the entire 55-year period has been found for the annual course in the case of lowest daily sums. Much lower diversity was noted for the courses of both mean and highest totals. The reason for greater variability in the annual course of lowest daily GSR totals as compared with highest is probably cloudiness. The highest daily sums were probably noted under a cloudless sky, while the lowest ones characterised an overcast sky. Optical conditions of the atmosphere are more differentiate under an overcast sky than a cloudless sky. As a result, the lowest daily sums for GSR show greater variability in their annual course than the highest ones.

Changes in the level of GSR in December, i.e. the month of the lowest mean sums for GSR, and in June, i.e. the month with the highest sums on average, are presented in Fig. 3 and 4. The highest mean sums of solar

Table 2. Statistical characteristics of areally averaged sums for global solar radiation (MJ·m^{-2}) in Central Europe in the period 1951–2005

Parameter	J	F	M	A	M	J	J	A	S	O	N	D	Year
Upper quartile	55.50	105.60	227.10	354.90	507.80	548.10	525.70	403.30	256.00	145.60	64.40	40.40	3202.40
Lower quartile	51.80	98.00	212.60	333.10	469.40	520.90	492.40	380.70	241.30	134.80	59.30	37.30	3071.80
Highest mean value	60.40	117.50	243.90	381.50	548.80	590.30	601.50	421.50	270.00	157.10	69.00	42.70	3354.50
Lowest mean value	47.50	88.10	200.70	312.20	445.10	483.10	461.30	355.00	226.40	122.80	54.70	33.30	2965.30
Mean	53.80	102.20	220.60	346.40	491.40	534.10	510.00	391.50	248.70	140.20	62.00	38.80	3139.70
Skewness	-0.30	0.00	0.30	0.20	0.10	0.20	0.60	-0.20	0.20	-0.10	-0.10	-0.60	0.40
Kurtosis	-0.22	0.63	0.11	-0.32	-0.55	-0.08	0.95	-0.16	-0.65	-0.21	-0.63	-0.22	-0.36
Variance	7.73	34.96	83.24	240.46	563.50	585.75	774.05	229.45	119.82	57.28	11.49	5.01	8429.50
Standard deviation	2.78	5.91	9.12	15.51	23.74	24.20	27.82	15.15	10.95	7.57	3.39	2.24	91.81
Variability coefficient (%)	5.20	5.80	4.10	4.50	4.80	4.50	5.50	3.90	4.40	5.40	5.50	5.80	2.90

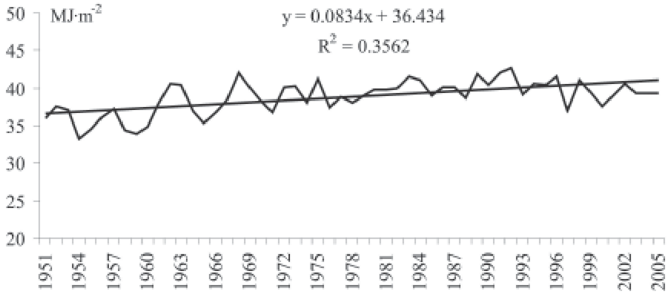

Figure 3. Long-term course for areally averaged sums of global solar radiation in December in Central Europe in the period 1951–2005

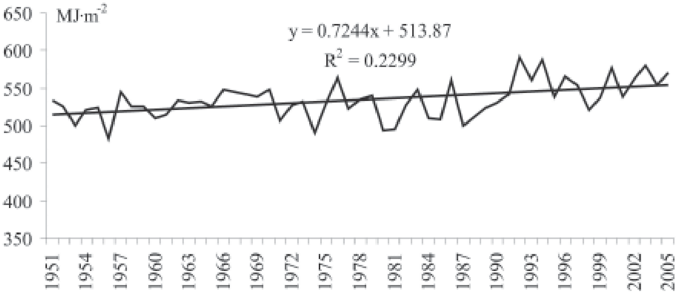

Figure 4. Long-term course for areally averaged sums of global solar radiation in June in Central Europe in the period 1951–2005

radiation in December was recorded in 1992 and equalled 42.7 MJ·m^{-2}; similar values (42.0 MJ·m^{-2}) being recorded in 1968 and 1991. The lowest values were noted in the 1950s, with especially low incoming GSR in 1954 (33.3 MJ·m^{-2}), as well as in 1959, 1958 and 1955. In June the situation was quite similar; the highest mean sums for GSR were recorded in 1992 (590.3 MJ·m^{-2}) and 1994 (588.2 MJ·m^{-2}), while the lowest came at the beginning of the research period, especially in 1956 (483.1 MJ·m^{-2}).

During the research period there was a decrease in the number of days of mean GSR (W·m^{-2}) not exceeding the value of the 10th percentile, and an increase in the number of days which exceeded the 90th percentile. In both cases these trends are statistically significant at $p < 0.05$. The spatial distributions for the linear trend coefficient for the number of days of that kind are presented in Fig. 5 and 6 respectively.

In the first case, the values for the linear trend coefficient range from -0.60 to -0.15, which means the number of days with GSR not exceeding the threshold value of the 10th percentile decreased over the entire study area (Fig. 5). The greatest decrease is recorded in the north- western part of the study area, i.e. over southern Scandinavia (-0.60), while the smallest is in the south of the study area (-0.15). In Poland the largest rate of change (-0.53) is recorded in the Bay of Gdańsk area (the grid point coordinates of φ=54.29°N, λ=18.75°E).

In the latter case, however, the values for the linear trend coefficient range from 0.27

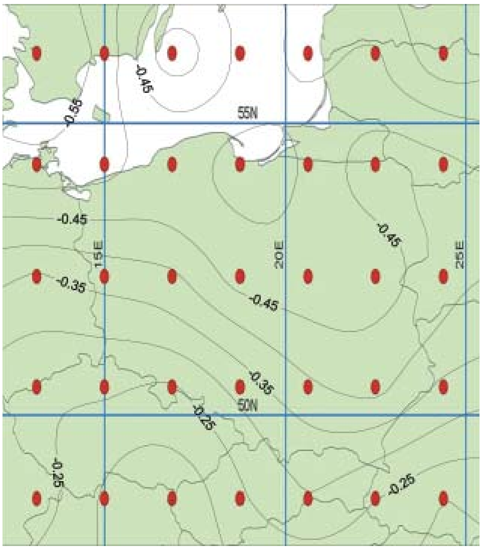

Figure 5. Trend coefficients (days·year^{-1}) for the number of cases of mean daily solar radiation (W·m^{-2}) not exceeding the 10th percentile in Central Europe in the period 1951–2005

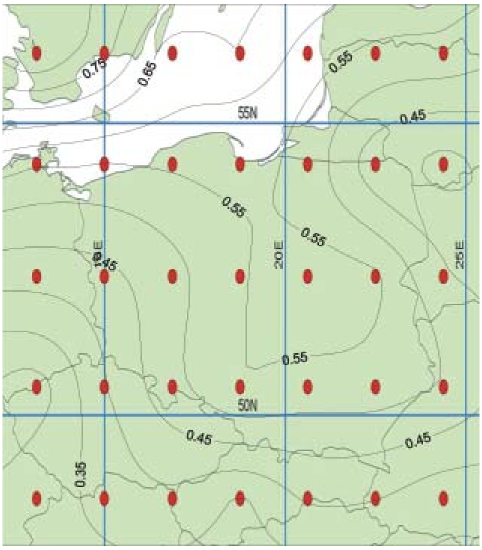

Figure 6. Trend coefficients (days·year^{-1}) for the number of cases of mean daily solar radiation (W·m^{-2}) exceeding the 90th percentile in Central Europe in the period 1951–2005

to 0.85 days a year (Fig. 6). The most rapid changes are recorded for the north-western parts of the study area, i.e. in the southern part of the Scandinavian Peninsula, while the slowest characterise the south-western part. In Poland, the highest values for the linear trend coefficient for the studied variable are recorded in the central part of the country and in the eastern section of the Baltic coast.

Distinct trends to changes are also recorded in individual months. The maps (Fig. 7, 8, 9 and 10) present the trends to changes in the number of days on which GSR did not exceed the threshold value of the 10th percentile, and those on which GSR exceeded the 90th percentile in the months of both the highest (June) and the lowest (December) levels of incoming solar radiation.

In June (Fig. 7 and 8) the area of the largest increase in incoming GSR is the north-western part of the study area, i.e. the southern edge of the Scandinavian Peninsula, while in Poland it is its north-western part. The above contention finds support in the observed decrease in the number of days on which the 10th percentile was not exceeded, and the increase in the number of days on which the 90th percentile was. On the other hand, in the southern and south-western part of the research area, the trend coefficients show the most limited changes in GSR inputs.

In December (Fig. 9 and 10), the area with the most marked decrease in the number of days with solar radiation not exceeding the 10th percentile threshold and exceeding the 90th percentile was in the north-east. In Poland, for the 10th percentile this is the area located north of: φ=52.38°N, λ=18.75°E and φ=52.38°N, λ=22.50°E, while in the case of the 90th percentile it is the area of the Bay of Gdańsk and the western part of the Mazurian Lakeland. In December, the smallest changes in incoming GSR in the study area were recorded in its southern and south-western parts.

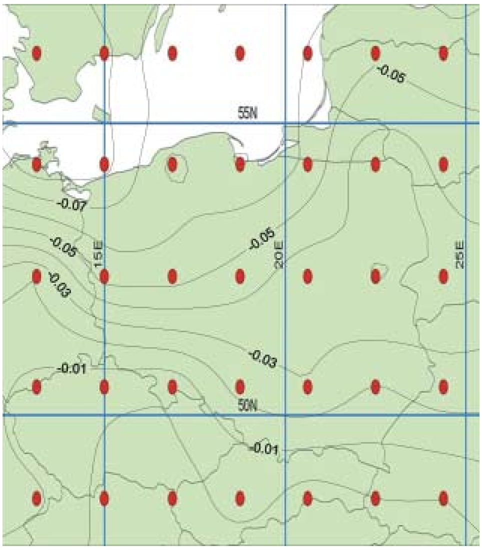

Figure 7. Trend coefficients (days·month^{-1}) for the number of cases of mean daily solar radiation (W·m^{-2}) not exceeding the 10th percentile in June in Central Europe in the period 1951–2005

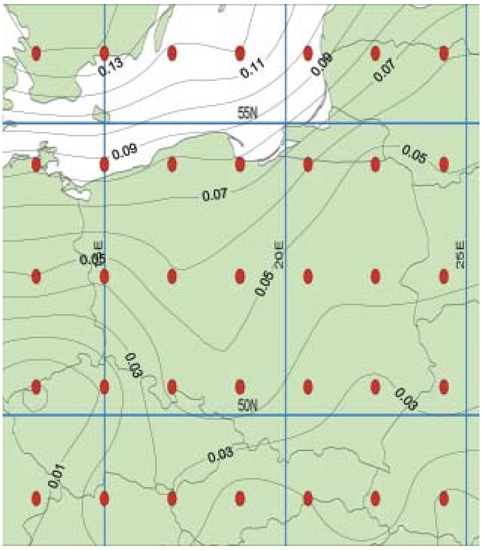

Figure 8. Trend coefficients (days·month^{-1}) for the number of cases of mean daily solar radiation (W·m^{-2}) exceeding the 90th percentile in June in Central Europe in the period 1951–2005

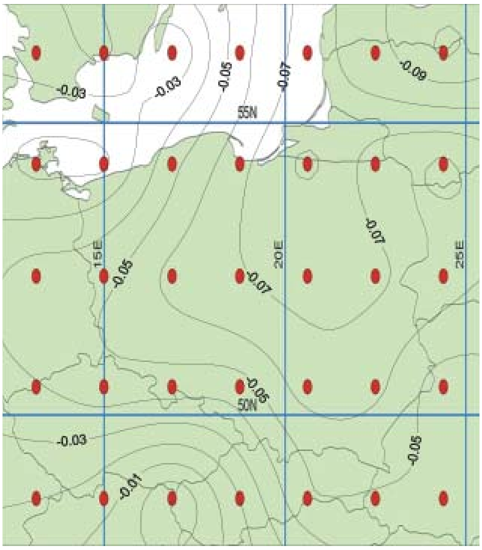

Figure 9. Trend coefficients (days·month^{-1}) for the number of cases of mean daily solar radiation (W·m^{-2}) not exceeding the 10th percentile in December in Central Europe in the period 1951–2005

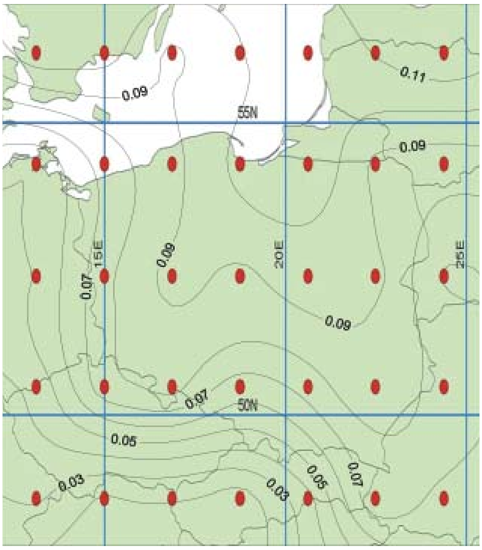

Figure 10. Trend coefficients (days·month^{-1}) for the number of cases of mean daily solar radiation (W·m^{-2}) exceeding the 90th percentile in December in Central Europe in the period 1951–2005

DISCUSSION OF THE RESULTS AND CONCLUDING REMARKS

The research reveals an increase in incoming GSR in the study area between 1951 and 2005. It must be stressed, however, that the study is based on NCEP/NCAR reanalysis data. Kalnay *et al*. (1996) used a numerical model for the calculation of these data. Thus the results presented here must be treated with caution. The comparison undertaken with data from selected meteorological stations operating in Poland shows that the NCEP/NCAR reanalysis data need correcting. Actinometric stations are often located in cities, while data from the reanalysis refer to larger areas of various level of human transformation. Thus, the station selected for comparison should be located where the influence of human activity on the atmosphere is relatively low. Such a comparison was made for the IMGW actinometric station in Mikołajki (φ=53.78°N, λ=21.58°E) and the grid point coordinates of φ=54.29°N, λ=22.50°E. The available data for 1961–1995 (Bogdańska and Podogrocki 2000) for the individual months and for the year were used to compare them with the mean sums for GSR for the selected station and grid point. According to the results of the comparison for the winter months (December and January) and for the end of autumn (November) the reanalysis data are overstated (by 9.6, 3.1 and 7.8% respectively). For the other months, however, the reanalysis data are understated by a few to a dozen per cent (from 6.0% in April to 17.8% in September), excluding August for which they are understated by 23.3%. In the case of the reanalysis data, the mean annual sum of GSR incoming to the Earth's surface is understated by 13% if compared with the measurement data from the IMGW network for the research period (1961–1995). These differences do not relate solely to mean values; also referring to trends for changes in the amount of radiation. GSR measured at the station in Mikołajki shows an increase statistically significant at the 0.05 level in May, while yielding decrease statistically significant at the same level in September. Mean annual values attest to an increase in GSR, but this is not statistically significant (Bogdańska and Podogrocki 2000). As far as the grid point selected for comparison for the period 1961–1995 is concerned, an increase statistically significant at the 0.05 level was also recorded in May, as well as in November and December. A decrease in radiation, similarly to Mikołajki, was recorded in September, though it was not statistically significant. The mean annual values show a statistically significant increase.

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MEAN AND EXTREME WIND VELOCITIES IN CENTRAL EUROPE 1951–2005 (ON THE BASIS OF DATA FROM NCEP/NCAR REANALYSIS PROJECT)

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Abstract: The paper presents the results of research on variability of wind speed in Central Europe between 1951 and 2005. According to NCEP/NCAR reanalysis data from 35 grids, Central Europe has witnessed increases in mean wind speed as well as in the number of days with strong wind, both statistically significant. This attests to the fact that the number of extreme phenomena connected with high wind velocities has increased recently.

Key words: wind speed, NCEP/NCAR reanalysis, Central Europe.

INTRODUCTION

Extreme natural (inter alia climatic) phenomena bringing both material and non-material damage have always been a part of human life. Initially, people were effectively powerless in the face of weather phenomena. However, as great material and human losses ensue, extreme meteorological phenomena have been assuming importance as issues for policy makers (Houghton *et al.* (eds.) 2001). The last decade of the 20th century brought a significant increase in climatic extremes (Katz and Brown 1992; Karl *et al.* 1999; Houghton *et al.* (eds.) 2001; Przybylak *et al.* 2006). Extreme meteorological phenomena often result in extreme events in other elements of the environment, be these hydrological or geomorphological, for example (Starkel 2003).

Recently, interest in high wind velocities in Europe, and the effects thereof, has grown significantly among geographers. This is mainly in anticipation of an increase in strong winds (Houghton *et al.* (eds.) 2001), and has been reflected in more and more careful analysis showing a significant increases in wind speeds throughout Europe. Thanks to its accessibility on the Internet, most studies have been based around reanalysis of NCEP/NCAR data for selected areas of Europe at various isobar levels (e.g.: Frank 2001, Larsén *et al.* 2006, Pryor *et al.* 2005, Marosz 2005, Pryor *et al.* 2006).

Nowadays wind energy also arouses renewed interest, being one of the oldest renewable energy sources to be exploited (e.g. Lorenc 1996, Soliński 1999, Pudlik 2003). The authorities of the European Union are assuming a steady increase in the role of renewable energy sources play in total energy production. By 2020 about 20% of the energy used in the European Union should be coming from renewable energy sources, which are theoretically eternal.

AIM, DATA, AREA AND METHODS

The aim of this study was to analyse mean and extreme wind velocities in Central Europe between 1951 and 2005. Due to a lack of complete data from meteorological stations in the area, the NCEP/NCAR data available at www.cdc.noaa.gov were analysed (Kalnay *at al*. 1996). The collected data for the years 1951–2005 include mean daily values for both zonal (U) and meridional (V) components of the wind velocity vector at a height 10 m above ground level (a.g.l.), these being used to calculate mean values for wind speed. The data from 35 grids in Central Europe were used in the research. This area is covered with grids at intervals of almost two degrees longitude and latitude. The way every four grids are located leaves the area between them of the same size (see dots in Fig. 1, 3 or 6).

The values calculated in this study include: monthly and annual mean values for wind speed, standard deviations and linear trends. Maximum mean wind velocities for individual months and the entire year were obtained. The number of days with strong (> 8 m·s^{-1}) wind was also estimated. Moreover, values for 1st, 10th, 90th and 99th percentiles were calculated for the individual grids. Also estimated was the number of times the 1st and 10th percentiles were not reached, and the frequency with which the 90th and 99th percentiles were exceeded. Additionally, the spatial distribution of wind velocities in Poland based on meteorological stations (Lorenc 1996, 2005) was compared to that based on the NCEP/NCAR reanalysis data.

RESULTS AND DISCUSSION

As the obtained results show, there are marked spatial and temporal differences to mean annual wind speed in Central Europe. Within the studied area this decreases from the south to the north-east (Figs. 1A-D). Such spatial diversity to wind speed over Central Europe is connected with orography. Recorded wind velocities are higher where altitude is greater. They are about twice as high in the Carpathians as in the lowlands and lakelands and on the Baltic coast. For most of the area the mean annual value for wind speed is of 2.6–3.6 m·s^{-1}. The highest mean annual values were recorded on mountain peaks, i.e. in the Carpathians and Sudetan Mountains (over 5 m·s^{-1}), cf. the lowest values in the lakelands of north-east Poland and Lithuania (about 2.6 m·s^{-1}) (Fig. 1C).

Mean annual wind speed for individual years deviates markedly from the long-term mean. In the entire analyzed period the lowest mean annual value for wind speed (3.1 m·s^{-1}) in Central Europe (area mean of all 35 grids) was recorded in 1952 and 1963, cf. the highest (3.7 m·s^{-1}) in 1983 (Fig. 2). Wind velocities much higher than the long-term mean values for the entire period were predominantly recorded between 1983 and 1998. Across Central Europe mean annual values of wind speed range from 2.2 m·s^{-1} (in 1960 in the western part of Belarus and the eastern part of Poland's Mazovian Lowland), to 6.7 m·s^{-1} (in 1983 over the western part of the Carpathians). Between 1951 and 2005, mean wind speed in Central Europe

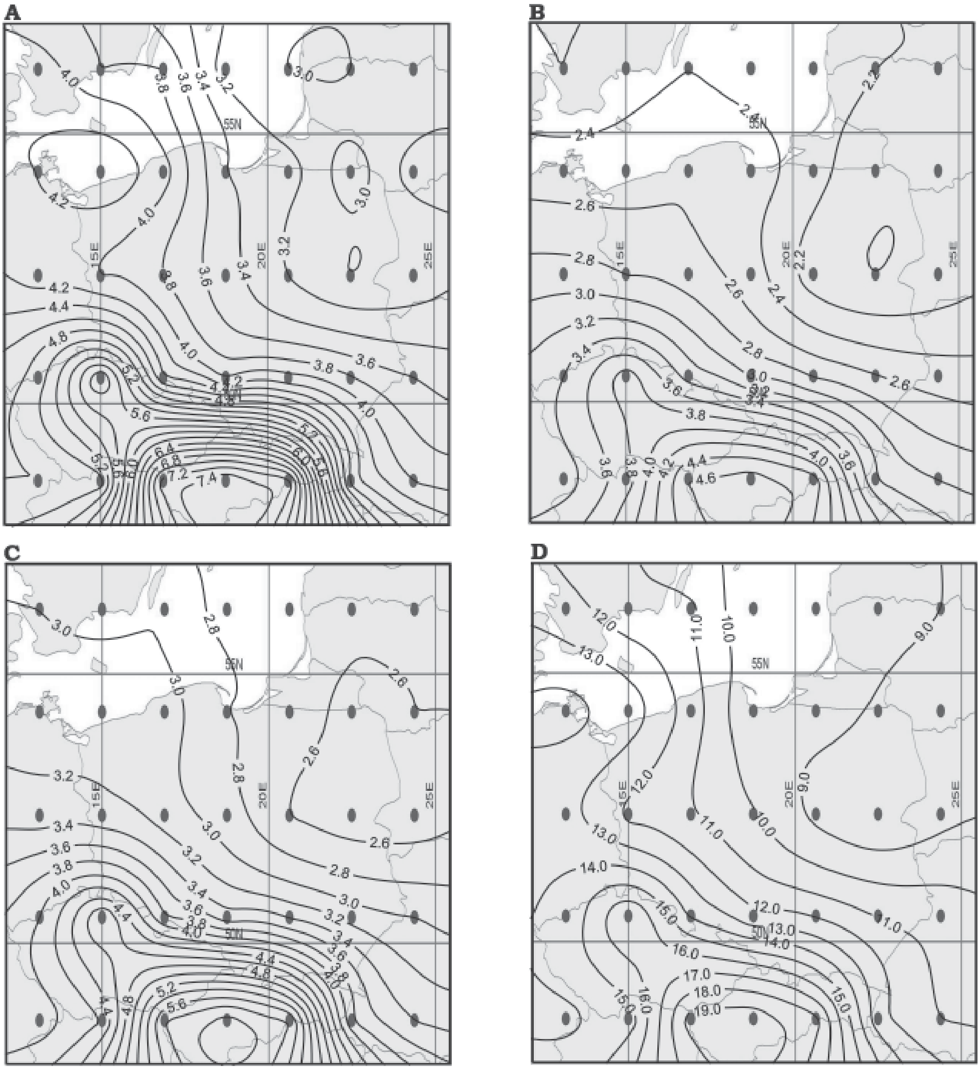

Figure 1. Mean values for wind speed (m·s^{-1}) in January (A), June (B) and annually (C), as well as maximum daily mean values for wind speed (D) in Central Europe, between 1951 and 2005

from all 35 grids grew by 0.03 m·s^{-1}·10 years^{-1} (Fig. 2). This increase was statistically significant at $\alpha = 0.05$. Trend coefficients for the mean annual values for wind speed in the individual grids are positive, excluding two located in northern Lithuania (Fig. 3B). The highest rate of change in Central Europe was that recorded in the western part of Germany and the Czech Republic, where the mean wind speed grew by over 0.06 m·s^{-1}·10 years^{-1}.

The highest mean annual wind speed in the entire studied area was recorded in January 1993 on the top parts of the Western

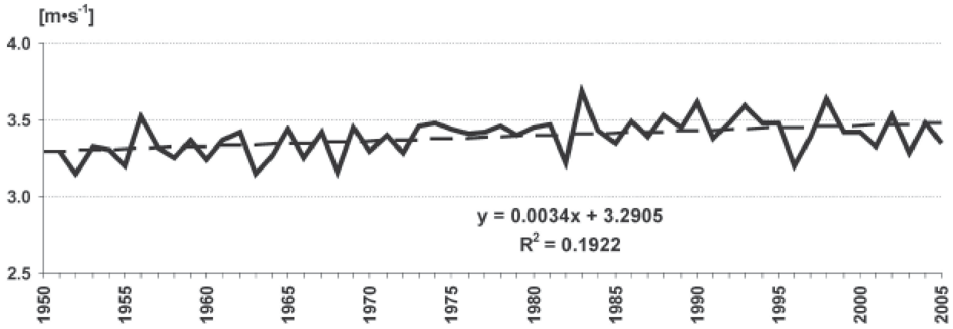

Figure 2. Course for mean annual wind speed (m·s^{-1}) in Central Europe between 1951 and 2005

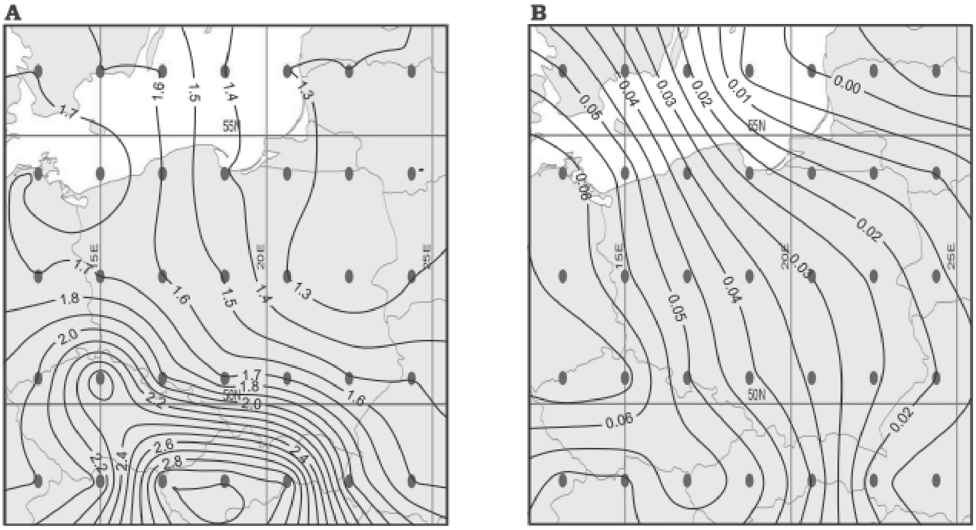

Figure 3. Standard deviation of mean daily wind speed (m·s^{-1})
(A) as well as values of the linear trend coefficient for mean annual wind speed (m·s^{-1}·10 years^{-1})
(B) in Central Europe between 1951 and 2005

Carpathians (10.4 m·s^{-1}), while the lowest was the 1.4 m·s^{-1} in June 1999 and July 1988 in the eastern part of the Polish Lowland, as well as in August 1967 above the northern part of the Mazurian Lakeland.

The yearly course is characterised by highest mean wind velocities in the winter months; for most of the grids this was January or, sporadically, December (Fig. 4). They are the result of large horizontal gradients in atmospheric pressure, frequent at that time of the year. During these months mean wind speed over most of Central Europe varied between 3 and 4 m·s^{-1} (Fig. 1A). Pryor *et al.* (2005) obtained similar values for this area over a shorter period (1953–2001), on the basis of data from the NCEP/NCAR reanalysis. In the Carpathians, wind speed during the winter months exceeds 7 m·s^{-1}. In January (the month of highest mean wind speed), the highest mean values of wind speed anywhere in the area were recorded in 1983 and 1993 (5.8 and 5.7 m·s^{-1} respectively), while the lowest (3.2 m·s^{-1}) characterized 1963 and 1973. Between 1951 and 2005, Central Europe experienced a statistically significant (α = 0.05) increase in mean wind speed in January (0.08 m·s^{-1}·10 years^{-1}).

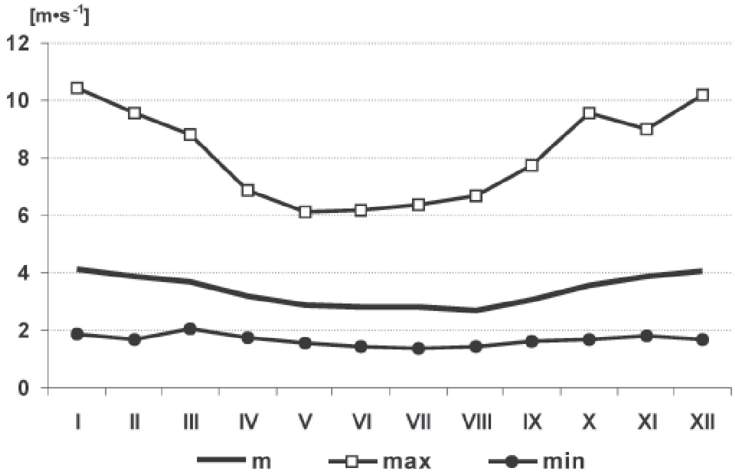

Figure 4. Annual course for wind speed values (m·s^{-1}) in Central Europe between 1951 and 2005

The lowest mean wind velocities were recorded in summer, with the minimum in August (Fig. 4). The analysis of August (as the month of lowest mean wind speed) over the entire area (35 grids) shows that wind velocities were lowest in 1997 (at 2.2 m·s^{-1}), and the highest in 1959 and 1998 (3.2 m·s^{-1}). During the entire studied period, Central Europe has nevertheless experienced a small decrease in mean wind speed in August (0.01 m·s^{-1}·10 years^{-1}).

Much greater diversity is to be noted where daily mean wind speed is concerned, especially during the cold season. The values for standard deviation from the daily mean values for wind speed over the entire study area range from 1.2 m·s^{-1} (over the north-eastern part of the analysed area) to 3.0 m·s^{-1} (over the southern part of Central Europe) (Fig. 3A). The distribution of the highest mean daily values for wind speed is similar to that for standard deviation as regards wind speed (Fig. 1D). The highest value (19.6 m·s^{-1}) was recorded on 22 January 1993 in the western part of the Carpathians in Slovakia. In most of the analysed area (24 out of 35 grids, excluding the north-eastern part of the studied area) the highest values for mean daily wind velocities exceeded 10 m·s^{-1}. According to the analysis, the values for the variability coefficient of wind velocity are between 0.48 (in the western part of Ukraine) and 0.57 (the southern part of the Scandinavian Peninsula).

Extreme phenomena such as strong winds (> 8 m·s^{-1}) are important for the way people feel. The maximum frequency of strong winds falls in winter, while the minimum is in summer. Strong winds in winter are connected with the fast movement of cyclones over the Atlantic Ocean towards Eastern Europe. The areas in which strong winds occur most frequently are the mountain tops of the Carpathians (22–25% days of a year). In individual years, the number of days with strong winds here may amount to over 100 annually. The number of days with strong wind compared to the mean value for wind speed shows that areas of high mean wind speed also record a large number of days with strong wind. Year-to-year changes in the frequency of strong winds between 1951 and 2005 in Central Europe are as presented in Fig. 5. Between 1951 and 2005, the smallest number of days with strong winds over the entire studied region was recorded in 1968, the largest in 1983. The number of days with strong winds in the analysed period is characterised by a statistically upward trend (0.7 days $\cdot 10$ years^{-1}) that achieves significance at $\alpha = 0.05$. Such results attest to an increased number of extreme phenomena connected with high wind velocities over the analysed area. The increase in mean wind velocity and in numbers of days with strong wind is connected with intense cyclonic activity over Europe over recent years. This upward trend to the activity of low-pressure systems can be observed clearly over the northern Atlantic (e.g. Gulev *et al.*, 2001; Wang *et al.* 2006).

Table 1 and Figs. 6 A-D present the spatial distribution and mean, minimum and maximum values for the 1st, 10th, 90th and 99th percentiles of daily mean values for wind speed in Central Europe between 1951 and 2005. The isolines of the individual percentiles correlate with the distribution of annual mean values for wind velocities (Fig. 1C). Generally, the study area is divided into two separate parts along a NW-SE profile. Central Europe is divided in the following way: the value of 0.4 $m \cdot s^{-1}$ of the 1st percentile, the value of 1.3 $m \cdot s^{-1}$ of the 10th percentile, the value of 5.0 $m \cdot s^{-1}$ of the 90th percentile, and the value of 7.0 $m \cdot s^{-1}$ of the 99th percentile (Fig. 6A-D).

The source data used for this analysis come from the calculations of a numerical model, and should as such be treated with caution. Comparative analysis with data from meteorological stations in Central Europe proved that data from the NCEP/NCAR reanalysis need correcting. The com-

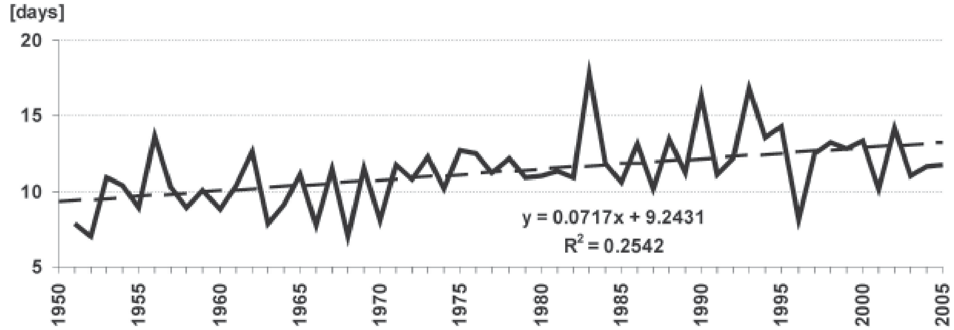

Figure 5. Year-to-year course of number of days with strong wind ($v > 8\ m \cdot s^{-1}$) in Central Europe between 1951 and 2005

Table 1. Highest (H), mean (M) and lowest (L) values for the 1st, 10th, 90th and 99th percentiles of daily wind speed ($m \cdot s^{-1}$) in Central Europe (35 grids), between 1951 and 2005

Percentiles	Elements	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
1st	H	1.1	0.8	0.9	0.5	0.6	0.5	0.6	0.6	0.8	1.1	1.2	1.1
	M	0.5	0.5	0.5	0.4	0.4	0.3	0.3	0.3	0.4	0.5	0.5	0.5
	L	0.3	0.3	0.4	0.3	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3
10th	H	3.3	2.7	2.9	2.0	1.8	1.6	1.7	1.9	2.5	3.1	3.4	3.2
	M	1.7	1.5	1.5	1.2	1.2	1.1	1.1	1.1	1.2	1.5	1.6	1.7
	L	1.2	1.1	1.2	0.9	0.9	0.8	0.8	0.8	0.9	1.1	1.1	1.2
90th	H	12.0	11.0	10.4	8.9	7.9	7.4	8.0	8.4	9.7	11.0	11.4	11.7
	M	6.8	6.3	6.1	5.3	4.7	4.5	4.6	4.5	5.1	5.8	6.4	6.6
	L	4.7	4.6	4.4	4.0	3.4	3.4	3.3	3.2	3.7	4.2	4.6	4.6
99th	H	15.0	14.4	13.2	12.9	11.2	10.8	11.3	11.8	13.5	14.3	14.6	15.1
	M	9.1	8.8	8.2	7.4	6.5	6.3	6.3	6.3	7.0	7.8	8.5	8.7
	L	6.3	6.3	6.0	5.5	4.7	4.7	4.6	4.6	5.2	5.7	6.0	6.0

parison was undertaken for Poland (Lorenc 1996, 2005), for both annual and monthly means at the selected points. According to the analysis, the reanalysis data are underestimated. For instance, the analysis of the distribution of mean annual wind speed in Poland (along the north-south profile), the values from the meteorological stations from the years 1971–2000 (Lorenc 2005) are higher: by the Baltic Sea: for example Elbląg by 0.7 $m \cdot s^{-1}$ and Hel by 1.6 $m \cdot s^{-1}$, in central Poland: Łódź by 0.9 $m \cdot s^{-1}$ and Warsaw by 1.5 $m \cdot s^{-1}$, while on Kasprowy Wierch in the Tatras by 1.7 $m \cdot s^{-1}$. The same kinds of differences between the two data sets were also obtained for mean monthly values. The presented values for wind velocities from the NCEP/NCAR reanalysis not only are too small, but their spatial distribution over Poland is also highly problematic. As far as spatial distribution is concerned, one of the most important differences between the data from the synoptic stations and those from the NCEP/NCAR reanalysis is the lack of high speed winds characteristic for the Baltic Sea shore.

CONCLUSIONS

The detailed analysis of wind speed values over Central Europe between 1951 and 2005 as based on data form the NCEP/NCAR reanalysis has allowed the authors to draw the following conclusions:

- Between 1951 and 2005 a statistically significant increase in mean annual wind speed was recorded in Central Europe. Values for wind speed were exceptionally high in the 1980s and 1990s.
- Considering the annual course, the highest mean wind velocities were recorded in January, the lowest in August. Between 1951 and 2005 a significant increase in January wind velocities (and a slight decrease in August wind velocities) were recorded.
- Significantly higher wind velocities are to be noted in mountainous areas (the Carpathians and the Sudetan Mountains). These velocities are about twice as high as in the surrounding areas.
- In the analysed period the annual average number of days with strong wind showed a statistically significant upward trend.

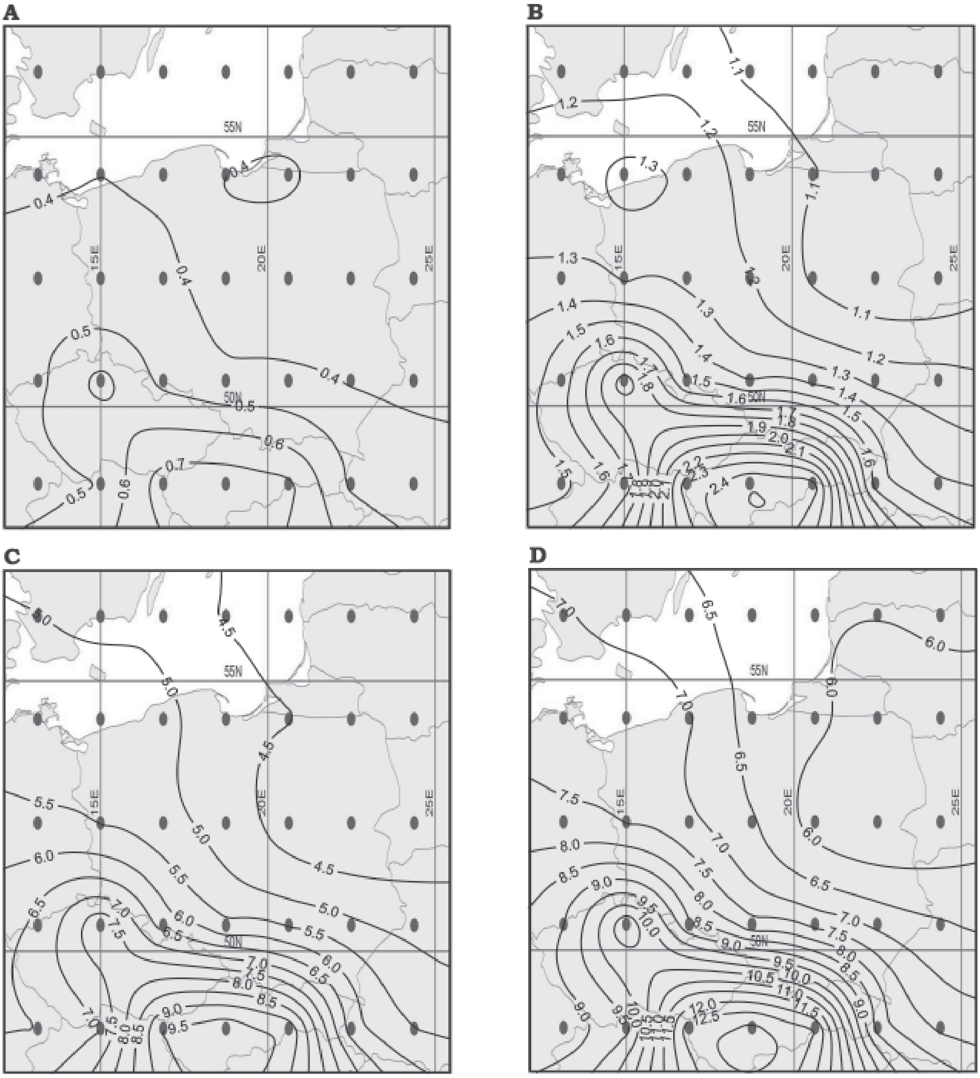

Figure 6. Values of the 1st (A), 10th (B), 90th (C) and 99th (D) percentile of wind speed (m·s^{-1}) in Central Europe between 1951 and 2005

- Reference to the number of days with strong wind compared to the mean value for wind speed makes it clear that areas with a high mean wind speed also recorded a great number of days with strong wind.
- The comparative analysis of the wind velocities from the NCEP/NCAR reanalysis and the data obtained from the meteorological stations in Central Europe show that reanalysis data are underestimated by about 1–1.5 m·s^{-1}.

ACKNOWLEDGEMENTS

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RIVER TRAINING VS. FLOOD RISK IN THE UPPER VISTULA BASIN, POLAND

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Abstract: This paper assesses the effect of river training in the 20th century on the evolution of flood risk in the middle and lower courses of certain Polish mountain and upland rivers, and in the lowland Carpathian foreland. The overall anthropogenic impact on the flood risk is a combination of two contradictory trends: (a) the shortening of the floodplain inundation time (between the levees) as a result of the deepening of the trained channel; and (b) the increasing height of the flood water and frequency of flood culminations, a result of the flood wave transformation. The author, in his flood risk analysis, regards the former trend as the more influential. The highest levels of all types of flood risks were found along the valley reaches with unembanked channels that displayed a tendency to reduce both their depth and gradient. This type of reach occurs immediately downstream of embanked reaches with a deepened channel. The author also addresses ways to mitigate flood risk levels, taking into account limitations stemming from local land development and legal conservation status.

Key words: flood risk, flood, upper Vistula basin, river training.

INTRODUCTION

Flood risk should be understood as the likelihood of economic losses being suffered within a floodplain as a result of flooding by overbank culminations of a moving flood wave. It depends on the duration of the overbank discharge and the vertical and horizontal extents of flooding within the embankments. Contemporary flood risk is modified by human activity, and its level is a combination of the hydrological effects of processes of long duration, such as drainage basin deforestation, agricultural expansion, urbanisation and river training. This activity modifies, not just the duration and extent of flooding, but also the pace of concentration and speed of flood wave movement.

One of the purposes of river training is to reduce the flood risk by accelerating the drainage of a submerged floodplain along a deliberately shortened channel. River training projects trigger processes of systematic deepening along the shortened and steepened reaches, and shallowing along reaches with a less steep gradient (Brookes 1990; Łajczak 1995a). This accelerates the flow velocity and, in embanked rivers, also increases the water level amplitude. Along the reaches with fast deepening channels the duration with an overbank water level may tend to reduce. However, an increased concentration of flood waves and increased water level amplitude in the upstream reach may increase the flood risk along those less steep reaches further downstream where the embanked cross-section volumes are low (Punzet 1991; Wyżga 1993; Łajczak 1995a). It is possible to control floods on trained rivers effectively by means of river dams (Punzet 1959, 1973). This is however impossible on rivers utilised for navigation, since this type of hydrotechnical structure is absent.

River training has been increasingly perceived as a controversial activity and sometimes also as a contradictory one that does not produce the expected reduction in flood risk (Kajak and Okruszko 1990; Andrews and Burgess 1991; Finlayson 1991; Angelstam and Arnold 1993; Łajczak 2006a, b). A heightened flood risk resulting from river training has only been noted over the last 20 years (e.g. Cooper *et al.* 1987; Howard 1992; Kajak 1993). This can be seen, in particular, along those reaches that are becoming shallower. A heightened ground water table in the valley, one of the effects of the channel shallowing downstream of the fast-deepening channel reaches (Żelazo 1993), further extends the duration and extent of excessive water content within the floodplain beyond the flood embankments.

STUDY OBJECTIVE AND MATERIALS

This paper looks at the change in the flood risk in the upper Vistula drainage basin, as a result of river training during the 20th century. The study focuses on three rivers running through mountains, foothills, uplands and lowland forelands (the Rivers Raba and Nida, and the foreland course of the Vistula). The paper is based on the literature, the author's own research in the upper Vistula and Nida Valleys, and on data supplied by the Institute of Meteorology and Water Management.

STUDY AREA

In Poland there are two areas in which summertime or early springtime floods predominate, and turn into catastrophic events every few years (Fig. 1). One covers the drainage basins of the mountain tributaries of the rivers Vistula and Odra and the foreland courses of those rivers, while the other spans the Vistula's and Odra's upland and lowland tributaries, including those located in foreland areas. Most of the upper Vistula river system features a predominance of summer rain floods, both annually and in the long-term. On the River Raba, a typical Western Carpathian watercourse, the flood risk is restricted to the summer season, while on the River Nida, the longest upland tributary of the upper Vistula, it is restricted to the early springtime, and less often the summertime. The foreland course of the upper Vistula has a hydrological regimen driven primarily by its mountain tributaries. Currently, the flood risk along this course of the river is limited to the summer months, but the early spring is also added, downstream of the River San confluence (Dynowska 1971; Ziemońska 1973; Punzet 1991).

About a century ago, the beginning of hydrological records (on water levels and discharges) coincided with the first active and passive measures mitigating flood risk in the Upper Vistula valley. The records can now be used to assess the evolution of flood-risk patterns, whether caused by natural or by human-induced processes.

The attempts at river training olong the course of the River Vistula that form the subject of this study started at the end of the 19th c. and lasted throughout the 20th. They changed the earlier trends in the channel

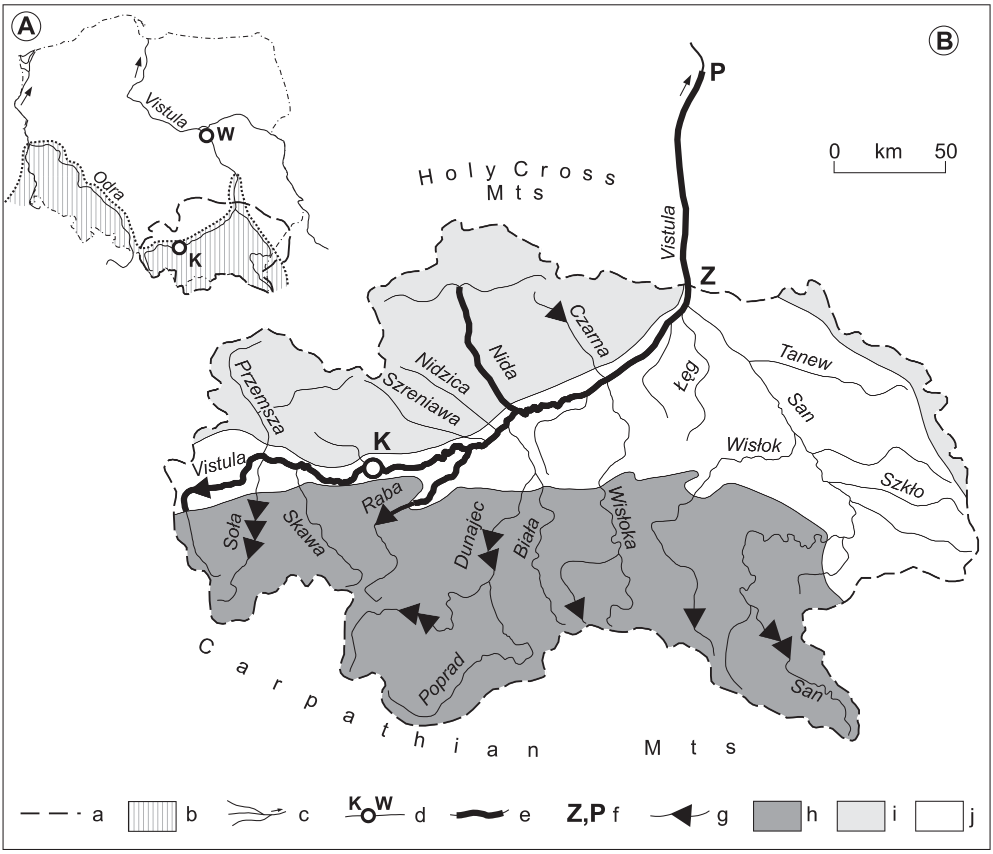

Figure 1. The upper Vistula drainage basin on the map of Poland (A).
River network against principal geomorphological units (B).
a) limit of the upper River Vistula drainage basin, b) area dominated by summer rain floods,
c) main rivers, d) Cracow (K) and Warsaw (W), e) river reaches (Vistula, Raba and Nida) analysed
in the paper, f) water gauge at Zawichost (Z) and Puławy (P) measuring the outflow
from the upper Vistula drainage basin, g) large dams. Principal geomorphological units in the basin:
h) Carpathian Mts., i) Polish Uplands, j) Sub-Carpathian basins.

development of its tributaries, involving both shallowing and broadening. The morphology of the Carpathian river channels, which are crucial for the supply of water and bedload and suspended load to the Vistula, exhibit regional differences (Klimek 1979). The westernmost gravel-bedded tributaries down to and including the River Dunajec are more susceptible to change under the influence of river training than the eastern tributaries (the Wisłoka, Wisłok and San), which often feature bedrock channels along their mountain courses in the Beskidy Mountains. The erection of numerous rubble dams in the Carpathian Mts. reduced bedload transport along the upper courses of mountain rivers and streams, while river dams, the first of which was built in the 1930s, have been intercepting all of the bedload and most of the suspended material. As a result, the pace of shallowing downstream of the dams has been reduced. This has been further assisted by a reduction in the supply of bedload from the channel banks after their reinforcement with stone bands. From the flood-risk point of view, the greatest hydrological consequences have been engendered by the deepening and narrowing of the channels, a process started in the early 20th c. On the River Vistula and the lower courses of its mountain tributaries this process was mostly driven by channel shortening (Punzet 1981; Klimek 1987; Wyżga 1993; Łajczak 1995a; Wyżga and Lach 2002). Along the upper courses of the Carpathian rivers, this development trend is assisted by a growing afforestation of their drainage basins, since the mid 20th century, and by the trend for field tracks in the depopulated areas of the Beskid Niski and Western Bieszczady ranges to revegetate (Izmaiłow *et al.* 2003).

River training has also included flood embankments erected along the foreland course of the Vistula, along the lower courses of its Carpathian tributaries and also locally along their intra-mountain-basin courses, along the lowland tributaries and some of the upland tributaries (Hennig 1991). The insufficient embankment-to-embankment space that resulted has reduced the zone liable to flooding by a factor that is often larger than 10 (on the River Vistula). Subsequent effects included higher maximum water levels on the River Vistula, (up to twice as high along the Cracow reach), and a faster travelling flood wave (Soja and Mrozek 1990; Punzet 1991).

CHANGES IN FLOOD RISK DURING THE 20TH C.

CARPATHIAN RIVERS USING THE EXAMPLE OF THE MIDDLE AND LOWER RABA

The River Raba provides an example of a gravel-bedded Western Carpathian river draining the Beskidy Mts., the Carpathian Foothills and the lowland Carpathian foreland (Fig. 2). The newly constructed river training along the course of the river has led to a shorter, narrower and deeper channel. In the aftermath of the river training measures the channel deepened by more than three metres in its middle and lower course, a typical value recorded on the lower courses of other Carpathian tributaries of the River Vistula. The channel also increased in compactness through a lowering of the width to average depth ratio. This change resulted in an increased water flow velocity, particularly during flood events, and consequently in greater concentrations of flood waves and increased speeds of flood wave travel (Wyżga 1993). As a further consequence, the differences between the maximum flood water levels recorded during the same events on the lower course of the Raba and on the middle course of the river have been increasing since the second half of the 20th century. (Fig. 3). The faster flow in the deeper channel results in a higher bankfull discharge at the expense of overbank discharge. The narrow embankment-to-embankment space in the lower course of the river additionally forces maximum water levels to become ever higher, while shortening the duration of the flood wave event and increasing the flood wave velocity. Such a flood wave profile has a considerable impact on the flood situation along the River Vistula.

The Raba is one of those Carpathian rivers wherein the assessment of the impact of river training on the evolution of the flood risk is far from easy and straightforward. On the one hand, engineering has brought a reduction in flood risks along the trained reaches in terms of flood duration and area affected. Indeed, the flood wave travel times and the number of overbank discharge days have been reduced, and the floodplain inundation time is down dramatically. On the other hand, the greater flood wave speeds may, in certain situations, shorten the time local communities have to mount an

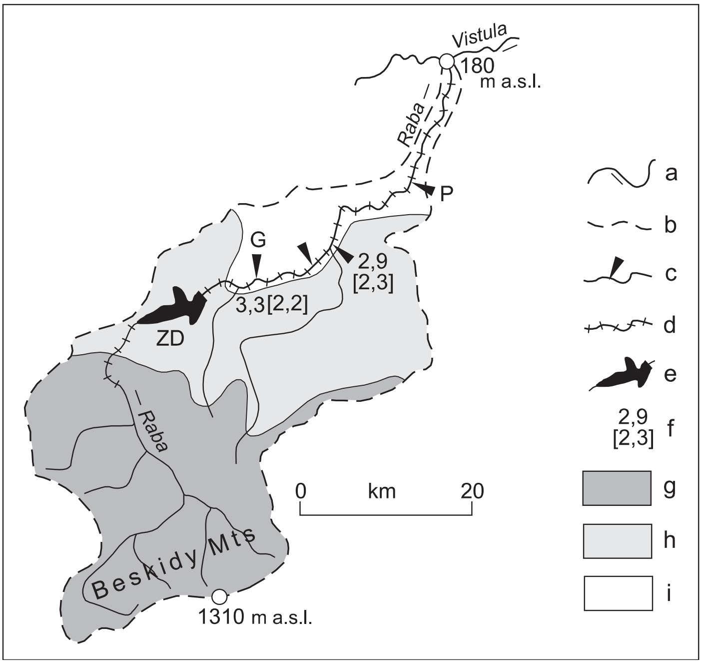

Figure 2. The River Raba drainage basin.
a) main rivers, b) limit of the drainage basin, c) selected water gauges in the middle and lower courses of the river, G- Gdów, P- Proszówki, d) partly or fully trained reach of the river, e) artificial lake Dobczyce (ZD), f) deepening [m] of the Raba channel at selected water gauges following river training in the 20th century, in parenthesis the value related to the second half of the 20th century (according to Wyżga 1993). Geomorphological units in the basin: g) Beskidy Mts., h) Carpathian Foothills, i) Sub-Carpathian basins.

adequate response, and therefore be considered to increase the flood risk. Additionally, river training has increased flood risks along the untrained reaches downstream, as reflected by the increasing maximum flood wave levels in the lower course during the largest events. This trend is observed despite a parallel trend to reduce the volume of the flood wave, as measured above the bankfull stage. A further flood risk improvement could be achieved via effective use of the Dobczyce Dam, especially in view of the mostly positive experience with dams as flood management instruments on other Carpathian tributaries of the Vistula (see: Punzet 1959, 1973, 1991).

UPPLAND RIVERS EXEMPLIFIED BY THE MIDDLE AND LOWER NIDA

The River Nida is an example of an upland river with a sandy channel and a low gradient in its middle and lower courses (0.2–0.5‰). Along this stretch, the river meanders with a meander coefficient that reaches 2.0 locally. Its floodplain is regularly submerged during springtime floods, and less often during summertime, and the water can stagnate for over three months. During the period 1950–1995, the middle course (between Brzegi and Pińczów) was shortened and partly equipped with flood embankments, and extensive wetlands were also drained within the floodplain, especially along a long anastomosing

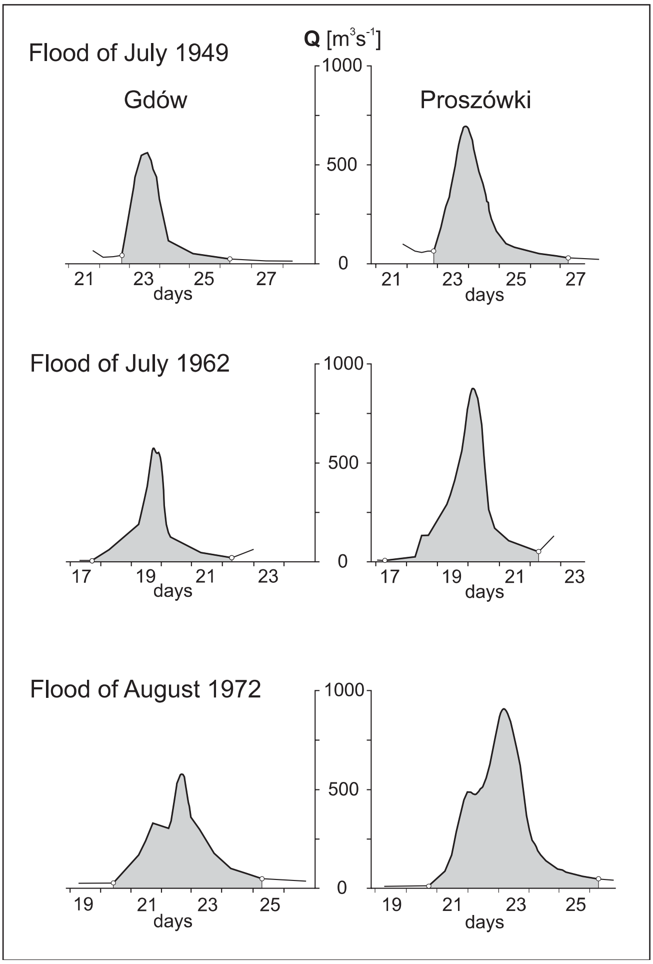

Figure 3. Hydrograph of selected flood waves in the middle and lower River Raba courses between Gdów and Proszówki.

reach near Umianowice (Łajczak 2006b). The lower course of the river (downstream from Pińczów) has remained untrained, with a natural channel and floodplain (Fig. 4). The river training has been aimed at accelerating the draining of flooded areas and the drying out of the floodplain. From the point of view of flood control, the result has been mixed.

The river has begun to deepen its shortened channel, as recorded by a water gauge at Brzegi (Fig. 5). Because of the slow transport of sand, the river has been observed to become shallower downstream around Pińczów, initially in the old channel but more recently (since 1970) also in the new, initially deep channel. This process varies in speed, and depends on the intensity of the upstream river training work. The zone subject to the shallowing process is moving, but has not yet reached the next water gauge at Wiślica. The slow downcutting trend along the mouth

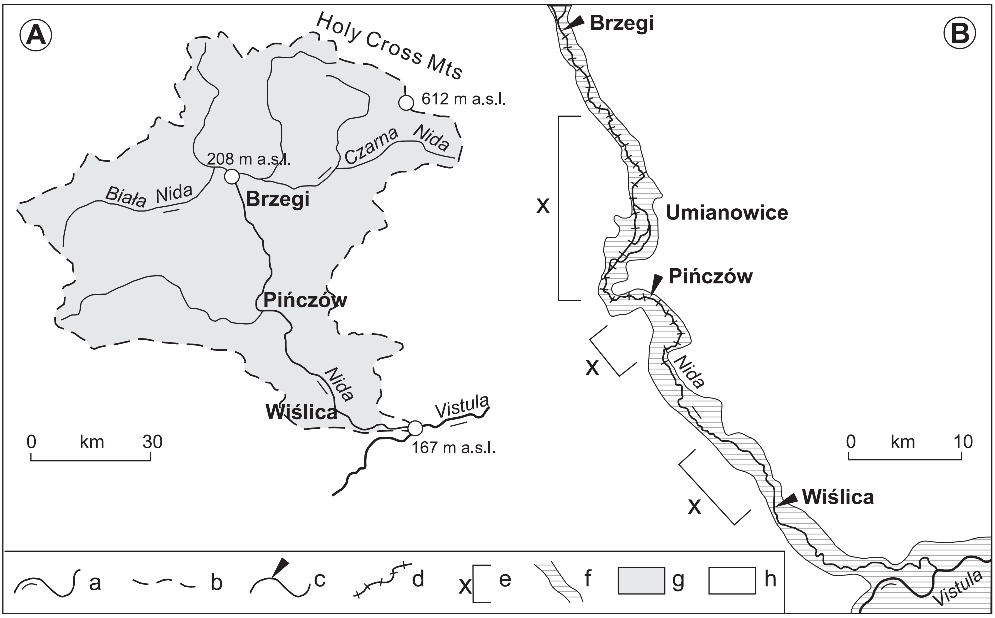

Figure 4. River Nida drainage basin (A) and middle and lower courses of the river (B).
a) main rivers, b) limit of the drainage basin, c) water gauges, d) partly trained river reach,
e) formerly anastomosing reaches of the river currently partly or fully trained, f) floodplain extent.
Geomorphological units in the basin: g) Polish Uplands, h) Sub-Carpathian basins.

reach of the Nida below Wiślica is a result of a similar trend on the Vistula since the beginning of its training in the late 19th century. On the deepened reach of the Nida, the bankfull discharge volume has been growing, as recorded by the water gauge at Brzegi. During the period 1939–1990, this produced a trend whereby the number of overbank discharge days was reduced from 10 to less than 2 days. The extension of the floodplain inundation time observed along this reach since 1990 is independent of a gradual deepening of the channel, and is caused by the increasing frequency of large floods. Along the shallowing channel the duration of the floodplain flooding has been growing into long periods that are independent of long-term river discharge patterns. The inundation time near Pińczów had been growing until 1969 (reaching 80 days per year), after which it shrank to less than ten days and increased again during the last decade (to 30 days per year). The main cause of the increase in the flood risk near Pińczów (the largest town on the river) observed since the mid-1990s seems to be the continuing shallowing of the river channel, as a result of misguided training and drainage projects, and only partly due to the greater frequency of large flood events. The engineering measures have resulted in effective drainage of large marshy areas adjacent to the anastomosing reaches. The flood risks near Pińczów could be partly mitigated by a revitalisation of the drained wetlands and by returning their functions (Łajczak 2006b). In the mouth reach of the river, downstream from Wiślica, the Vistula backwater effect generates a very high flood risk level, manifested by the long duration of floodplain flooding (up to 100 days) and

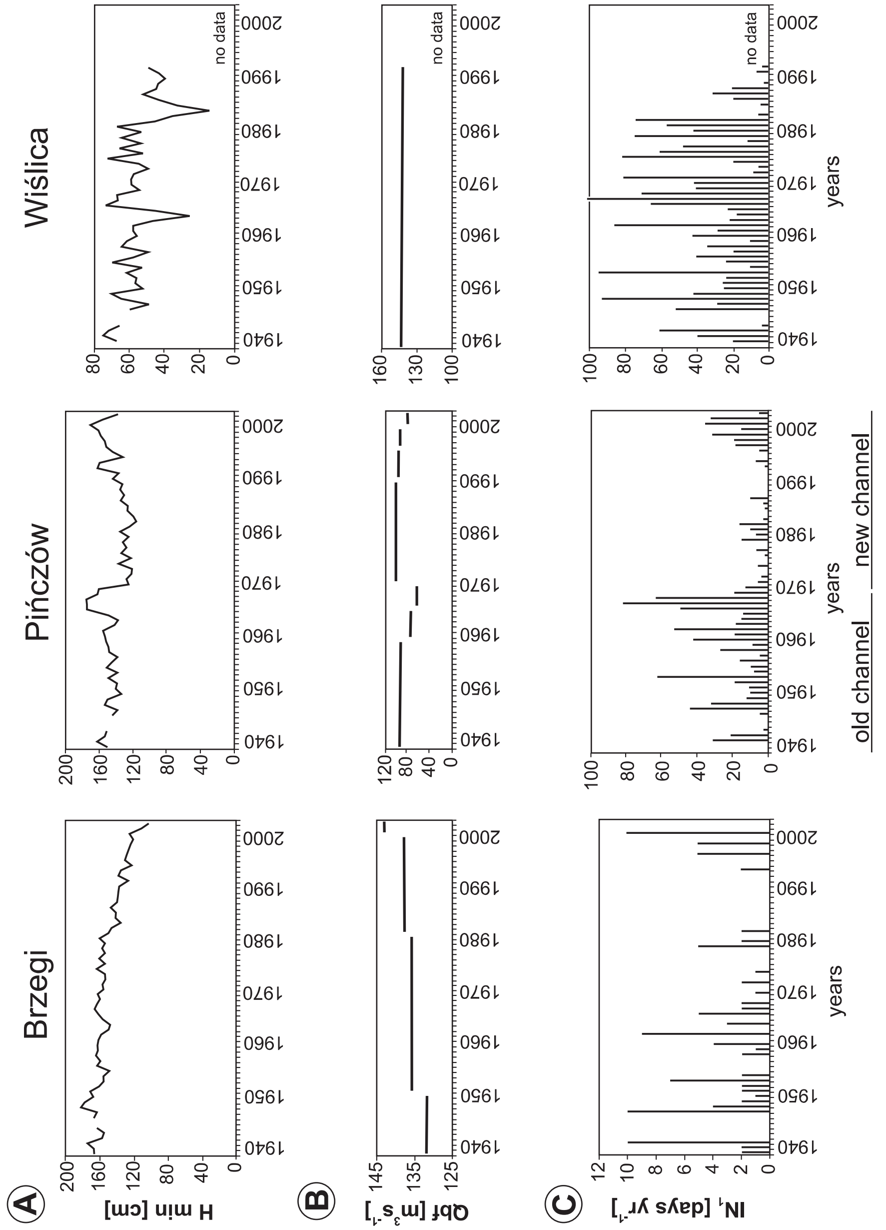

Figure 5. Minimum annual water levels Hmin during 1939–2003 (A) and change in the bankfull discharge Qbf (B), as well as the change of the overbank IN$_1$ water levels (C) at water gauge stations in Brzegi, Pińczów and Wiślica.

the highest water levels recorded along the entire river. The fluctuation in the Vistula water level in the area reaches up to nine metres, and the backwater effect can go up to Wiślica when large flood events are taking place on the main river. With its long retention of flood water, the Nida river has seen a mixture of flood risk improvement and deterioration, depending on the reach, as a result of river training. The only significant changes in the risk levels include the floodplain inundation duration and territorial extent. The river has no significant impact on flood risks in the Vistula valley.

Uniquely among major tributaries of the upper Vistula, the Nida has a valley already subject to several legal conservation statuses (including as a Landscape Park, an ecological corridor and a *Natura 2000* area), which only allows environmentally sound methods of flood risk mitigation (Łajczak 2006a, b). These methods might include revitalisation of the extensive wetlands, now mostly drained, and an expansion of the territory between the embankments to increase its volume. The earlier plans to erect a dam on the Nida upstream of Brzegi, and indeed any training measures that would introduce large quantities of sand, should be seen as undesirable.

THE FORELAND COURSE OF THE RIVER VISTULA

The foreland course of the River Vistula is the most thoroughly investigated part of the study area in terms of changes to the flood risk caused by river training. The engineering projects, involving an approximately 30% reduction in channel length, new stone spurs and bank protection, were designed to prepare the river for its role as the country's main waterway, and to protect adjacent areas from flooding. During the 20th century, modifications to the cross-section of the river channel included deepening by an average of two metres (and a maximum of 4 m) and large scale deposition in the bank zones. Local level differences in the channel cross-section increased three-fold compared to the early 20th century. Conversely, there were also cases of the channel becoming shallower, i.e. in the Oświęcimska Basin upstream of the Przemsza and Soła confluences and over a longer reach where the river breaks through the Polish Uplands. The alternating pattern of deepened channel sections and sections becoming shallower is therefore a characteristic feature of the foreland River Vistula during the river-training era (Fig. 6). Another characteristic of the channel morphology's impact on the discharge conditions is the continuing trend for the channel's width to average depth to decrease, as measured at water gauges (Łajczak 1995a). As a result of an increased speed of flow, caused by modifications to the cross- and longitudinal sections of the channel, the bankfull volumes continue to grow at various rates, as recorded by the gauges (Fig. 7). The bankfull volumes tend to differ ever more from the average medium-high discharge, to which they were similar prior to the first river training projects. During the 20th c., this increase in the bankfull discharge varied along the river course studied and reached three-fold, depending on the scale of the cross-section change.

The combined average duration of the flooding within the embanked floodplain and the number of flood events vary greatly along the stretch of river being investigated (Fig. 8). Both of these characteristics express an increase in flood risk , and display a relationship wih the scale of the post-river training cross-section evolution. They are highest in the reaches which have become shallower, and only slightly lower in the least deepening reaches. Conversely, the lowest values are observed along the most deepened channel reaches. As an example, the reach of the Vistula crossing the Polish Uplands gap has a frequency and combined duration of flood

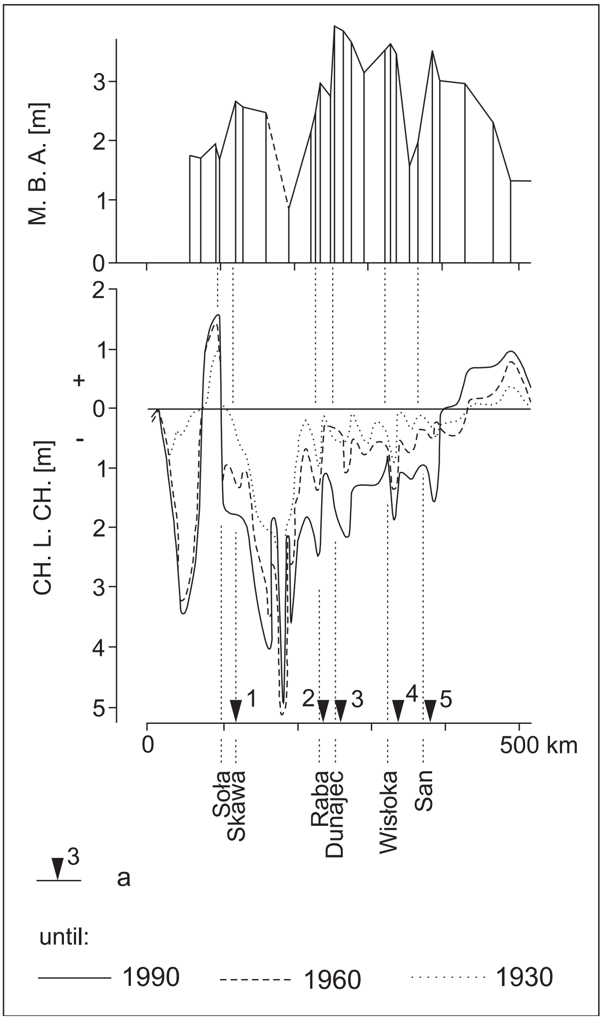

Figure 6. Change in channel depth following river training in the foreland River Vistula CH.L.CH. and average thickness of deposits in bank zones M.B.A.
a) selected water gauges (1—Smolice, 2—Jagodniki, 3—Karsy, 4—Koło, 5—Zawichost).
The confluences of the principal Carpathian tributaries are also indicated. Changes in the depth of channel until 1930, 1960 and 1990.

events up to 15 times greater than along the Cracow reach of the river.

Since at least 1930, the foreland Vistula has displayed a trend whereby the overbank water levels have been shrinking. Until 1990, this trend was unrelated to the long-term discharge fluctuations and was a result of channel deepening (Fig. 9). The trend is proportionally related to the deepening rate (Łajczak 1995a, 1999). However during the period 1931–1990, the duration of the overbank water levels along the most deepened

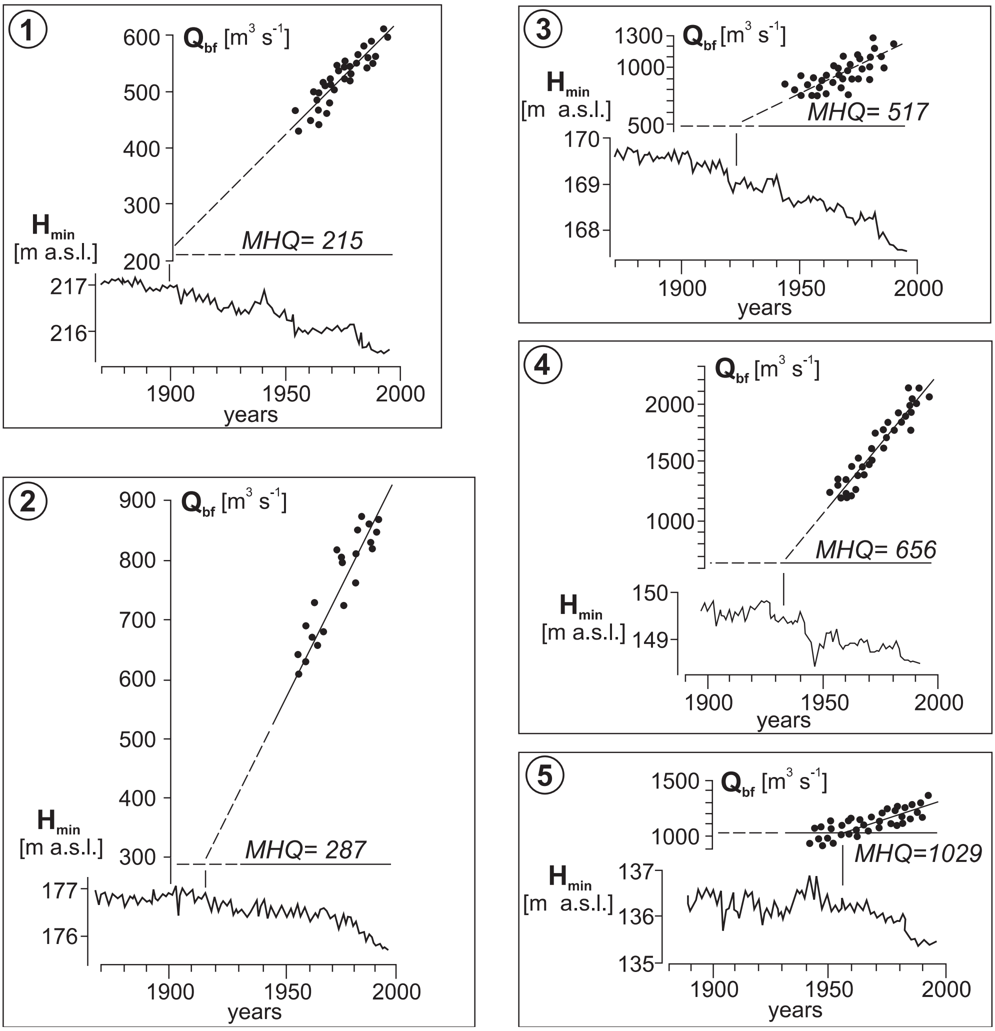

Figure 7. Change to bankfull discharge Qbf compared to medium high discharge MHQ against minimum annual water levels Hmin at selected water gauges on the foreland River Vistula. Water gauges are numbered as in Fig. 6.

reaches of the channel displayed only a weak decline, accompanied by generally low values of the IN_1 parameter, up to a maximum of approximately ten days per year. This may mean that the decline in this parameter along the most deepened reaches had already started before 1930. Lack of data prevents a similar analysis of the overbank water level duration after 1990, when a number of large flood events occurred. During the period 1931–1990, overbank discharge along the most deepened Vistula channels occurred on average every second year, but prolonged periods of up to ten years without such periods were also recorded. Further downstream, along less deepened reaches of

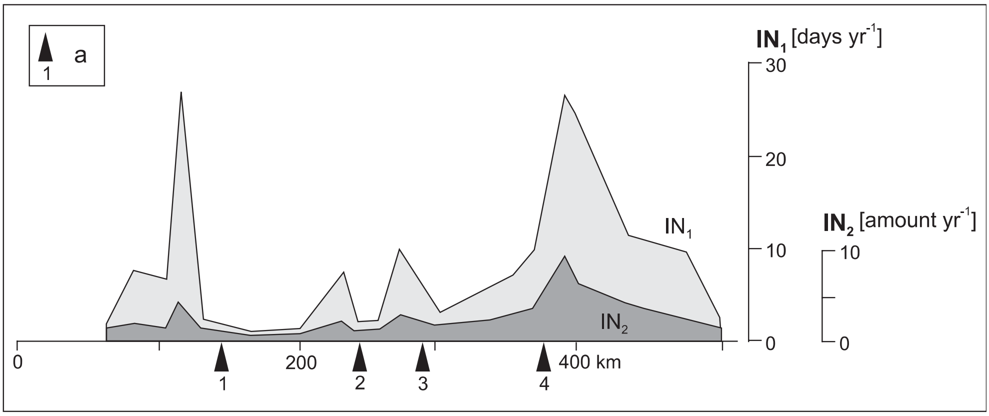

Figure 8. Differentiation of duration of overbank IN$_1$ water levels and number of flood events with such water levels per year IN$_2$, along the foreland course of the River Vistula. a) selected water gauges (1—Smolice,2—Jagodniki, 3—Szczucin, 4—Zawichost).

the river, the decline in the duration of flooding on the floodplain was more marked. Downstream from the Dunajec confluence the IN$_1$ parameter dropped from approximately 10–20 days per year during the years 1931–1960 to less than ten days before 1990. Over the period 1931–1990, this section of the river experienced overbank water levels nearly every year, which may mean that the duration of the flooding of the embanked space is shortened more effectively during the initial period of channel deepening following river training than at an advanced stage of change in the geometry of a trained channel. Downstream of the River San confluence, the Vistula channel is not subject to intensive deepening, and there are places where it may even be becoming shallower. Overbank water levels were recorded every year of the study period—peaking at 50–70 days per annum during the 1931–mid 1960s period. Afterwards, the number of days with overbank water levels declined again to a maximum of 30 days annually in the 1980s.

The lack of a clear-cut trend involving a reduction in the number of days with overbank water levels along the foreland course of the Vistula from 1931 to 1990 might suggest that such a trend may have prevailed earlier on, i.e. in the late 19th century and during the first three decades of the 20th century, when the pace of channel deepening was already advanced, such as near Cracow. Downstream, where the deepening process only started after the 1930s, the trend towards a rapid decline in the periods of floodplain flooding between the embankments was only noted after 1930. Below the confluence of the River San the trend to a decline in the number of days with overbank water levels is not very advanced, and started only in the 1970–1980s because the river training efforts along this stretch of the river starting later than elsewhere.

Another result of the engineering projects in the foreland course of the Vistula is the restriction of flooding of the embanked floodplain along the considerably deepened channel (> 2 m) to just the summer season. Where the deepening is only minor (< 1 m), or the channel is becoming shallower, this part of the floodplain may also be flooded during rapid thaws. Prior to river training, the entire course of the river floodplain experienced flooding during both rapid thaw floods and summer floods. The foreland-course engineering projects effectively eliminated the early-springtime flood risk along the most modified reaches alone. During summertime, floods have only become shorter as a result of the training measures, except along the upland gap reach.

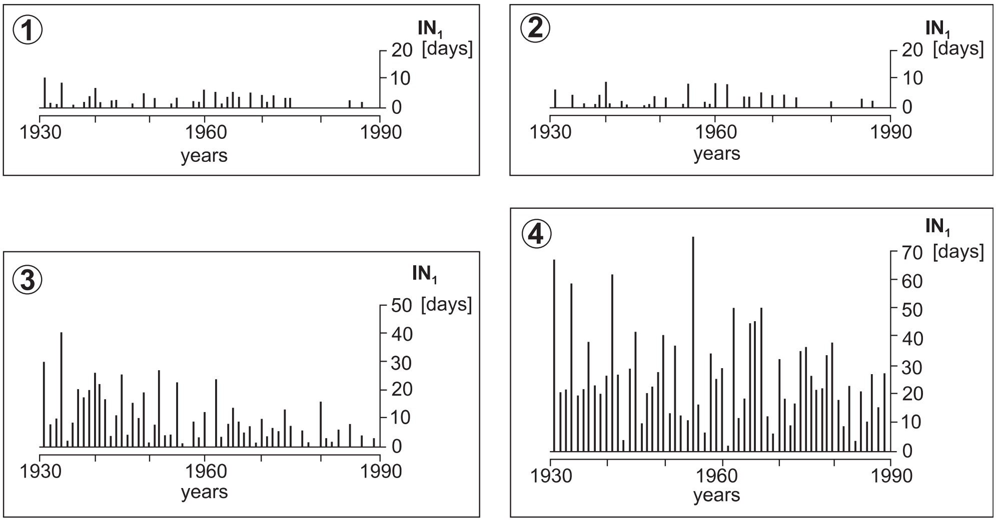

Figure 9. Change of duration of overbank water levels IN$_1$ at selected water gauges on the foreland course of the River Vistula during 1931–1990. Water gauges numbered as in Fig. 8.

Another effect of the training of the Vistula foreland is an increased concentration of flood waves, as a result of the accelerated flow observed across the entire spectrum of water levels (Punzet 1991; Łajczak 1995a). According to Punzet, during the 20th c., the Cracow reach displayed a trend to a shortened duration and increased height of the flood wave, as well as to an increase in the frequency of extraordinary flood peaks. A combined effect of these changes has been to cause the flood wave travel time to shorten along the foreland course of the river, including by one-third between Goczałkowice and Zawichost, and by a half between Smolice (the confluence of the River Skawa) and Sierosławice (the confluence of the River Raba), the latter being the most deepened channel section. The accelerated movement of the flood waves along the deepened reaches of the foreland Vistula is considerably influenced by the greater concentration of similarly-induced flood waves on the lower courses of the Carpathian tributaries (Punzet 1991; Wyżga 1993). The post-river training development of the foreland Vistula channel has produced a trend for the volume of the flood waves to be reduced as a result of their greater concentration and higher peaks (Punzet 1991). This could be partly explained by the effect that the bankfull discharge has been growing at the expense of the overbank discharge following the advent of the river training projects, an effect previously overlooked. The trend for a declining duration of the overbank water level periods, initiated at various dates in the 20th c., has been observed along the considerably deepened reaches, and is independent of the long-term fluctuations of the Vistula discharge (Łajczak 1995a).

The erection of flood embankments has reduced the flooding zone up to 50-fold along the foreland course. Events whereby the water tops the new embankments and spills over are very rare, and limited to days with extreme water levels. Combined with the causes mentioned above, this dramatic reduction of the flooding zone has led to increased water level amplitudes along the course of the Vistula we are examining, especially after 1920 (Osuch 1991; Punzet 1991). They are currently double the value recorded before the embankments, and may reach nine metres (Soja and Mrozek 1990).

Just as in the tributaries, assessment of the foreland course of the Vistula in terms of the impact of river training on flood risk is complex. Taking into account the duration of the overbank stages and the extent of the flooding zone, the duration and area aspects of the flood risk were reduced during the 20th century. This is a result of faster flood wave travel, and of the fact that minor summertime floods and all the thaw floods remain within the bankfull stage. The number of days with overbank discharge was reduced, with the exception of reaches without any significant deepening effect or with a shallowing trend. Just as in the Carpathian rivers, the increased flood wave speed may, , be regarded as an additional risk factor in certain circumstances. The third feature of flood risk, i.e. the height of peak river water levels, demonstrates a growing flood risk along the entire channel, within the embankments only, during the 20th century. Only extremely high water level events threaten to spill over and undermine the embankments, which then need maintenance. This is a result of:

- a trend for peak river water levels during subsequent large flood events to increase, and for their durations to shorten;
- a trend towards an increasing frequency of exceptional flood peaks;
- an increasing speed of large flood waves.

DISCUSSION AND CONCLUSIONS

As demonstrated by reference to the example of the trained foreland course of the Vistula, the alternating pattern of reaches featuring varying degrees of cross-section modification translates into hydrological effects, especially with regard to flood risk. This situation is typical for the entire course of the river (Łajczak 1995a). The reach downstream of the River San confluence, where the deposition is at its most intensive, stands out as having the greatest flood risk along the river (Jędrysik and Rusak 1982). This should be seen as a consequence of the shallowing and broadening processes, along the entire channel length, that began at least as far back as in the 17th century, driven by the deforestation of the drainage basin. Only since the 20th century should this be seen as a consequence of the river-training triggered development of the upstream reach (above the River San confluence). Along the entire foreland Vistula, as well as in the lower courses of the Carpathian tributaries and in the upland and lowland tributaries, the current flood risk is critically determined by the effects of river training measures. I would therefore confirm Punzet's conclusion (1991) that river training as broadly understood, along the course of the Upper River Vistula has a large impact on the process of flood wave formation in the river.

The anthropogenic aspects to the current evolution of flood risks in the foreland course of the Vistula and in the middle and lower courses of its tributaries involve an overlap effect of two contradictory trends: (a) the falling risk level in view of the shortening of floodplain inundation time and territory, and (b) the growing risk from the increasing height of the flood water. These two trends are typical over most of the river course where its channel has been deepened. The former of the two trends (a) seems to be more significant for this analysis of flood risks. Indeed the benefit of the shortening of the inundation time over the unembanked area or the undeveloped embanked floodplain is greater than the losses incurred, because of the rare cases of flooding of inhabited and agriculturally used areas, as a result of breaches in the adequately high levees. This can be illustrated by the foreland course of the Vistula between the confluences of the Dunajec and Wisłoka rivers, where—after the erection of up to six-metre-high embankments—the floodplain inundation time was reduced 10-fold and the area 20-fold during the period 1930–1990. The coinciding increase in the water level amplitude to nine metres was a result of the simultaneous channel deepening and maximum floodwave level increase (Punzet 1981, 1991; Jędrysik and Rusak 1982; Soja and Mrozek 1990; Hennig 1991; Osuch 1991; Łajczak 1995a, 2006a). The areas beyond the levees remain unprotected from exceptionally high floodwaves, despite the vertical extension of the embankments after the great floods, and other maintenance measures.

The greatest flood risk levels along the river course analysed, in all three respects, were recorded in the valley sections coinciding with the channel reaches that displayed a shallowing process, lower gradients and only partial or no embankments. This type of valley section is typically found at the end of long stretches where the channel has been significantly shortened, narrowed and deepened (its slope gradient additionally increased) as a result of training measures, which normally included long uninterrupted embankments on both sides of a narrow floodplain. An illustration of this pattern is found using certain water gauges on the Rivers Nida and Vistula. On the Nida near Pińczów, the inundation times were extended more than fourfold during the period 1939–1969. In 1970, the construction of an artificial channel reduced that time to just a few days per year, but a backlash reaction returned it to ten times more. While at Pińczów the embankments reduce the flooded area to a very narrow strip, just two kilometres downstream from the town they disappear for the rest of the river course all the way to its confluence with the Vistula, exposing a floodplain up to three kilometres wide. The historically unprecedented extreme flood wave recorded during the 1997 summer flood not only topped the embankments along many reaches, but remained high throughout the lower course of the river, causing a high degree of damage. Along its partly embanked upland gap reach, the Vistula has a broad floodplain of up to one kilometre. Unlike its long upstream reach, this section of the river displayed no reduction of flooding time, but a slow opposite trend after 1930. The numbers of days with flood effects varied across a broad range of 10–70. The currently higher flood risks observed along this reach are also partly a result of the heightened culminating floodwaves developing in the upstream reach with its deepening channel (Łajczak 1995a,b, 2006a,b).

When looking at various flood risk mitigation options in the foreland course of the Vistula and the middle and lower courses of its tributaries it must by assumed that the current channel development trends, initiated or accelerated by the training projects, will continue in the long term (Łajczak 1995a, 1999). These options tend to be much more limited in the valley sections with shallowing channels than those with deepened channels. In the former case the risk could be mitigated by halting the channel deepening process, or by even less realistic measures, such as a broadening of the distance between the embankments or an increase in their height. In the latter case, featuring long reaches of deepened channels with fast-moving flood waves travelling along a narrow floodplain between the embankments, the risk could only be mitigated by heightening the embankments. Where the deepened channel reach is relatively short there is an option of setting aside large polders beyond the embankments, such as between the confluences of the rivers Soła and Skawinka along the Vistula valley (Nachlik and Wit 1997; Nachlik 1998; Wit 1999). The role of a polder can also be played by the often inundated floodplain along a shallowing river channel, such as along the lower Nida. Halting a channel deepening process that provides sandy material for a downstream shallowing reach is feasible on a small scale, such as along an anastomosing reach of the middle-course River Nida. In this case it would require a parallel reinstatement of the nearby former wetlands, which could play the role of an effective deposit accumulation zone (Łajczak 2006b).

Measures to mitigate the flood risk must also take into account the valley's conservation status. Where no legal conservation is involved, such as in the Carpathian rivers or along the foreland course of the Vistula, a more active floodwave management can be achieved by controlling discharge from artificial lakes. Ideally, this could produce a flattened floodwave extended in time (Punzet 1959, 1973, 1991). In the River Nida valley, subject to several conservation statuses, only environmentally sound methods are feasible, such as reinstatement of the natural qualities of the anastomosing reaches and the adjacent wetlands, or expanding the territory between the embankments.

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FACTORS INFLUENCING FLOODS IN THE URBANIZED AND INDUSTRIALIZED AREAS OF THE UPPER SILESIA INDUSTRIAL REGION IN THE 19TH AND 20TH CENTURIES

(THE KŁODNICA CATCHMENT CASE STUDY)

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Abstract: The occurrence and pattern of floods in urban industrial areas depend on both the hydro-meteorological and physico-geographical properties of the catchment area and on the degree of anthropogenic transformation of land. The area selected for research is one of the largest urban mining-industrial districts in Europe, known as the Upper Silesian Industrial Region (USIR). Besides the 'typical' flood risk, which manifests itself in rivers overflowing their banks, this catchment is also threatened with floods that do not depend on meteorological factors but are caused by the formation of flood lands in areas transformed due to deep mining of hard coal. The pattern of floods in the catchment has also been influenced by changes in the forms of land use resulting from the growth of urbanized areas. Because of the increasing flood risk and the fact that it is impossible to build water storage reservoirs other possibilities of improving water retention capacity in the catchment have been indicated.

Key words: hydrology, flood, human impact, urban area, Poland.

INTRODUCTION

The occurrence and pattern of floods in urban industrial areas depend on both hydrometeorological and physicogeographical properties of the catchment and on the degree of anthropogenic transformation of land. Urban mining-industrial areas have a specific pattern of floods and inundations outside river valleys because the occurrence and pattern of this phenomenon depends to a greater extent on the effects of human economic activity than on natural factors.

The Kłodnica is a right-bank tributary of the Odra, draining a river basin area of 1085 km^2. The Bytomka, on the other hand, is a right-bank tributary of the Kłodnica, draining a river basin area of 144.5 km^2. The present study concerns the upper part of the Kłodnica river basin (catchment area A = 505 km^2).

Mean annual discharge of the Kłodnica at the Gliwice gauging station (catchment area A = 444 km^2), calculated on the basis of data from the years 1961–1999 reaches 6.41 m^3 s^{-1}, and the annual Bytomka discharge at the Gliwice gauging station (A = 136.5 km^2), calculated on the basis of data from the same period amounts to 2.61 m^3 s^{-1}. Individual discharge values amount, respectively to: 14.4 dm^3 s^{-1} km^{-2} for the Kłodnica catchment and 19.1 dm^3 s^{-1} km^{-2} for the Bytomka catchment.

Both catchments are currently urbanized to a great extent and intensive mining activity is carried out there. Due to this fact both rivers also carry foreign water, from outside the catchment (for the water supply system) and deep mining waters originating from the draining of workings in hard coal mines.

The area selected for research is one of the largest urban mining-industrial districts in Europe known as the Upper Silesian Industrial Region (USIR). Its western part lies within the Kłodnica catchment (Fig. 1), where detailed hydro-meteorological observations have been carried out since the mid 19th century. The collected material made possible the accurate evaluation of human impact on the pattern of catastrophic floods and inundations in areas located outside river valleys.

FLOODING RISK

The whole area under research is located within the Silesian Upland. The geographical location and elevation of this area above sea level were decisive factors in determining the precipitation total, which is 700 mm on average. The greatest water runoff occurs in the thaw period (March, April), while the maximum discharge occurs after long-term or torrential rains, usually in June and July

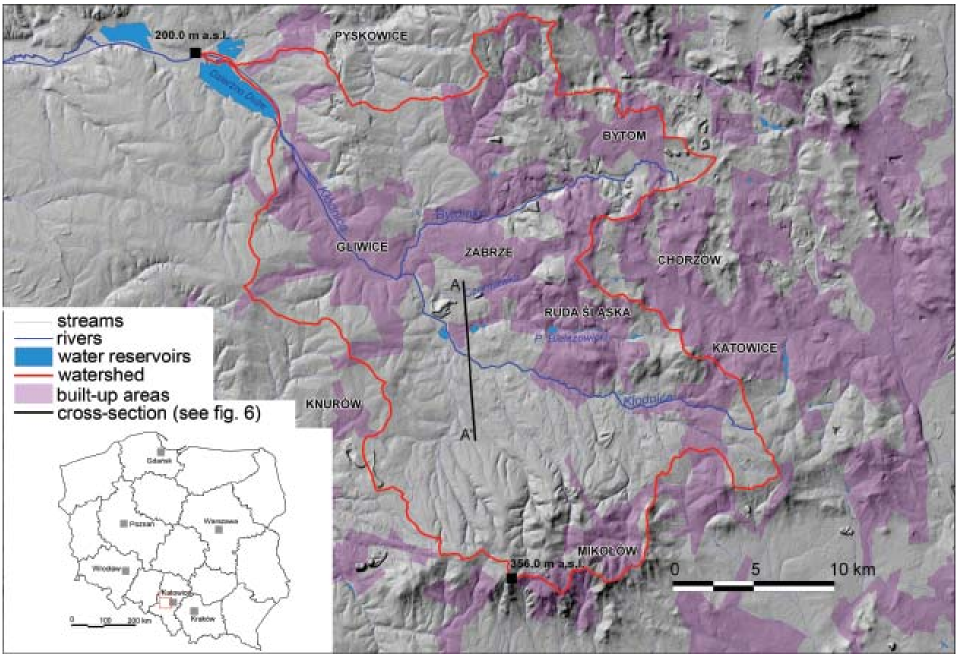

Figure 1. The Kłodnica catchment against the background of a digital terrain model

(Czaja and Jankowski 1993; Absalon *et al.* 2001). High-water stages after long-term and torrential rains pose the greatest flooding threat in the USIR area.

While evaluating the flood patterns of this area in accordance with the criterion linking the level of the high-water stage with the probability of peak discharge, the USIR district falls into the category of areas in which normal high water prevails, where the flood discharge:

$$Q_{50\%} \geq Q_{\max} \geq (\overline{Q} + Q_{50\%}) / 2,$$

and medium high water, where the flood discharge:

$$Q_{10\%} \geq Q_{\max} \geq Q_{50\%},$$

Great high-water, where the flood discharge:

$$Q_{50\%} \geq Q_{\max} \geq Q_{10\%},$$

occurs very rarely, and catastrophic floods, where the flood discharge:

$$Q_{\max} > Q_{5\%},$$

occurred only twice within the last 200 years—in 1940 and 1997 (Fischer 1915; Powódź… 1967; Powódź… 1975; Ocena sytuacji… 1997).

where:

$Q_{\max}$—maximum instantaneous discharge (peak discharge),

$Q_{p\%}$—maximum instantaneous discharge (probability p%).

Human economic activity radically transformed natural conditions of the occurrence of floods in the USIR area. Extremely intensive development of mining and industry and the urbanization of the area have taken place since the mid 19th century. This activity has resulted in distinct changes in the geographical environment of the area, on the one hand resulting in orogenic drainage in areas where drainage of coal mining floors also results in lowering of first-level water table—this usually happens in places where Quaternary surface deposits lie directly above the exploited Carboniferous level. On the other hand, water-logging due to the formation of extensive subsidence basins and hollows may occur in areas of the deep mining of hard coal. These basins are often filled with water from surface runoff or groundwater recharge. The formation of basins and hollows in river valleys also leads to local disruptions in falls of the ground.

These processes result in changes in surface and underground water retention and in the conditions for infiltration and surface runoff. A major role in modifying the conditions of water circulation and therefore in generating floods in the area in question has been played by changes in spatial development and the surface hydrographical network. In the mid 1730s forests and coppices comprised about 45% of the Kłodnica catchment area, arable land, meadows and pastures nearly 46% and ponds and reservoirs 6% (Wieland 1736). However, as early as in the 1830s, major changes in the development of this area were observed. Forests were cut down on a large scale mainly for the purposes of the mining industry, which caused the diminution of their area by nearly 40% (Czaja 1999). There were also changes in forest structure. Deciduous forests were substituted by quick-growing pines and spruces. In the 19th century the dominant forms of land use were arable lands, meadows and pastures, which constituted over 70% of the described area (Tables 1, 2).

From the end of the 19th century onwards, further changes in land development of the catchment took place. The arable land, which had prevailed in the landscape, was taken over for the purposes of construction and industrial development. In the 20th century, there was a steady decrease in the area of arable land in favour of residential and industrial buildings and roads and

Table 1. Land use in the Bytomka catchment

	1827		1887		1960		2000	
Land use	km^2	%	km^2	%	km^2	%	km^2	%
Forests	35.5	24.1	27.2	18.5	21.0	14.3	26.2	19.2
Arable land	93.4	63.4	89.5	60.8	66.6	45.2	44.8	32.9
Meadows and pastures	13.5	9.2	13.8	9.3	10.2	6.9	9.2	6.8
Urban area	4.7	3.2	7.5	5.1	18.7	12.6	25.2	18.5
Industrial area	0.0	0.0	2.4	1.6	7.3	5.0	11.2	8.2
Roads and railway lines	0.0	0.0	0.3	0.2	3.0	2.0	1.8	1.3
Green areas	0.0	0.0	0.6	0.4	3.8	2.6	8.6	6.3
Wasteland and post-industrial lands	0.0	0.0	5.7	3.9	14.7	10.0	8.0	5.9
Water reservoirs	0.2	0.1	0.3	0.2	2.0	1.4	1.2	0.9
Total	147.3	100.0	147.3	100.0	147.3	100.0	136.2	100.0

Table 2. Land use in the Kłodnica catchment

	1827		1887		1960		2000	
Land use	km^2	%	km^2	%	km^2	%	km^2	%
Forests	104.1	29.0	97.6	27.3	76.7	21.4	90.4	25.2
Arable land	208.5	58.2	207.7	57.9	182.4	50.9	135.0	37.7
Meadows and pastures	35.2	9.8	35.7	9.9	32.0	8.9	28.6	8.0
Urban area	8.2	2.3	10.6	3.0	33.3	9.3	55.6	15.5
Industrial area	0.0	0.0	2.4	0.7	12.2	3.4	20.3	5.7
Roads and railway lines	0.0	0.0	0.4	0.1	2.1	0.6	1.0	0.3
Green areas	0.0	0.0	0.5	0.1	7.5	2.1	11.2	3.1
Wasteland and post-industrial lands	0.0	0.0	3.3	0.9	10.7	3.0	13.0	3.6
Water reservoirs	2.4	0.7	0.2	0.1	1.5	0.4	3.3	0.9
Total	358.4	100.0	358.4	100.0	358.4	100.0	358.4	100.0

railway lines. These processes were particularly intensive within the catchment of the Bytomka, the main tributary of the Kłodnica, draining the most urbanized and industrialized part of the Upper Silesian Industrial Region (Tables 1, 2). Until the end of the 18th century dispersed settlement prevailed here, with small villages and hamlets with farm buildings. These took up about 2% of catchment area. By the end of 19th century, the number and area of settlements had increased slightly. Rapid urban development occurred towards the end of the 19th century, when numerous residential districts for factory workers and miners were built and former villages were turned into urban settlements. By this time, such areas were comprising about 10% of the Bytomka catchment, though only 3.5% of the Kłodnica catchment. The figures at the end of the 20th century were 27% and 21%, respectively (Figs 2, 3, 4 and 5).

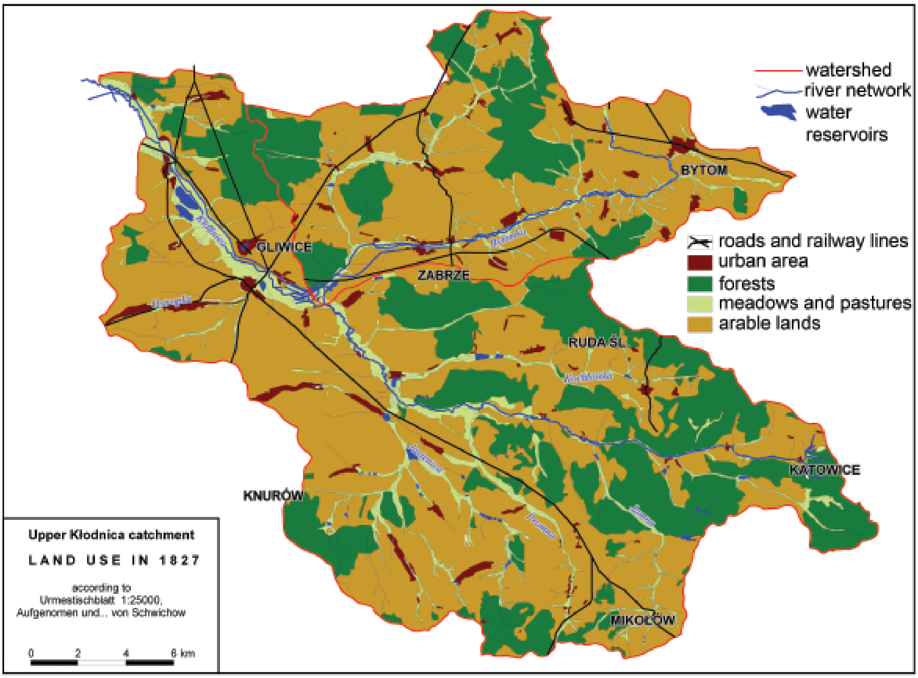

Figure 2. Land use in the upper Kłodnica catchment in 1827

With the development of industry and urbanization the research area witnessed rapid growth of degraded and post-industrial land. The main reason was storage of mining waste (barren rock) and metallurgical waste (slag and post-flotation waste) mainly on agricultural land and grassland. At the end of the 19th century, degraded areas constituted nearly 4%, and at the end of the 20th century, 6% of the Bytomka catchment area.

A positive trend in the changes in spatial development aiming at amelioration of water circulation conditions is reclamation of some of the post-industrial lands for their afforestation and the creation of parks and green areas. Urban green areas have only been playing a role since the mid 20th century. These areas currently account for over 6% of the Bytomka catchment.

The Kłodnica and Bytomka catchments are not unusual in their transformation of the land surface—as early as at the beginning of the 1970s, it was estimated that about 9% of the area of the Upper Silesian conurbation had been subject to 100% change (Żmuda 1973). In the 1980s the conurbation went through intensive transformations of water relations over an area of about 1,600 km^2 (Jankowski 1987).

Changes in surface hydrographical network are another important factor in the formation of floods in the Kłodnica valley and the valleys of its tributaries, which

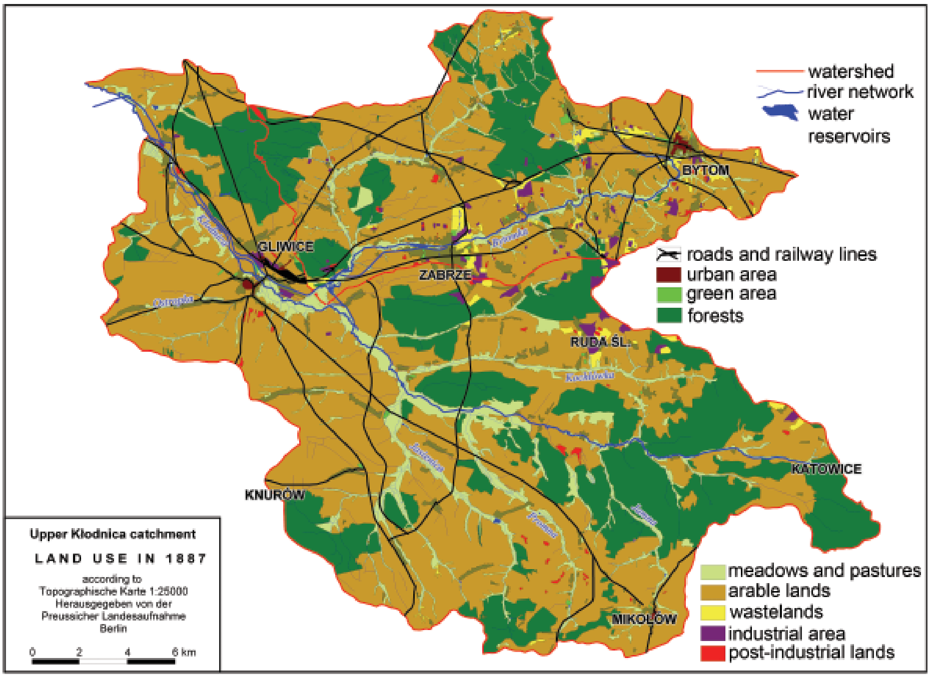

Figure 3. Land use in the upper Kłodnica catchment in 1887

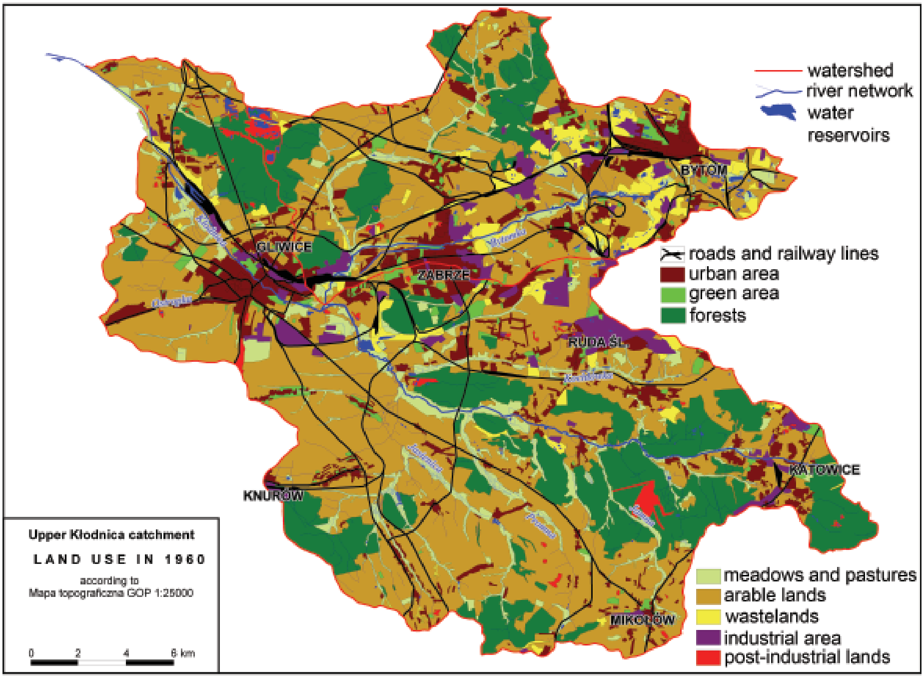

Figure 4. Land use in the upper Kłodnica catchment in 1960

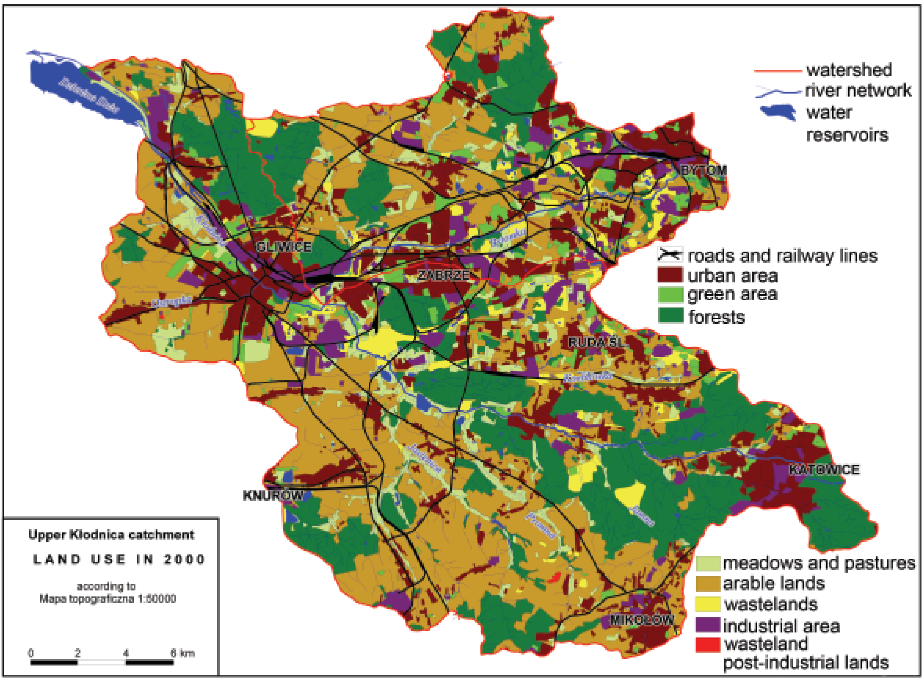

Figure 5. Land use in the upper Kłodnica catchment in 2000

are heavily transformed anthropogenically. Most of the fishponds and dam reservoirs on rivers and streams so numerous in the 18th and 19th centuries have disappeared, something that significantly diminished the water retention properties of the catchment and hurried surface water runoff. At the same time hydrotechnical works and regulation of rivers and streams have caused their shortening, making them steeper and as a consequence quickened water runoff (Czaja 1999). It follows from the analysis of historical topographic maps from the 19th and 20th centuries that the river network in the Bytomka catchment (excluding the Mikulczycki stream catchment) was 89.9 km long in 1827 and 36.4 km long in 2000.

Mining activity and the development of the sewerage network in the urbanized areas located in zones crossed by watersheds result in major changes in catchment area, something that influences the magnitude of calculated hydrological parameters. Depending on the extent of subsidence, its location off the centre of the basin or hollow and the location of major sewerage collector outlets areas came to be included into or excluded from one catchment or another. This phenomenon was observed in the Bytomka catchment, which lost 11 km^2 (7.5% of total catchment area) in the years 1960–2000.

The present occurrence of floods and inundations in the USIR part of the Kłodnica catchment area is connected mainly with land deformations due to open pit and deep mining. Numerous subsidence basins and hollows are formed, both within active mining fields and on their edges. Subsidence basins and hollows are formed within mining fields as the result of the exploitation of resources carried out using the roof-fall method. Land surface deformations in mining subsidence zones often cause changes in the direction of surface and underground water runoff, leading in consequence to flooding of land located beyond river valleys (Fig. 6).

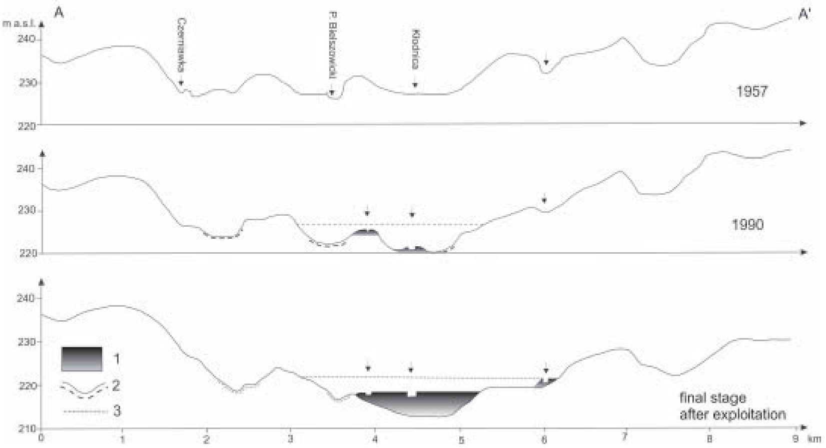

Figure 6. Changes in surface features in the Kłodnica valley (transverse section):
1—flat waste heaps of barren rock, 2—local subsidence basins,
3—potential level of water in land depressions.
Source: Szczypek, Wach (1987)

The specific character of the described area results from the fact that, in natural conditions, normal and medium-sized floods prevailed there. Changes in geological structure (as the result of mining activity) caused great ground subsidence, which in turn brought permanent inundations of river valleys. This phenomenon is particularly dangerous in the built-up areas of the region. In times of flooding, inundations of considerable areas can be observed in mining subsidence zones, mainly in connection with obstructed flow of surface and ground waters (Szczypek and Wach 1987; Wach and Szczypek 1996; Czaja and Wach 1999).

Besides inundations due to the subsidence and sinking of ground, the USIR area is threatened with flooding caused by the obstructed flow of surface waters into the river network. These obstructions result from rivers and streams draining areas within the zones of hollows and extensive subsidence basins. The riverbeds have been sealed by building stone and concrete troughs and flood embankments. Intensive ground subsidence made it necessary to raise embankments, which has resultedraised the surface of water in rivers much above valley-floors. In many cases the level of water in an embanked riverbed is a few metres higher than the valley-floor beyond the embankments. This often causes the formation of wide flood-lands collecting precipitation waters in river valleys. Flood-lands forming along the embankments of rivers and streams are particularly dangerous when it rains. The scale of flooding risk in river valleys in the USIR area can be proven by the extent of flooded land during the July 1997 flood. In some sections of the Kłodnica and its tributaries and other rivers of the region the extent of flooding was wider than the theoretical range of inundation of these valleys with the probability of peak discharge of $Q_{0.1\%}$.

THE HISTORY OF FLOODING

In the 19th and 20th centuries floods on the upper Kłodnica were quite frequent. The 1803 flood caused considerable loss to property, destroying quite a long section of the newly-built Kłodnicki Canal. Water in the river in the Gliwice area reached the level of 2.0—3.3 m, as was the case in 1803, 1903, 1913, 1915, 1925 and 1930. Unfortunately no discharge data are available for the period before 1911 (the gauging station was installed in 1908) and we only know the descriptions of the magnitude, extent and effects of the floods from historical sources (Mann 1905, Fischer 1915, Knothe 1939).

Since the moment when systematic observations of water stages started to be carried out at the Gliwice gauging-station the peak flood discharges recorded in different years were: 1913—61.0 m^3s^{-1}; 1915—83.0 m^3s^{-1}; 1925—66.6 m^3s^{-1}; 1930—64.7 m^3s^{-1}. The lar-gest flood was recorded on the Kłodnica in late May and early June 1940. In Gliwice, the recorded water stage was H = 505 cm and discharge Q = 121.5 m^3s^{-1}. Within 22 hours there was an increase in discharge from 11.0 m^3s^{-1} to 121.5 m^3s^{-1}, the result being flooding in large areas of Gliwice, mostly in the vicinity of the present Silesian Technical University (Figs. 7, 8).

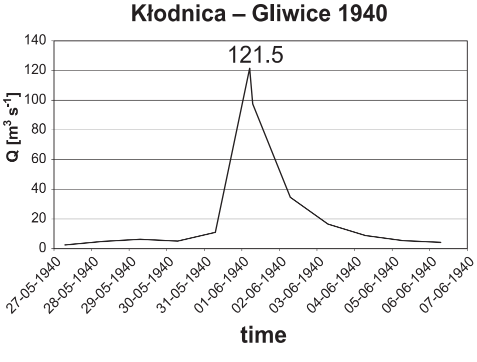

Figure 7. The pattern to peak high water along the Kłodnica in 1940

Figure 8. Gliwice during the 1940 flood – Krakowska Street area.

Such a rapid increase in discharge attests to a considerable intensity of rainfall over a comparably small area, because the time of discharge concentration should be taken into account. The flood of 19–20 August 1854 was quite similar. It follows from interpolation of flood marks that the discharge of the Kłodnica in Gliwice might then have equalled 80 m^3s^{-1}. Since those floods there have been other large events, the next major one being the flood of July 1997. The estimated discharge of the Kłodnica on the Gliwice gauging-station was 88.1 m^3s^{-1}. Slightly smaller discharges were recorded during floods in: 1968—52.1 m^3s^{-1}, 1972—50.3 m^3s^{-1} and 1985—48.2 m^3s^{-1} (Kompleksowy program… 1998).

The origin of most floods in the Kłodnica and Bytomka catchments may be sought in the spring thaw period. Only the largest floods resulted from storm rainfall, as in May/June 1940.

An analysis of the peak high water observed on the largest tributary of the Kłodnica—the Bytomka—was also carried out. The Bytomka catchment, as has been shown before, is one of the most urbanized and transformed areas in the Kłodnica catchment. Unfortunately, as regards this catchment, hydrological data are confined to the last 50 years, since the gauging-station was only installed in 1955. Due to smaller catchment area, the observed peak discharges are lower (Figs. 9, 10 and 11). The analysis points to the Bytomka flood wave usually being part of the Kłodnica flood wave, since its peak is observed over a dozen hours (12—18 hours) before the peak on the Kłodnica. The flood of 1997 was different because the Kłodnica peak occurred 12 hours earlier than the Bytomka one (Fig. 12).

The last 40 years has have also witnessed larger increases in discharges along the Kłodnica than the Bytomka. This is due to much more major changes occurring in the upper Kłodnica as compared to the Bytomka. These changes mainly include river control works resulting in the strengthening and shortening of the river network and changes in land use in the catchment area in the direction of urban development, and the resulting development of a storm-water drainage network. A similar situation was

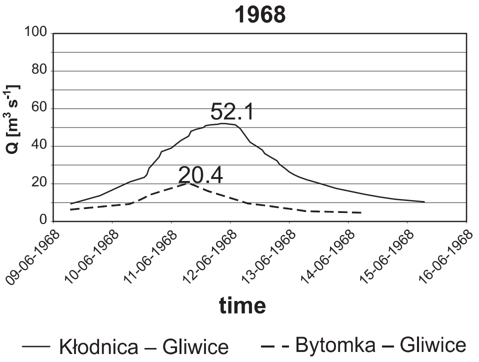

Figure 9. Patterns to peak high water on the Bytomka and Kłodnica in 1968.

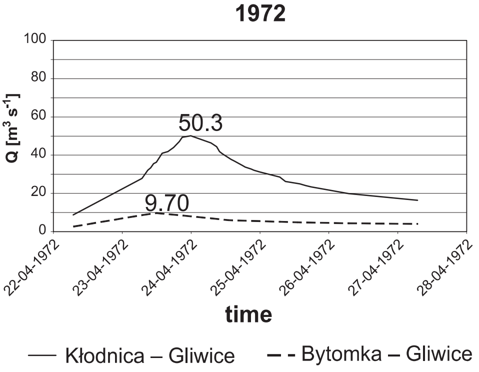

Figure 10. Patterns to peak high water on the Bytomka and Kłodnica in 1972.

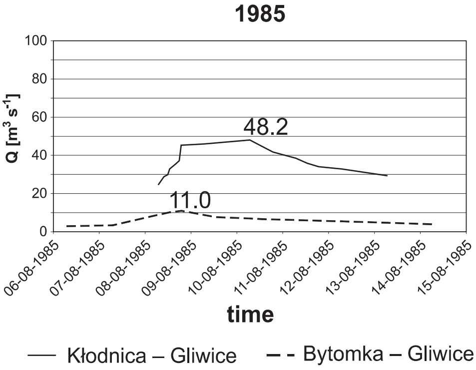

Figure 11. Patterns to peak high water on the Bytomka and Kłodnica in 1985.

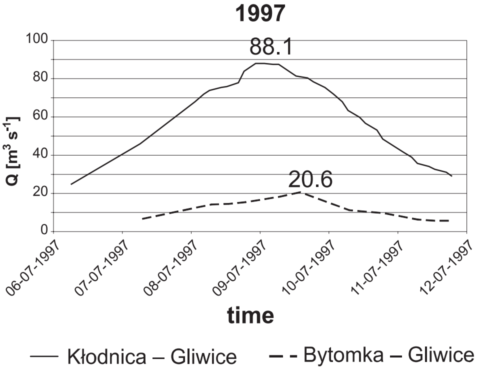

Figure 12. Patterns to peak high water on the Bytomka and Kłodnica in 1997.

observed in the Ruhr Area (Ruhrgebiet), where channelling of rivers and streams and the building of embankments resulted in larg-scale inundations between the embankments and the Emscher Valley escarpment (Brüggenmeier, Rommelspacher 1992; Emschergenossenschaft 1910).

The assessment of the impact of small man-made reservoirs on the pattern of floods in the Kłodnica catchment is a very difficult task requiring individual research. In the second half of the 20th century two opposing tendencies were in conflict in this catchment. On the one hand, due to the deterioration of water quality and economic transformations many fishponds disappeared. On the other hand an unintended effect of deep mining was the formation of subsidence basins, these becoming filled with water under certain morphological and hydrogeological conditions. We are currently unable to define the relative proportions of these two phenomena, particularly because the situation of water-filled depressions is subject to dynamic change, these often becoming filled up with waste barren rock from coal mining. In a situation of diminishing natural water retention in the catchment, retaining some of the water-filled depressions should be considered, in order to improve retention. One of the largest water-filled post-mining depressions in the Kłodnica Valley played a positive role, e.g. during the flood of 1997.

CONCLUSIONS AND FINAL REMARKS

The area of the Upper Silesia Industrial Region has been heavily transformed as the result of long-term mining activity, urbanization and industrialization. A minor flood risk resulting from natural conditions has been multiplied mainly by mining activity and urbanization. The main rivers draining the region have been controlled and prepared to carry flood waters with a probability of peak discharge of even 0.3—0.1%. However, most of the USIR areas are threatened by floods caused by surface flow and underground runoff, which leads to flooding not only of river valleys but also of considerable areas located beyond them. Very often these are highly developed areas, such as areas of urban and industrial development, railway lines, etc. This threat overlaps with the location of the ground subsidence zone. Because it is impossible to restore the natural water retaining capacity of the catchment, and practically also impossible to build water storage reservoirs, the use of some of the transformed mining areas and in particular water-filled depressions forming as a result of ground subsidence should be considered to improve water retaining capacity of the catchment. Other flood prevention activities in the catchment should aim at:

- the afforestation of wastelands,
- the proper irrigation and drainage of agricultural lands,
- limiting the construction of flood embankments outside densely built-up urban areas,
- improving water retention of riverbeds, e.g. by building multipartite channels.
- limiting the urbanization in river valleys.

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STUDIES ON HISTORICAL FLOODS IN GDAŃSK
(A METHODOLOGICAL BACKGROUND)

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Abstract: The analysis and reconstruction of historical floods not only enriches historical documentation, but can also be perceived as a useful auxiliary tool in the planning of contemporary flood management techniques. The reconstruction of floods on the basis of historical documents can be carried out with the help of a GIS (Geographical Information System) equipped with the spatial analysis tools allowing the extent of flooding to be mapped. The present study reviews historical floods in Gdańsk briefly, before attempting to reconstruct one particular historical flood.

Key words: flood, reconstruction, historical documents, DEM, GIS, Gdańsk, Poland.

INTRODUCTION

The investigation of floods from the past is an element of paleohydrology or historical hydrology (depending on the level of documentation available). Paleofloods are defined as: *any past or ancient flood events which occurred prior to the time of human observation or direct measurement by modern hydrological procedures*, while historical floods are defined as: *any flood events documented by human observation and recorded prior to the development of systematic streamflow measurements* (Hirschboeck 2003). Historic hydrology is an emerging branch in the hydrological sciences. One definition, proposed by Brázdil and Kundzewicz (2006) reads: *a field situated at the interface of hydrology and (environmental) history, dealing mainly with documentary sources and using both hydrological and historical methodologies*.

However, it is not the mere merging of the two disciplines of hydrology and history, as could be expected by the term and the quoted definition. Rather, the research utilises input from other disciplines, such as geography, cartography, climatology, geomorphology, town-planning and environmental engineering.

FLOODS IN GDAŃSK

Since the beginning of its existence, Gdańsk has been under permanent threat of flooding, due to its location. The immediate proximity of the Vistula River delta as well as of the Baltic Sea augments the risk, and a flood may enter from either side (cf. Fig. 1).

During its multi-century history Gdańsk has survived many types of flooding caused by such mechanisms as rainfall, snowmelt, ice jams, and coastal storm surges. Human

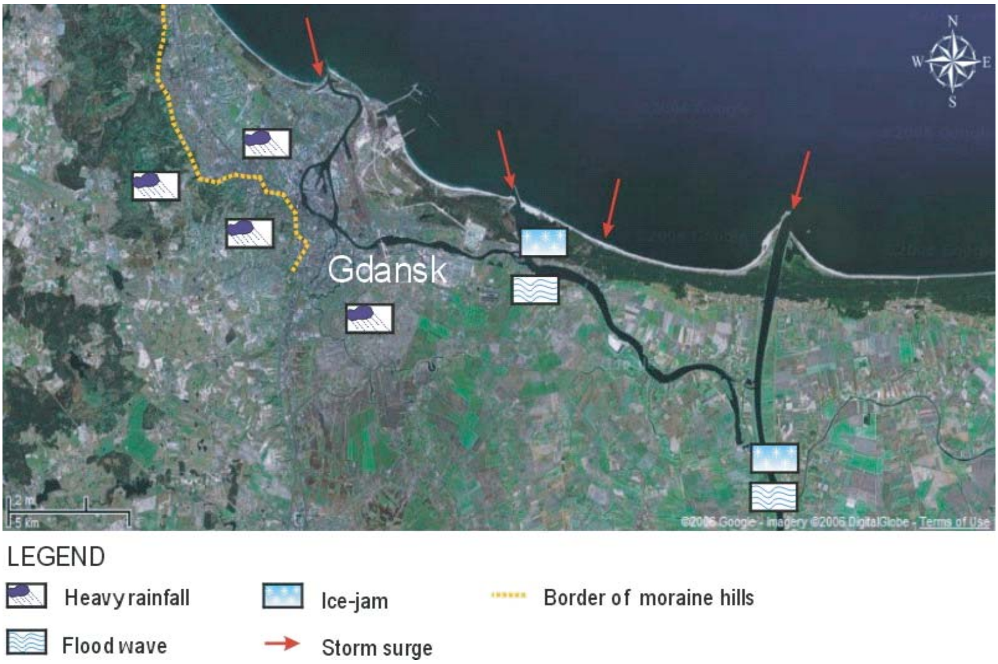

Figure 1. Natural causes of floods in Gdańsk.

activity (advertent or inadvertent) was also the cause of so-called anthropogenic floods. In the past, the improper use of the hydrotechnical devices so numerous in the Żuławy area, or insufficient care in the conservation of levees were causes of frequent floods in the western part of the Vistula River delta, the Żuławy of Gdańsk and Gdańsk city itself (1456, 1512 and 1854). Levees were also deliberately destroyed during the wars in which Gdańsk was often involved as one of the major Hanseatic cities (e.g. that between Poland and Sweden in 1656).

THE SIGNIFICANCE OF DOCUMENTARY SOURCES

Dramatic events such as catastrophic floods have always drawn people's attention. They exert considerable impacts on both the natural and built environment and on the population of the cities. They may also serve as sources of inspiration for painters, poets and chroniclers, who testify to the tragic events in question.

Catastrophic floods from the past were commemorated by the flood marks (high-water signs), cf. Fig. 2. Three of these still remain in Gdańsk: on the wall of the Maiden Granary on Ołowianka Island, near the Stągiewny Bridge, and on the bridge near the Stone Flood-gate.

Figure 2. High-water mark on the Maiden Granary.

The key part in the process of reconstruction of historical floods is played by various documents describing the event, and it is crucial to use different sources wherever possible (Barnikel 2004). Such an approach allows the flood event itself to be looked at from many points of view. However, over 80% of historical events (from the time before the advent of regular hydrological observations) were documented by a single manuscript only. The rule that appears to be valid is that, the more recent the event, the more complete the documentation available (Barnikel 2004). Another rule states that "the more extreme the event is, the more widespread and detailed the description that can be found" (Glaser and Stangl 2004).

Depending on the assumed criteria, the sources of information can be divided into specific groups. The main criterion is the source age (archive *vs* contemporary sources). Numerous libraries and cartographic sources are available for cities that constituted an important part of a country's economic and political life. Documentation was created by order of a city mayor or a King, and was usually so expensive that not every settlement could even afford it. In the case of archival sources, one of the major problems for the unskilled scientist lies in major difficulties with their interpretation. One of the reasons in the Polish case is that the territory of the land is that is currently Poland was long divided between the three invading powers as Prussia, Austria and Russia, with different rules in each being obeyed as regards documentation. Moreover, some manuscripts have become partially damaged over time, and rendered partly or fully illegible. The above-mentioned difficulties are reinforced by the fact that the handwriting of authors of manuscripts may also be difficult to read.

Another criterion is ownership. Historical sources may be a part of private collections or national archives. In the case of national institutions, the search comprises museums, offices, water management administrations and other institutions. Information on the catastrophic flood may also be present in parish and monastery archives. Other sources are year-books, regulations and accountant registers. The form of information constitutes another criterion, e.g. old prints and manuscripts, or cartographic and graphical materials, such as pictures and photographs.

The search for documents is very time consuming and among the major problematic issues is the homogeneity of the information concerning one event, based on several different sources (Cyberski *et al.* 2006). The gathered material has to be interpreted with caution. Some documents may in fact be subjective, while historical descriptions may often contain vague information, such as: "the unparalleled catastrophe so far". The issue of authenticity of the sources is also important. Any relation taking place even within a few years of an event taking place may already be subject to distortion and confabulation (Barnikel 2004)

AN ATTEMPT TO RECONSTRUCT A HISTORICAL FLOOD

The first step in any attempt at the reconstruction of a flood event is the gathering of the documentation describing it: maps from the period/year concerned, descriptions of the flood extent and course thereof. It is not always possible to obtain all the necessary material–sometimes it might not even have been created.

In order to reconstruct a flood it is necessary to create a DEM–Digital Elevation Model. Unfortunately, the ordinates of the terrain at the time of the selected flood are not available in the case of Gdansk. The past elevation data do not correspond with modern elevations due to a change in sea level. Furthermore, homographic maps (created by mathematical projections) have been in use since the 17th century only. The maps used before that time, described as anamorphic, are a source of interpretation problems. Each map should be assessed with the help of several criteria, such as:

precision, faithfulness, cartometrics (coherence of distances, angles and surfaces with real values) and legibility. Sometimes the orientation of a map is not straightforward and should also therefore be identified (Jankowska and Lisiewicz 1998).

To create a DEM, there is a need to input the available data on elevation of different points, and subsequently to interpolate information for the area of interest. The final stage is the presentation of results. The quality of the projected surface depends greatly on the number of available data points, their spatial distribution and accuracy and the interpolation algorithm used (Magnuszewski 1999). Having generated the relief, the analyst may then try to identify the flooded area, using the historical information about the flood.

Using the transparency tool one can overlay the reconstruction of a historical flood on a city map corresponding to the time of the event. The archival map must be geo-positioned using the characteristic permanent markers on the contemporary topographic map. Such points may be streets, bridges or churches. Unfortunately, the archival cartographic material, while unquestionable at first glance, often proves to have been distorted considerably when applied in the geo-positioning process. For example, Fig. 3 illustrates an attempt at the geo-positioning of a map from (as relatively recently as) AD 1830. The process started with two corresponding points that seemed to be the most accurate. At this stage there was no indication that the map had not been prepared using the necessary mathematical pro-

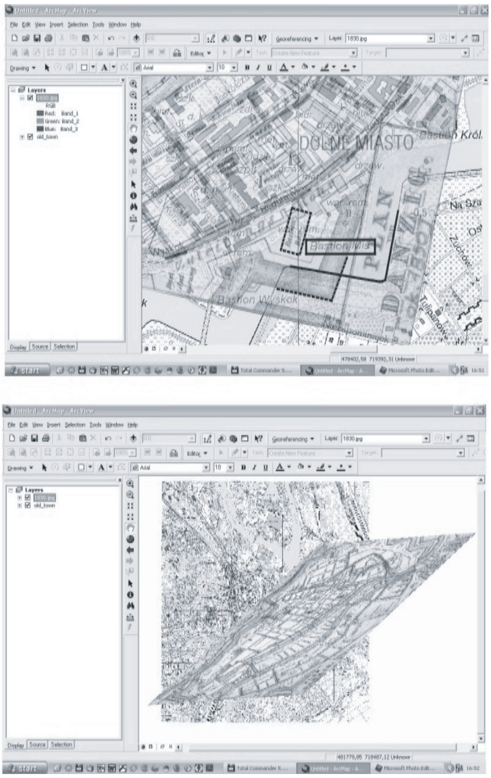

Figure 3. Illustration of a problem with geo-referencing a historical map (see details in the text).

jections. The third point was supposed to be the Bear Bastion. With the transparency at 40% it is easy to see how far apart the corresponding points lay on the archive material from AD 1830 (Bear Bastion–dashed line) and the contemporary map (Bear Bastion–solid line). Forcing the points overlay results in a significant distortion of the map.

Glaser and Stangl (2004) use a three-degree classification of the intensity of historical floods (after Sturn), cf. Tab. 1. Gdańsk has suffered from floods of all three degrees of severity, including frequent floods of the second and third degree. For example, the flood of 1829 was, according to experts, the most catastrophic in the history of Gdańsk. Flood-gates, ditches and bridges surrounding the city were destroyed. The Long Gardens disappeared under water to a depth of one metre. The water level in the Lower City reached the second floor. The water level at Ołowianka Island was 3.36 m above the mean sea level (Makowski 1994). The visualization allows for the classification of the event as "a great flood".

SUMMARY

Research on multiple historical documents is a time consuming and arduous process that requires the development and usage of proper methodology (Hohensinner *et al.* 2003). In the case of the search for archive material there can never be final certainty that everything has been discovered, hence it is often the case that a subsequent investigator may prove capable of extracting new information and interpreting an event of interest in a more reliable and accurate way. Thus, analysis and reconstruction of historical floods not only enriches the historical documentation, but can also improve our understanding of flood processes, and hence serve as a useful auxiliary tool where the planning of contemporary flood management techniques is concerned. Proper analysis of historical sources and the corollaries drawn from such analysis may be of use in the process of spatial planning and in the design of natural disaster protection systems (Tropeano and Turconi 2004).

Table 1. Classification of the intensity of historical floods by Sturn (after Glaser and Stangl 2004)

Level	Classification	Primary indicators	Secondary indicators
1	Smaller regional flood	Little damage, e.g. fields and gardens close to the river, wood supplies that were stored close to the river are moved to another place	Short-term flooding
2	Above average, or supra-regional flood	Damage to buildings and water-related infrastructure, such as dams, weirs, footbridges, bridges; and buildings located close to the river (e.g. mills). Water in buildings	Flood of average duration, severe damage to fields and gardens close to the river, loss of animals and sometimes people
3	Above average, or supra-regional flood of disastrous scale	Severe damage to buildings and water-related infrastructure, such as dams, weirs, footbridges, bridges; and buildings located close to the river (e.g. mills). Water in buildings. Some buildings are completely destroyed or torn away by the flood	Duration of flood: several days or weeks; severe damage to fields and gardens close to the river, extensive loss of animals and people; morpho-dynamic processes like sand sedimentation cause lasting damage and change the surface structure

Source: Glaser and Stangl 2004.

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HYDROLOGICAL DROUGHTS IN CENTRAL POLAND—TEMPORAL AND SPATIAL PATTERNS

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Abstract: The aim of this contribution has been to identify severe hydrological droughts in central Poland, and to analyse the temporal and spatial patterns they display. The distinguishing of low-flow periods was based on the threshold level method, where the SNQ (mean value of the minimum annual runoff) was used as the criterion. Basic calculations were made for daily discharge series at 29 gauging stations situated in the basins of the Rivers Warta, Pilica and Bzura over the time period 1966–1983. Analysis involved such parameters as: mean and maximum low-flow duration in half-years, low-flow type index, date of commencement and termination and characteristics connected with minimum runoff: date of occurrence, index of position as well as recession time index. The problems of hydrological drought stability over a multi-annual timeframe, as well as the spatial pattern thereto were also analysed.

Key words: hydrological drought, low flows, central Poland

INTRODUCTION

The low-flow problem attracts many researchers because of its connection with significant elements of the hydrological cycle, as well as its impact on the management of water resources. However, as an extreme event, low flows have been investigated to a much lesser extent than flood waves, which develop fast, and may have immediate destructive consequences. However, in the long run, drought and runoff deficit may reduce water resources to a level jeopardizing development of local areas or even whole countries. For this reason the identification of low flows and study of various aspects to their development have both practical and scientific importance.

The terms: hydrological drought and low-flow period are well-known in the field of hydrology. However, various methods define these phenomena in different ways. One approach is based on a threshold level. A period for which the runoff attains values below the established limit is selected as runoff deficit. Its two basic parameters are: low-flow duration and deficit volume (Fig. 1). There are two methodological approaches allowing analysts to select the threshold: conventional (connected with water management) or statistical. The former approach assumes that the threshold should be derived from a flow duration curve such as the percentile Q_{70} or Q_{90} (Hisdal et al. 2004). The latter uses the minimum annual daily discharge in the

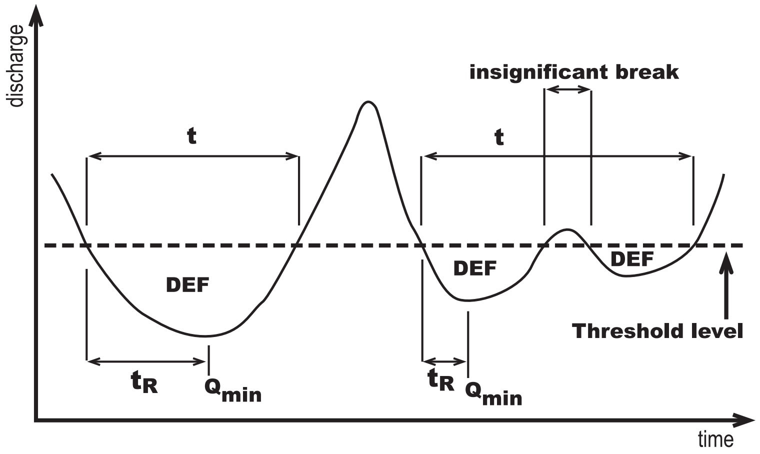

Figure 1. Parameters of a hydrological drought
DEF—runoff deficit, t—duration, t_R—recession time, Q_{min}—minimum low flow during hydrological drought

calculation of SNQ (mean minimum runoff), WNQ (maximum runoff out of the minima) or ZNQ (median minimum runoff), cf Ozga-Zielińska (1990).

STUDY AREA AND DATA

A set of 29 water-gauges situated in the basins of the Warta, the Pilica, and the Bzura (Fig. 2) was selected for analysis. It is worth noting that their location reflects simple regimes of small rivers in homogeneous basins, as well as a more complex alimentation regime in larger basins of heterogeneous water courses. Basic calculations were made for daily discharge series for the observation period 1966–1983, as published by the IMGW (Institute of Meteorology and Water Management).

One of the main purposes of this study was to distinguish the very major hydrological droughts appearing after severe meteorological droughts. Therefore, the most extreme option—SNQ was established as a threshold level for estimation. A comparison with other criteria showed that, in most cases, the estimated SNQ level reached the interval of 91%–99% on the flow duration curve (Fig. 3).

Two conditions other than SNQ level were also taken into consideration. A separate low-flow period had to be longer than or or equal to 5 days, and if the interval between two consecutive periods was of less than 3 days, both were treated as one period. The described procedure led to identification of the low-flow periods and an estimation of their basic parameters: date of commencement and termination, duration, runoff deficit, minimum runoff and its date of appearance, as well as recession time (Fig. 1). Basic computations were carried out using NIZOWKA 2003 software (Jakubowski 2004). The resulting parameters and characteristics, which were constructed on this basis, allowed the author to analyse hydrological droughts in both their temporal and spatial aspects.

TYPE AND DURATION OF HYDROLOGICAL DROUGHT

Basic analyses were made on the basis of seasonal characteristics. Firstly, the low-flow

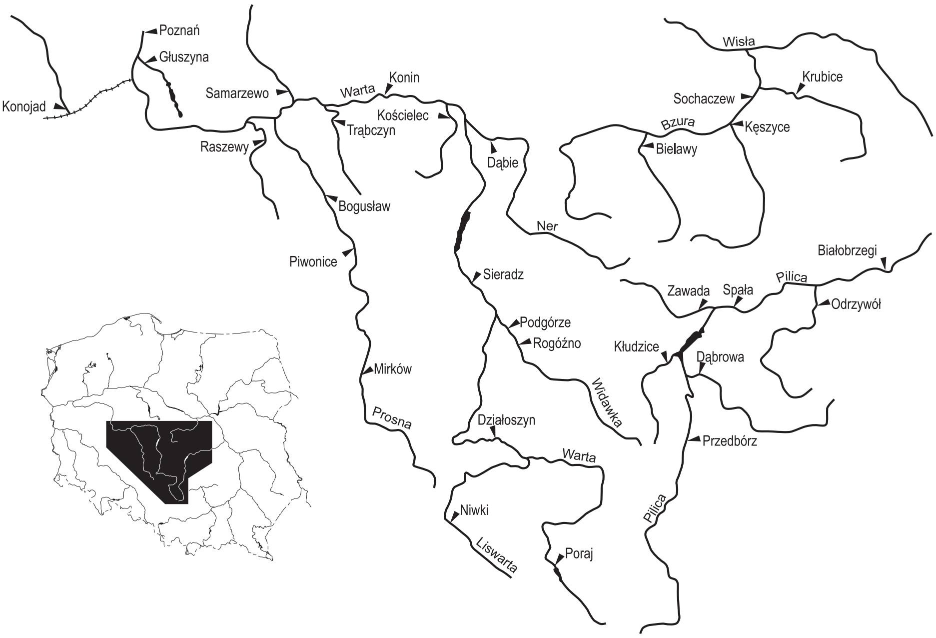

Figure 2. Locations of the studied water-gauges
Basin areas (km^2): River Warta – Poraj (390), Działoszyn (4089), Sieradz (8140), Konin (13351), Poznań (25911), River Liswarta – Niwki (218), River Widawka – Rogoźno (1269), Podgórze (2355), R. Ner – Dąbie (1713), R. Kiełbaska – Kościelec (476), R. Czarna Struga – Trąbczyn (423), R. Wrześnica – Samarzewo (361), R. Prosna – Mirków (1255), Piwonice (2938), Bogusław (4304), R. Lutynia – Raszewy (534), R. Mogilnica – Konojad (663), R. Kopel – Głuszyna (369), R. Pilica – Przedbórz (2536), Spała (5955), Białobrzegi (8664), R. Czarna Maleniecka – Dąbrowa (941), R. Luciąża – Kłudzice (506), R. Wolbórka – Zawada (616), R. Drzewiczka – Odrzywół (1004), R. Bzura – Sochaczew (6281), R. Mroga – Bielawy (467), R. Rawka – Kęszyce (1191), R. Utrata – Krubice (715).

type index (LFT) was constructed (Kasprzyk and Kupczyk 1998, Tokarczyk 2001). Its value shows the ratio of number of days with low flow in the summer (May—October) and winter (November—April) half-years.

$$LFT = \frac{N_S}{N_W} \tag{1}$$

where:

LFT—low-flow type index

N_S—number of days with low flow in summer half-year (V–X)

N_W—number of days with low flow in winter half-year (XI–IV)

Summer low flows were clearly dominating at all investigated stations. In some rivers, winter hydrological droughts did not exist at all. This refers to the zone which crosses the studied area in the central part—except for the middle and lower course of the Warta (Fig. 4). Winter hydrological droughts occur extremely rarely in this area and are very short. The high LFT level seems to be determined by summer vegetation and rain conditions, as well as mild winters without hard frost. The mean summer low-flow duration in this zone

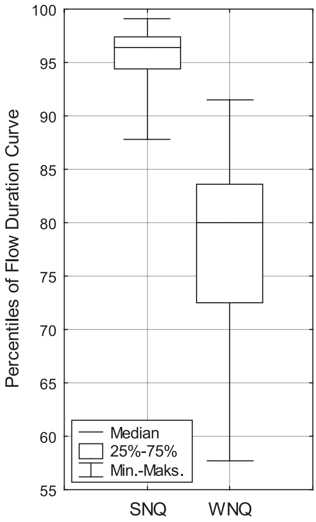

Figure 3. Distribution of estimated SNQ and WNQ values on the flow duration curve for 29 gauges

does not vary much, though its maximum value is much higher (up to 171 days) in small catchments, which are prone to strong water resources recession because of the shallow dissection of groundwater reservoirs by river channels. To the north and south of this zone, the predominance of summer low flows is rather less marked and, in some cases, mean winter low-flow duration can be even longer than mean summer low-flow. This means that winter conditions determining hydrological droughts are more stable, while during the summer half-year a runoff recession curve is very often broken by rainfall-based alimentation. In the middle and lower courses of the Warta, low flows are determined more by its tributaries than by local and regional conditions connected with hydrogeology, precipitation distribution and physiography. This results in a reduction of the summer low-flow predomination and a gradual lengthening of low-flow duration downstream.

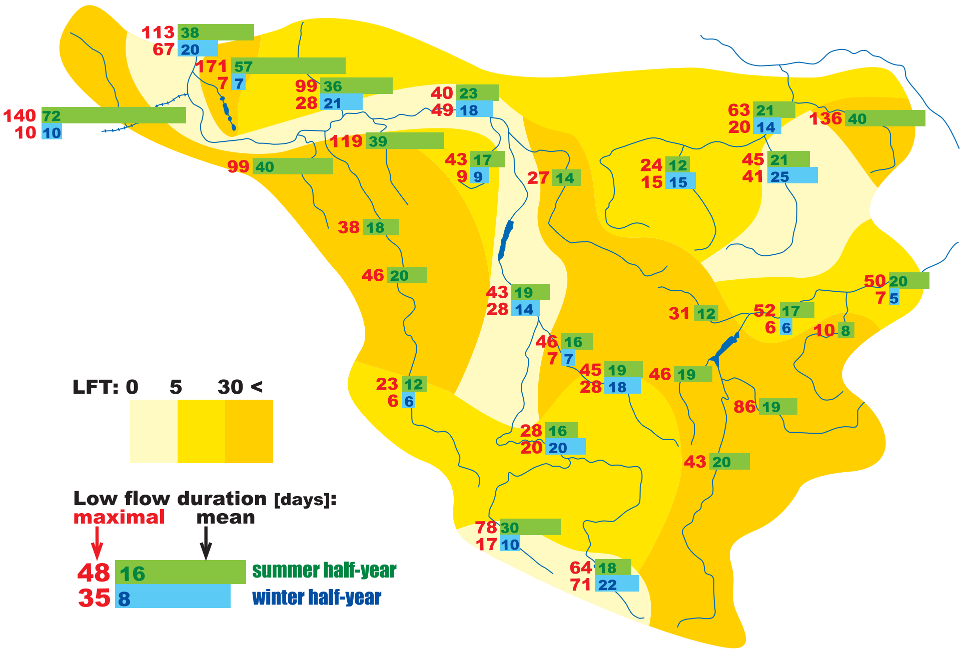

Figure 4. Spatial variation of the low-flow type index (LFT) and length of the hydrological droughts in half-years

Due to the relatively more limited importance of winter hydrological droughts in the investigated area, in both the quantitative and temporal contexts, subsequent analyses have been restricted to low flows in the summer half-year.

DATES OF OCCURRENCE

The mean date of commencement of low flow in summer is found to occur between 11th July and 28th August (Fig. 5). The first reaction to limited alimentation is noticeable in small catchments (the Lutynia, Czarna Struga, Luciąża and Mroga). In most rivers, the commencement date for hydrological drought occurrs in the second half of July. It is worth noting that, in the Warta River system, the commencement of low flow is gradually delayed downstream, due to increasing water resources and upper-course alimentation. Certain exceptions at a few gauging stations are connected with the major influence of local conditions like hydrogeology, water management or agriculture.

The stability of occurrence of low-flow periods over a multiannual horizon was measured by reference to a variation coefficient calculated in a statistical sense, on the basis of the quotient of the mean value and the standard deviation. Its value is directly proportional to the height of the boxes on the map according to the scale showed in the legend. The commencement date of summer hydrological drought (CV_{DS}) shows considerable stability in the investigated area (Fig. 5). However, there is a group of small catchments in which the commencement date does vary quite significantly, and in which there is a proneness to the marked variability in weather conditions (the Wrześnica, Liswarta, Ner and Czarna Struga). Hydrological droughts in the larger (especially the transit) rivers start at a very similar time.

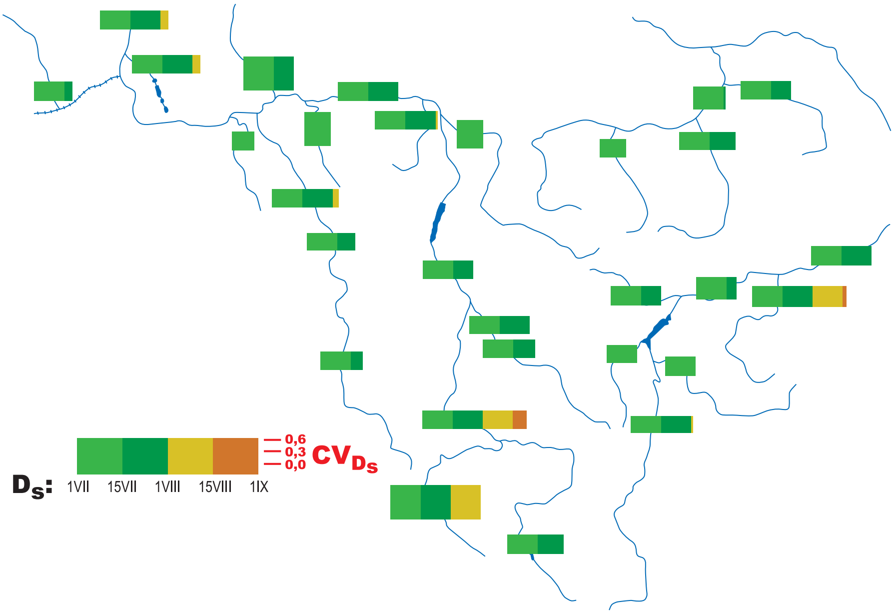

Figure 5. Spatial variation of summer hydrological drought commencement date and its variation
D_S—date of commencement of summer hydrological drought
CV_{Ds}—variation coefficient of D_S

The mean date of occurrence of minimum summer low-flow differs much less than the starting date (Fig. 6). This parameter tends to lag downstream. The variation coefficient (CV_{DM}) for this characteristic is also very similar, and not too high. Such spatial and temporal stability results from the major role played by hydrogeological conditions, which determine the recession rate of groundwater, especially where levels of their resources are low. Notwithstanding significant spatial variability (Kożuchowski, Wibig 1988), climate conditions, especially pluvial, seem to modify the present state only.

RECESSION TIME AND MINIMUM POSITION

One of the important characteristics of the development of hydrological drought is the time after which runoff reaches its minimum level (see Fig. 1). The length of this period (t_R) depends on stationary factors mainly connected with the hydrogeological conditions of groundwater reservoirs, depicted by the master recession curve, which may be modified by local and temporary factors, such as weather, temperature, and vegetation. The mean time between the commencement of low flow and the lowest discharge during the summer hydrological drought fluctuates between 4 and 40 days (Fig. 7). In general, the upper courses of rivers attain minimum flow much earlier than the lower ones. However, it is worth noting that some small tributaries along the lower course of the Warta (the Kopel, Mogilnica, Lutynia, Czarna Struga and Wrześnica) also display a long run-in time to minimum discharge—over 15 days, something that probably results from the predomination of autumn precipitation in these areas (Kożuchowski and Wibig 1988). As a result, the discharge recession rate is significantly slowed down.

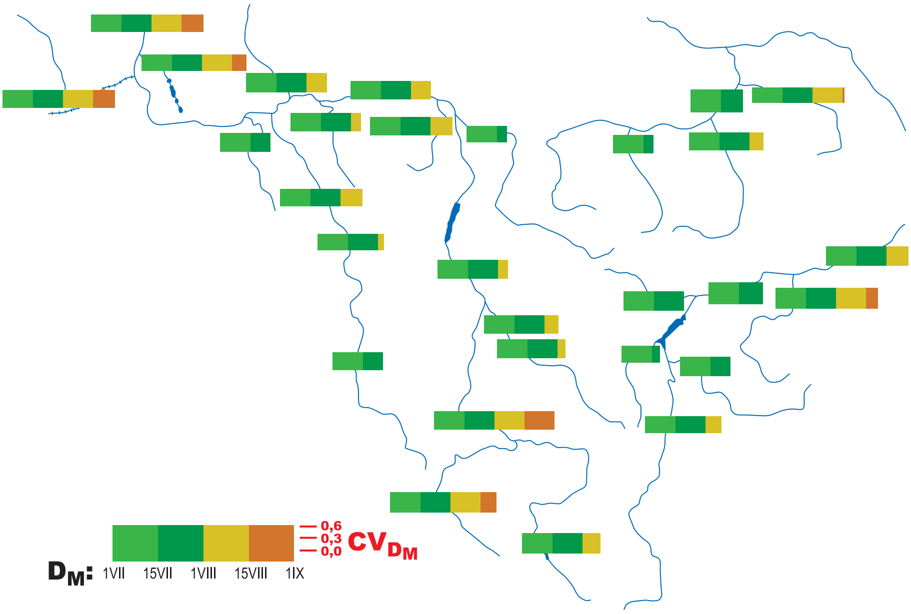

Figure 6. Spatial variation of summer low-flow minimum date and its variation
D_M—minimum date of the summer low flow
CV_{DM}—variation coefficient of D_M

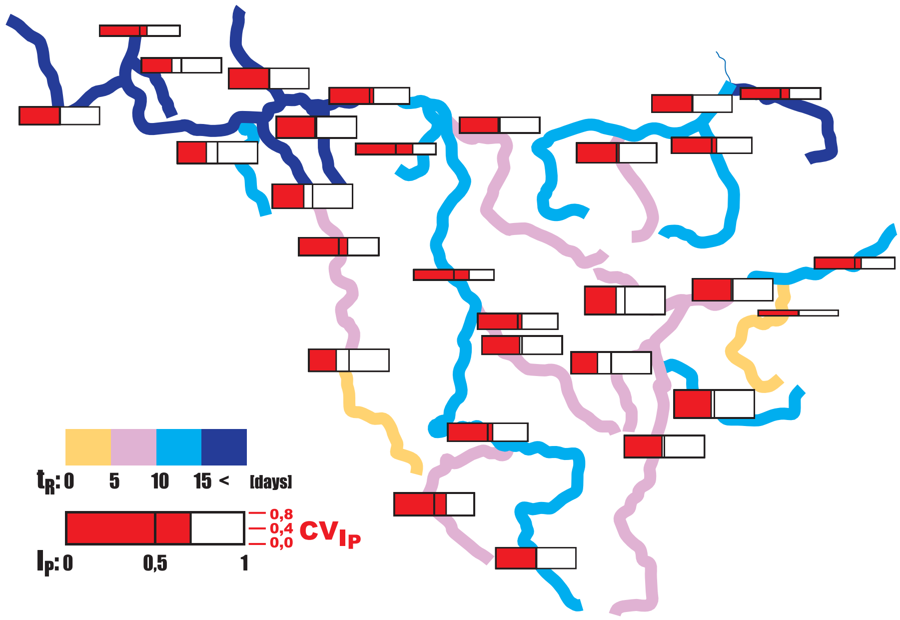

Figure 7. Recession time and the minimum low-flow position of summer hydrological drought t_R—recession time, I_P—index of minimum low-flow position, CV_{Ip}—variation coefficient of I_P

When it comes to the time structure of a hydrological drought, the position of the minimum flow plays a significant role. A characteristic which quantifies this property should be relative to the commencement and termination dates of the low-flow period:

$$I_P = \frac{t_R}{t} \qquad (2)$$

where:

I_P—index of minimum flow position

t_R—time between start point and minimum flow point during hydrological drought

t —duration of hydrological drought

The above parameter assumes values in the range between 0 and 1. Its interpretation is quite easy because, if the calculated value is equal to 0.5, the minimum point is situated exactly in the middle of the low-flow period. In the investigated rivers, the minimum flow position is reached after the midpoint as frequently as before (Fig. 7). There does not seem to be any dominating order to the spatial distribution of this parameter. This may indicate that, in that case, local conditions play a very important role. In general, many tributaries have a tendency to reach an I_P value equal to or less than 0.5, whereas main rivers remain above that level. Moreover, a high I_P level is very often connected with considerable stability of this index multiannually (CV_{Ip}). This results in a slow response to rapid recession of groundwater resources, and in the reaching of a long-term groundwater flow limit at a very late phase of the hydrological drought.

CONCLUSIONS

The analyses presented allow us to make a few general statements pertaining to content, as well as to the method applied:

- the SNQ level seems the most appropriate threshold in estimating major hydrological drought,
- hydrological droughts in the winter half-year appear very seldom in central Poland, or even do not occur at all,
- the temporal characteristics of hydrological droughts demonstrate a spatial order quite precisely (some zones appear or some directions of spatial variability are noticeable), and are determined by local as well as regional conditions,
- information about recession time as well as minimum flow position may be useful in describing the regime of low-flow formation, because it shows relationships between recession and the renewal rate of groundwater resources and their multiannual variability.

ACKNOWLEDGEMENTS

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A DESCRIPTION OF HYDROLOGICAL DROUGHTS IN THE BIAŁOWIEŻA PRIMEVAL FOREST IN THE YEARS 2003—2005

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Abstract: The Białowieża National Park is located in northeastern Poland, in the Narewka River Basin upstream of the Narewka gauge profile. Discharge records at this gauge were investigated and streamflow drought parameters, such as minimum and average discharges occurring during the drought, drought durations and deficit volumes were determined. These parameters define hydrological droughts and can serve in an indirect way to assess the degree of deformation of forest site types. The investigations covered the extremely dry 2003–2005 period, during which hydrological droughts occurred in each year. In order to check whether these droughts were more intense than those observed previously, characteristics were compared with those corresponding to the earlier period 1951–2002. The characteristics of intensity, minimum and average streamflow drought in the recent years were not found to have been more extreme than in the last multi-decade period. However, the streamflow droughts of 2003 and 2004 were extremely protracted, lasting 134 and 67 days. The drought of 2003 was in the nature of a “disaster”, though was still not an event more extreme than any noted in past records.

Key words: streamflow drought, hydrological drought, Białowieża Forest

INTRODUCTION

Poland is a country exposed to the periodic occurrence of hydrological droughts defined as deficits of surface water and groundwater. The Podlasie Lowland situated in the northeastern part of the country is one of the regions in which droughts occur most frequently (Farat *et al.* 1995, Kaznowska and Ciepielowski 2006). The hydrological droughts occurring there are a threat, especially to the hydrogenic forest sites of the Białowieża Forest, which represents natural and cultural heritage on the global scale. The aim of the study described here was to find out whether the droughts occurring at the site in the period 2003–2005 were more intense than those observed previously.

Investigations by Mager *et al.* (2000), based on daily water levels in the years 1891–1950 as well as river runoff in the period 1951–1995, showed that the mean frequency of hydrological droughts in Poland in the last 45 years was greater (at one dry year in each 3.2-year period on average) than in the whole period under analysis (one dry year per 44.0-year period). This resulted from frequency analyses of streamflow drought occurrence since the year 988, based on historical notes in the "chronicles of elementary disasters" and records from water level measuring gauges as presented by Fal (2004), that years with hydrological droughts built groups within multi-year cycles; with 2-year and 3-year cycles being most common. The longest dry period occurred in the 20th century, when years with streamflow droughts occurred one after another in the period 1947–1954.

However, the frequency analysis of the occurrence of hydrological droughts in the country in successive decades starting from 1951 makes it clear that the most years with streamflow drought were noted in the period 1951–1960 (Table 1). Recently, the period 2001–2006 brought four years with streamflow droughts(Kaznowska and Ciepielowski 2006). The results of investigations of the causes of the occurrence of dry year series pointed to the presence of climatic circulation features that enhance the occurrence and severity of droughts. These investigations also revealed that the last 25–30 years have witnessed a reorientation of circulation types in Central Europe, not only in summer periods. An increase in the occurrence of blocking masses (high air pressure) was noted, this favouring meridional inflows of air masses linked with a lack of precipitation over Europe (Lorenc 2006).

Poland is a country located in a region of marked sensitivity to possible changes in climatic relations (Kaczmarek 1996), so the warming reported by IPCC (2001) enhanced the formation of streamflow droughts. Thus, events in recent years (the spring drought of 2000 and the summer droughts of 1992 and 2003) might be regarded as harbingers of the more frequent dry years predicted by the IPCC for the temperate latitude zones (Kundzewicz 2003). The projections of global climatic change also foresee a much greater climatic threat to forest ecosystems than can actually be seen today (Sadowski and Galinski 1998). More frequent drought periods and high air temperatures could adversely affect the stability of forests and increase their vulnerability to industrial pollution and to the stress imposed by insect pests and fungal pathogens (MICE Team 2005). Long-lived forest trees might prove incapable of adaptation to changing site conditions.

The analysis of hydrological droughts in the Białowieża Forest area between 2003 and 2005 included an estimation of the severity and intensity of streamflow droughts along the Narewka River. That river together with its tributaries drains the central and northern parts of the Białowieża Forest. It is a tributary of the Narew situated in the Vistula River Basin. In order to examine whether the recent streamflow droughts were more intensive than earlier ones, a comparison of parameters of droughts from the 1951–2002 and 2003/2005 periods was made.

THE RESEARCH AREA

The Narewka River Basin is situated in the northeastern part of Poland in the Białowieża Forest area, this being a large forest tract with a prevalence of natural forests extending along both sides of the Polish-Belarussian border. The Białowieża Forest constitutes 73% of the catchment, while meadows and marshes of the Narewka River lowland form the majority of the remaining part. The Białowieża National Park of 10,502 ha is located in the central part of the catchment, in

Table 1. The frequency (numbers) of streamflow droughts in successive decades in the later 20th century in Poland.

Decade	1951–1960	1961–1970	1971–1980	1981–1990	1991–2000
Number of years with drought	6	5	0	4	3

the interfluve between the Narewka and the Hwozna. This is the most pristine forest anywhere in Europe, in which broadleaved trees predominate. It has been on the UNESCO List of World Heritage Sites since 1979 (Fig. 1) and among the European Heritage sites (in line with a status bestowed by the Council of Europe) since 1998. Unique, rare and endemic, species of flora and fauna occur here

Figure 1. Location of the investigated area.

The average stand age in the Białowieża National Park is 130 years, i.e. almost twice that of the same Forest's managed part. Almost all forest site types found on the central European lowland are present. Fresh soil sites dominate, accounting for 59.6% of the total. Moist represent 25.3%, and marshy sites 15.1% of the area. Moist-soil broadleaved and ash-alder forest sites account for the greatest share among moist and marshy forest sites. The share of bog and bog mixed coniferous forest is smallest. Moist and bog forest sites bear tree stands of considerable species diversity, while pine, spruce, and alder predominate (Chojnacki 2004).

The Narewka River springs are situated in the Belarussian part of the Forest (there referred to as Belovezhskaya) at an altitude of 159 m a.s.l. The catchment area up to the Narewka River gauge profile, in both riparian countries, Poland and Belarus, is 635.4 km^2, 346.2 km^2 of this being on the Polish side. The river bed slope is 0.4‰, and its length 50.1 km. The upper reach of the river in Belarus is regulated and the catchment managed. Downstream from the Poland-Belarus frontier the Narewka River flows through the Torfowisko Wysokie forest reserve, before passing through the hamlet of Białowieża itself. In that reach the Narewka was regulated as early as in the 18th century, but the final straightening of its channel was done in the early 1960s. Two ponds established by damming the Narewka at the end of the 19th century are situated on the Białowieża Glade; a weir dams the water for the ponds. The Braszcza, Hwozna and Lutownia rivulets are the main tributaries.

Groundwater is generally present close to the surface, due to the lowland character of the catchment and to the less-pervious soil formations spread out at shallow depth. Boggy areas along river valleys and peatlands situated below the 151 m a.s.l contour line have groundwater at a shallow 0–1 m depth linked hydrostatically with the water level in the Narewka River and its tributaries (Głogowska 2005).

The climate of the area is subcontinental, moderately warm and moderately humid. The mean annual air temperature is +6.5°C, the mean annual amplitude being 22.5°C. The average air temperature of the coldest month (February) is -5.2°C, that of the warmest (July) +17.4°C (Prusinkiewicz and Michalczuk 1998). The average annual total for precipitation is 617 mm (1951–2002) in the case of the meteorological station at Białowieża; the lowest precipitation total noted was for 1954 (400 mm), as compared with the peak of 900 mm noted in 1970.

It is the catchment areas situated in the lowlands along the Narewka River and its tributary the Hwozna, as well as the adjacent sandy areas with a superficial water table that are most exposed to transformations of vegetation associations due to the adverse effects of streamflow droughts. The groundwater resources in biotopes are subject to depletion as a result of hydrological droughts. Forest sites begin to suffer from disturbances in water balance and this can be the cause of far-reaching changes in the species compositions of forest associations. Norway spruce, the dominant species in the Białowieża Forest, has a shallow root system and so is one of the species more sensitive to drought (Ciepielowski and Głogowska 2005). An analysis of the occurrence of streamflow drought in forest catchments can provide representative indices characterising water conditions in those forest sites whose functioning depends on the groundwater level.

DEFINITION OF THE FEATURE

Streamflow drought is a commonly used concept serving in the interpretation of the state of a river as this relates to the water flow in the channel. Notwithstanding an abundance of Polish and foreign literature devoted to this issue, there is a lack of a genetically-based and univocal definition of this feature. The definition of streamflow drought that is adopted and used most often entails a recognition of the period over which discharges are less than or equal to the assumed threshold level discharge. The method involving extraction of streamflow drought periods from daily discharge hydrographs using the assumed threshold value occurs in the literature under the TLM (threshold level method) name, having been first adopted in hydrology by Yevjevich (1967). The choice of threshold level depends on the research area and on the threshold definition criteria, e.g. hydrological or economic (Ozga-Zielińska 1990), or hydrobiological –connected with the survival capabilities of aquatic organisms (Kaznowska 2006).

A group of hydrologists proposed a unification of methods and techniques for analysing the streamflow drought phenomenon. They cooperate within the international FRIEND (Flow Regimes for International Experimental and Network Data) project within the IHP (International Hydrology Programme) affiliated to UNESCO. A comprehensive description of probabilistic and stochastic methods of researching streamflow drought parameters is contained in the monograph edited by Tallaksen and van Lanen (2004) produced in the context of the aforementioned project. The authors of the monograph suggest that the streamflow drought threshold discharge be defined as a the $Q_{70\%}$ discharge determined from the curve of discharge duration time sums.

However, the separation of features of streamflow drought from among the more common low-flow periods occurring every year as a natural feature of a river's hydrological river requires the adoption of a lower value of the threshold level. The use of the $Q_{90\%}$ discharge threshold gives such a possibility (Zelenhasic and Salvai 1987; Hisdal and Tallaksen 2000; FRIEND 2002; Fleig *et al.* 2005). The minimum discharge duration below the threshold value is used as an additional criterion by which to identify streamflow droughts. The range of 10–20 days is typically adopted as the minimum streamflow drought duration in research work carried out in Poland (Byczkowski 1999).

THE METHOD OF RESEARCH

A sequence of discharges of at least 10-day duration with values equal to or less than $Q_{90\%} = 0.79\ m^3s^{-1}$ was recognized as constituting a streamflow drought. Such streamflow droughts separated from each other by less than 5 days were treated as one and the same feature; in order to avoid connections between neighbouring droughts. Summer and winter streamflow droughts are caused by different mechanisms. The summer droughts result from long-lasting deficits of precipitation, while the winter droughts are caused by a lack of surface and subsurface alimentation of rivers. This can be due to negative air temperatures, resulting in, not only an accumulation of precipitation in the form of snow cover, but also in a break in the subterranean water supply of a river due to deep freezing of the bedrock.

Summer and winter droughts were analyzed separately in order to preserve the character of the feature under analysis, taking into account half-year periods during which those droughts occurred. Daily discharge hydrographs of hydrological years (running from 1 November to 31 October) served as the input data for the evaluation of hydrological droughts. The streamflow droughts were distinguished from daily discharge hydrographs, and were described by reference to the quantitative parameters minimum discharge, mean discharge, drought duration, and water deficit volume expressed by the space between the hydrograph line and the threshold level (Fig. 2). These parameters were identified using the Nizowka 2003 model (Jakubowski and Radczuk 2004).

The following characteristics were applied in assessing drought severity:

$$\overline{T} = \frac{\sum T_{ni}}{\sum n_i} \qquad (1)$$

where:

$\overline{T}$ is the average duration of streamflow drought per year [days];

$\Sigma\, ni$ is the occurrence of a number of streamflow droughts in N years of the period under research;

$\Sigma\, T_{ni}$ is the summed number of days on which streamflow droughts occurred in an N-year period: and

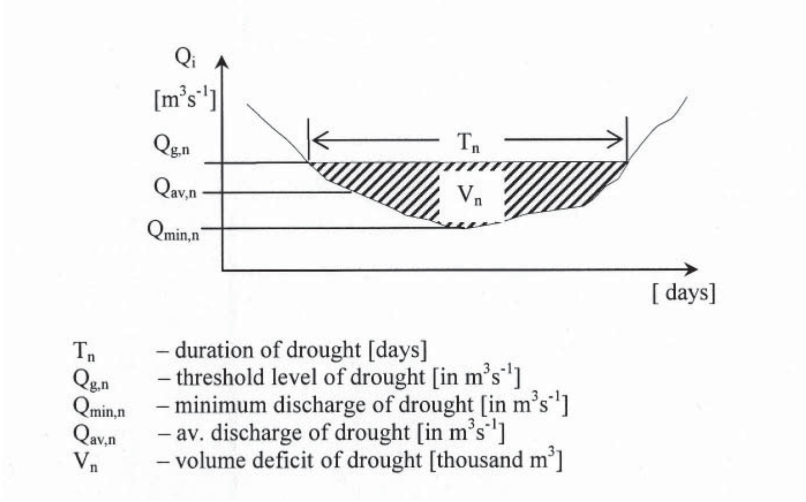

Figure 2. Parameters of streamflow drought.

N is the number of years in the research period;

$$\overline{V} = \frac{\sum V_{ni}}{\sum n_i} \tag{2}$$

where:

$\overline{V}$ is the average volume of streamflow drought deficit per year [th. m^3];

ΣV_{ni} is the sum of volumes of streamflow drought deficits in N years [th. m^3].

Characteristics describing either maximum or minimum values of analyzed parameters of individual streamflow droughts occurring in the analyzed multi-decade period were additionally defined as:

T_{max} – maximum duration of streamflow drought recorded in N years [days]

V_{max} – maximum volume of streamflow drought recorded in N years [th. m^3]

NQ_{min} – lowest discharge during streamflow droughts observed in N years [m^3s^{-1}]

SQ_{av} – average discharge during streamflow droughts observed in N years [m^3s^{-1}]

The mean intensity of streamflow drought in multi-year periods as given by Kasprzyk (2002) was the next streamflow drought characteristic taken into account. It was calculated as the ratio of the discharge deficit size and the number of days with low discharges in the multi-year period. This characteristic measuring the size of the discharge deficit per day of drought was recalculated in terms of percentage of mean annual discharge per day of drought:

$$I_{ar} = \frac{\sum V_{n_i}}{\sum T_{n_i}} \tag{3}$$

where:

the legend is as for equations (1) and (2).

RESULTS

Summer streamflow droughts predominate at the Narewka River gauge profile of the Narewka catchment, constituting 80% of all droughts occurring there. The beginning of streamflow drought occurrence in the summer half-year usually falls in July and June, while August, September and July are the months in which such droughts occur most often. Winter droughts occur most frequently in January and February (Table 2). The average duration of summer and winter streamflow droughts exceeds 40 days, and is about 30 days, respectively (Tab. 3).

In the period 2003–2005, streamflow droughts occurred every summer in the Narewka profile. Their characteristics were then compared with those of summer droughts occurring from 1951 to 2002. The intensity plus mean and minimum values for streamflow drought discharges of recent years were not found to be the most extreme on record in the multi-annual period. However, the streamflow droughts of 2003 and 2004 were very prolonged: at 134 and 67 days respectively (Table 3), while the nine 1951–2002 summer droughts lasting over 60 days constituted 26.5% of all summer droughts. Taking into account the recent years, the mean duration of a drought calculated from the multi-year period increased from 44 to 47 days (Fig. 3). The water deficits characterizing the 2003 and 2004 droughts can be classified as high. When recent years are taken into account in the process of calculating the mean deficit, this increases from 682,660 m^3 for 1951–2002 to 738,420 m^3 for 1951–2005.

The summer of 2003 merits special attention; an intensive and major hydrological drought following an exceptionally dry end of spring. This was noted over the prevailing part of the country. A detailed analysis of the causes and course of the 2003 drought was carried out by Mierkiewicz and Sasim (2005), who showed that the drought assumed disastrous dimensions for many regions of the country. The most unfavourable conditions occurred in August, when levels below the absolute minima were noted at 60 river-level gauges located mainly in south-western and southern Poland. However, the streamflow drought of 2003 was not yet the most extreme observed in the Narewka gauge profile. The longest and most severe stream-

Table 2. Streamflow drought occurrence by decades in the Narewka river (Narewka) in 1951–2005

Lata	XI			XII			I			II			III			IV			V			VI			VII			VIII			IX			X		
1951																										▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
1952	▨	▨	▨	▨	▨	▨	▨	▨	▨				▨	▨	▨	▨									▨	▨	▨	▨	▨	▨	▨					
1954					▨	▨	▨	▨	▨	▨	▨	▨	▨											▨	▨											
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1965	▨	▨								▨	▨	▨	▨													▨	▨		▨	▨	▨	▨	▨	▨	▨	▨
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flow drought lasted 194 days. It began on 12 July 1951 and ended on 23 January 1952, and its discharge deficit amounted to 5,002,560. m^3. The lowest discharge of the multi-annual period was recorded during that streamflow drought; featuring 0.30 m^{3}s^{-1} on 25 November 1951 (Table 3).

The streamflow drought of 2003 was shorter and shallower ($Q_{min} = 0.35$ m^{3}s^{-1}), as well as less intensive (0.021% < 0.027%). Not a single winter drought has been observed in recent years (since 1997). The lack of winter droughts can be attributed to the climatic warming that is to be observed now. An increase in average annual air temperature of 0.9°C was recorded at the Białowieża meteorological station located in the Narewka River Basin in the period 1950–2003. In recent years that increase has mainly occurred in winter (November–April) half years, these being warmer by 1.5°C than the multi-year average.

In the period 1989–2003, the mean temperature of the winter half-year was near to 0°C, while for the period 1951–2003 the warmest winter was observed in 1990, when the mean was 4.3°C (Czerepko *et al.* 2005). It also results from the comparison between the two periods 1966–1982 and 1983–2000 for the Białowieża observation station that the mean temperature in the winter half-year in recent years was higher (0.76°C) than in the earlier period (-0.24°C) (Maksymiuk *et al.* 2004).

Table 3. Characteristics of droughts in the Narewka river; S—summer drought, W—winter drought.

Periods	Type of Droughts	Characteristics of droughts								
		Σn_i	ΣTn_i	$\overline{T}$	$T_{max,n}$	$\overline{V}$	$V_{max,n}$	SQ_{av}	NQ_{min}	I_{av}
		/	days			th. m^3		m^{3}s^{-1}		%
1951–2002	S	34	1505	44	194	682.66	5002.56	0.66	0.30	0.016
	W	9	261	29	73	267.36	775.01	0.69	0.39	0.010
2003	S	1	134	134	134	2711.23	2711.23	0.56	0.35	0.021
	W	0								
2004	S	1	67	67	67	838.08	838.08	0.65	0.52	0.013
	W	0								
2005	S	1	16	16	16	154.66	154.66	0.68	0.58	0.010
	W	0								
1951–1971	S	25	1050	42	194	677.55	5002.56	0.66	0.30	0.018
	W	6	171	29	73	281.23	775.01	0.69	0.39	0.010
1983–2005	S	21	933	44	134	589.62	2711.23	0.67	0.35	0.014
	W	3	90	30	38	239.62	260.93	0.68	0.52	0.008

Symbols according to the formulae (1) to (3)

Two periods 1951–1971 and 1983–2005 are distinctly noted when days of droughts and drought deficits are summed up, year-by-year, within the period 1951–2005. Hydrological droughts occurred almost every year in those periods (Figs. 3 and 4). These periods are separated from each other by an interval of 11 years without streamflow droughts. The characteristics of drought severity described with formulae 1, 2, and 3 for both periods were compared with each other (Table 3). Mean drought duration, mean deficit, intensity, and mean and minimum discharges of both periods were not found to have differed significantly from one other.

The occurrence of two periods with streamflow droughts appearing almost every year in the multi-year period can be compared with the variability to annual precipitation totals recorded at the Białowieża meteorological station. During the periods 1951–1971 and 1983–2004, dry and average years predominated over moist ones, while in the period 1972–1982 moist and very moist years predominated over average and dry ones. This feature was found by reference to Kaczorowska's criterion (1962), through a comparison of the proportion of annual precipitation totals to mean multi-annual totals adopted as a norm.

CONCLUSIONS

The Narewka profile experienced hydrological droughts every year in the period 2003–2005. In the years 2003 and 2004 the scale of the phenomenon was major, and the streamflow drought of 2003 being disastrous in nature. However, this was not the greatest one on record. The drought of 2003 lasted for 134 days, with a deficit equal to 2.82% of mean annual discharge in the multi-annual period. Research on streamflow droughts in Poland shows that years with hydrological droughts form clusters in multi-annual cycles. Droughts in the 2003–2005 period can be regarded as a fragment of a longer cycle, the beginning of which occurred in 1991.

The tendency towards the annual occurrence of droughts visible in recent years is related to prolonged deficits of precipitation. Since 1982, permanent droughts have been observed in two 4–5-year periods, though atmospheric droughts did not occur over the greater part of the country. Consider-

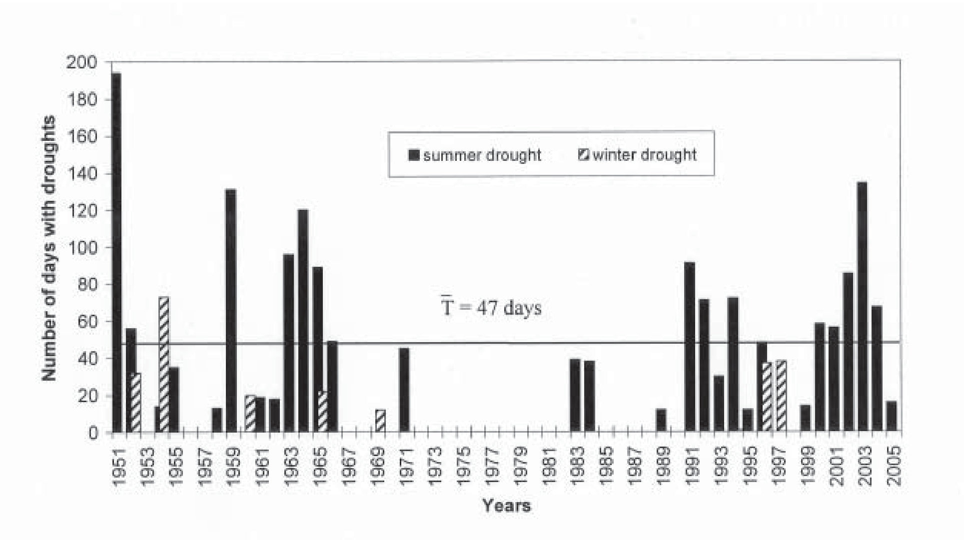

Figure 3. Number of days with streamflow droughts in the multi-annual 1951–2005 period in the Narewka river down to the Narewka gauging station.

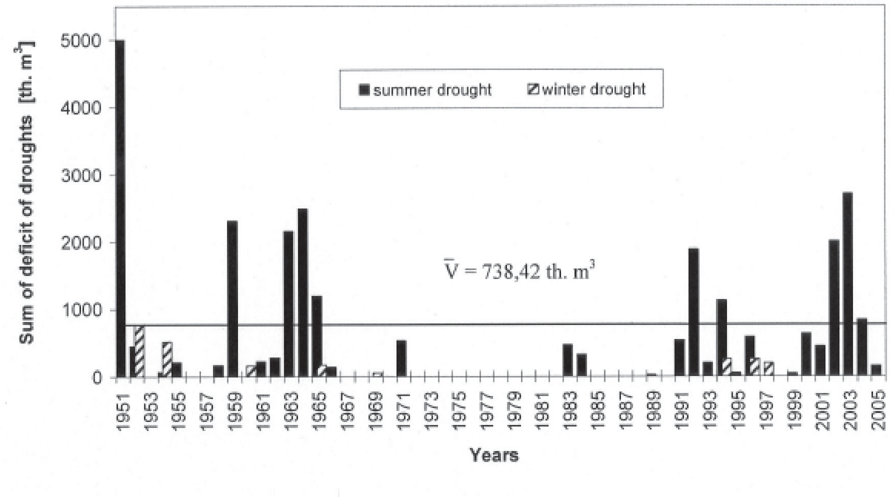

Figure 4. Deficit of streamflow droughts in the multi-annual 1951–2005 periods in the Narewka river down to the Narewka gauging station.

able and long-lasting precipitation deficits have been observed, especially during the last 15–20 snowless winters (Lorenc 2006). In the period 1983–2000, the mean precipitation total for the winter half-year at the Białowieża observing station was lower (at 235 mm) than in the period 1966–1982 (at 262 mm) (Maksymiuk *et al.* 2004).

The long-lasting streamflow droughts noted in the Narewka River Basin in recent years pose a threat to riparian forest ecosystems in lowland areas and adjacent territories with relatively shallow groundwater. Research carried out in the Białowieża Forest on especially valuable sites proved that the groundwater level in forest wetland biotopes decreased by 10 cm in the years 1985–2004 (Czerepko *et al.* 2005a). The lowering of groundwater levels caused by the occurrence of streamflow droughts in rivers normally derived from groundwater discharge, influences the dynamics of forest associations.

Comparison of the affected percentages of Białowieża Forest sites from the years 1998 and 2002 reveals a decrease in the percentage of moist and marshy sites, and an increase in fresh-soil sites. In 1998 the fresh-soil, moist and marshy sites together accounted for 55.2%, 28.2%, and 16.6% of the total respectively (BULiGL 1998), while in 2002 the figures were: 59.6%, 25.3%, and 15.1% (Chojnacki 2004). These results, and the tendency towards the annual occurrence of streamflow droughts indicate that an increase in retention and a decrease in water discharge are needed. The analysis of streamflow droughts can establish measures characterising the state of water conditions for the functioning of forest sites.

The problem of decline in the number of moist sites in the Białowieża Forest should be of particular interest and importance for the forest service due to the need to protect the natural diversity of forest sites as established in the rules of forest management in the State Forests (Rozwałka 2003).

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GEOMORPHIC ACTIVITY OF DEBRIS FLOWS IN THE TATRA MTS AND IN OTHER EUROPEAN MOUNTAINS

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Abstract: Debris flows constitute the dominant high-energy slope processes in the high-mountain belt of the Tatra Mountains, the Alps and other European mountain massifs. Rainfall intensities responsible for triggering recent flows include that of ca 35–40 mm in one hour. Under such a condition, whole talus slopes several hundred meters long are affected by rapid flow in the High Tatras, on both the Polish and Slovak sides, and the maximum volume of debris removed and accumulated by such events is ca. 25,000 m^3 . Debris flows with a maximum volume of ca. 500,000 m^3 are triggered by rainstorms of similar totals and intensities in the Alps.

Key words: debris flows, extreme rainfall events, Tatra Mountains, European geomorphic hazards.

INTRODUCTION

The present-day development of the relief of the Tatras, like other mountains, is determined by active and passive elements of the natural environment. Relief dynamics are conditioned by geological setting, especially by lithology, while relief energy is controlled by relative and absolute heights, gradients and dissection of slopes. However, relief dynamics are simultaneously conditioned by hydrometeorological factors which vary over time and space. In high-mountain areas, the considerable elevation above sea level leads to the development of systems of vertical circulation of heat, water and loose rocks. Vegetation, superimposed on relief elements and Quaternary covers of diversified origin, determines geoecological altitudinal belts, wherein a permanent circulation of water and mineral substances occurs. In the highest European massifs this circulation is controlled to a significant extent by the presence of mountain glaciers. In studies on the evolution of the present-day high-mountain relief, two vertical zones are distinguished in the Alps: *haute montagne alpine*–the zone subjected to glacial morphogenesis–and *haute montagne pyrénéene*–the zone without glaciers, yet with all other environmental features of the high-mountain landscape (Galibert 1960). The studies carried out in the highest parts of the glaciated Alps, rising above 4,000 m a.s.l., support a belief that the *haute montagne alpine* zone experiences a slower evolution than the *haute montagne pyrénéene zone*. The highest zone in the Alps is ‘protected’ by a snow-ice cover cemented to the substratum. Due to numerous days with frost (ca. 250 days a year) this cover never melts in the hottest months of a year.

AIM AND METHODOLOGY OF THE STUDY IN THE POLISH TATRAS

The purpose of the study is to analyse the imprint of debris flows on the present-day relief in the Tatras in relation to the Alps and other European mountains. All comparisons have to refer to the same high-mountain zone–namely to the non-glaciarised *haute montagne pyrénéene* zone, because this zone has developed in all high mountain massifs of Europe, from the Scandinavian mountains to the Sierra Nevada in southern Spain. Consequently, such comparisons can be made for fast mass movements triggered by hydrometeorological factors. It has to be remembered that, in the highest parts of the Alps the non-glaciarised haute montagne pyrénéene zone is found below the glaciated alpine zone and vertical transfer of mineral substances and water, as a medium, takes place between these zones.

Several methods have been used in the Polish Tatras (Kotarba 1997, Kotarba *et al.* 1983), among them:

- an inventory of debris flows using airphoto interpretation, scale 1:10 000,
- periodic photogrammetry of selected sites, scale 1:1000–1:5000 for field experimental slopes located relatively close to meteorological stations (the Hala Gąsienicowa Valley),
- field experiments on rockfall talus, alluvial talus and debris-mantled slopes in the High Tatras, ongoing since 1975

GEOMORPHOLOGICAL AND GEOLOGICAL SETTING OF THE TATRAS

The Tatras are non-glaciated high-mountains (Fig. 1). The outstanding feature of such mountains is a presence of glacial and nival forms, although the system of the forms is of a relict nature, i.e. it was formed during the Pleistocene glacial cycle. Although, there is no glacial-nival climate in the Tatras nowadays, the mountains are affected by influences of nival, nival-pluvial and pluvial-nival climates, depending on elevation above sea level (Hess 1965). It denotes that at present in the areas of high-mountain relief, which were formed by the Pleistocene glaciers, long-lasting snow retention is sustained, perennial snow patches occur, and an abundant amount of water is supplied by rainfall, snowfall and snowmelt. In a renewal of the water resources and water circulation, rainwater contribution is the most important and amounts to 75% of recorded annual precipitation (Łajczak 1996). Rainfall totals as well as rainfall intensity reach their maximum in the summer months, i.e. from June to August.

The eastern part of the mountains, called the High Tatras, has a classic alpine relief characterized by the presence of glacial cirques and glacial troughs formed by, at least, triple valley glaciation. Glacial erosional forms are filled with moraine and glacifluvial covers originating from the last glaciation (Würm). The forms were transformed by periglacial processes during the Holocene. In the granodiorite High Tatras the glacial cirques lie one over the other, their floors, excluding that of the topmost cirque, are usually overdeepened and filled with lakes. Rocky sills separate the cirques from the glacial troughs. The glacial cirques form autonomous morphodynamic systems with a local erosional level to which present-day geomorphic processes respond. High rocky ridges with steep slopes rise among glacial valleys. The upper parts of the slopes were not glaciated and have periglacial relief. They are dissected by systems of rocky troughs which had been forming since the end of the last glaciation, during a retreat of the glaciers. At the rocky troughs' outlets late glacial heaps and alluvial talus cones formed (Klimaszewski 1996). During the Holocene evolution of glacial and periglacial relief of the High Tatras, hillslope debris flows played an important role.

In the Western Tatras, composed of less resistant gneisses and shales, glaciation was not extensive and covered only the upper

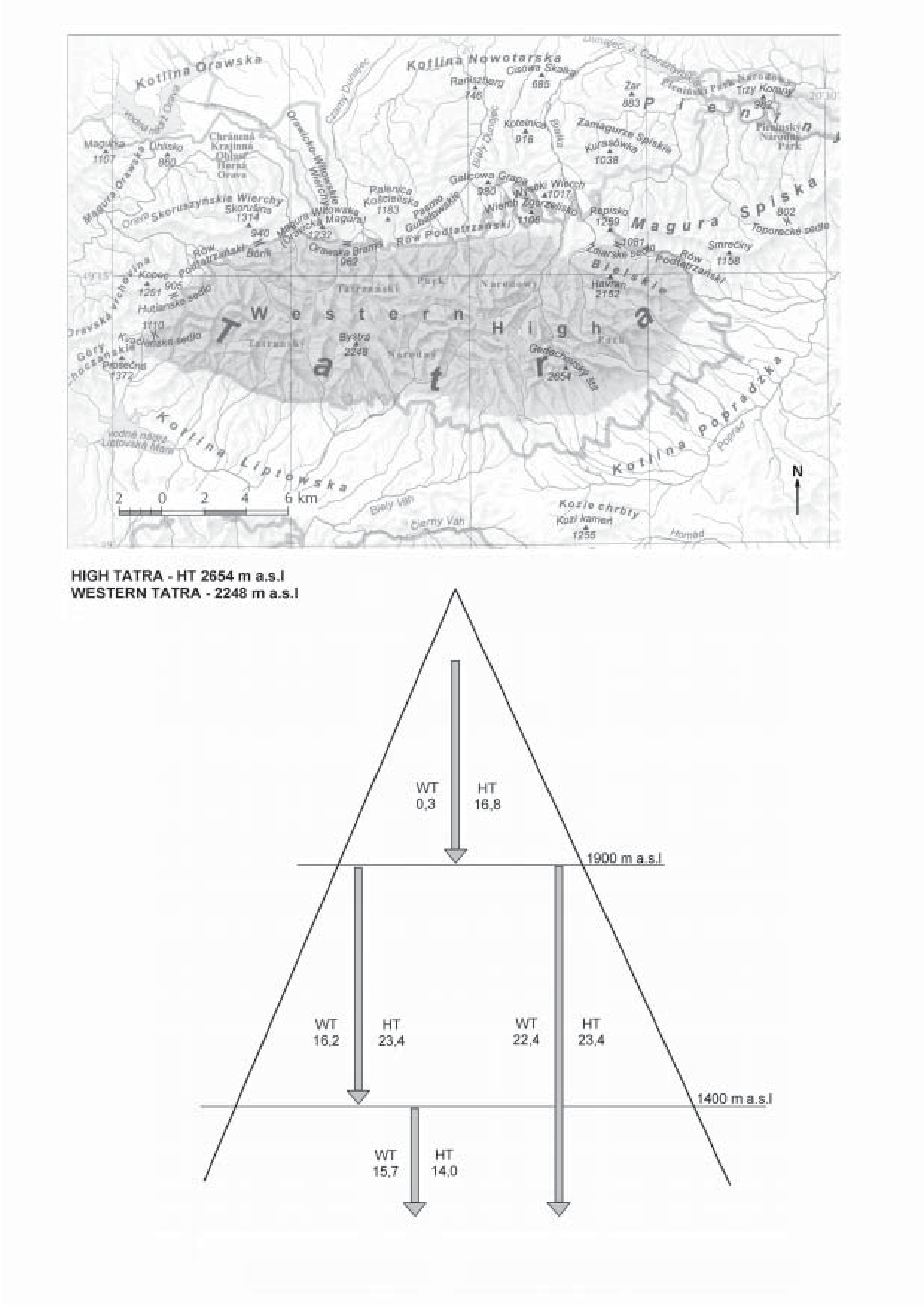

Figure 1. Tatra Mountains sketch and vertical distribution of debris flow tracks (%%) in the High (HT) and Western Tatras (WT), Slovakia. Source: Midriak, R. (1984)

sections of the valleys. In the limestones and dolomites of Czerwone Wierchy massif, only two glaciers formed definite systems of cirques separated from troughs by high rocky sills. Here, the slopes of glacial cirques are, in the majority, gentler when compared to their equivalents in the High Tatras and the valley bottoms were not overdeepened by glacial erosion. Longitudinal valley profiles are levelled out. In the Holocene relief evolution of the glaciarised parts of the Western Tatras, the role of valley-confined debris flows was particularly important.

The paper focuses on high-energy geomorphic events namely debris flows, which operate on these non-glaciated high mountains, mainly above the upper timber line.

DEBRIS FLOWS IN HIGH MOUNTAINS

Fast mass movements comprise debris flows, mud-debris flows and landslides. Their occurrence is most often, yet not always, associated with catastrophic precipitation and floods (Photo 1). At the lower border of the glaciarised alpine zone, the magnitude and dynamics of mass movements depends also on substrate properties of a ‘paraglacial’ environment. The term paraglacial environment refers to terrain which is at present being exposed from beneath melting glaciers. This terrain is rich in various-grained loose sediments. As the material is not consolidated, it is easily mobilized in the form of fast debris flows. Along with the retreat of

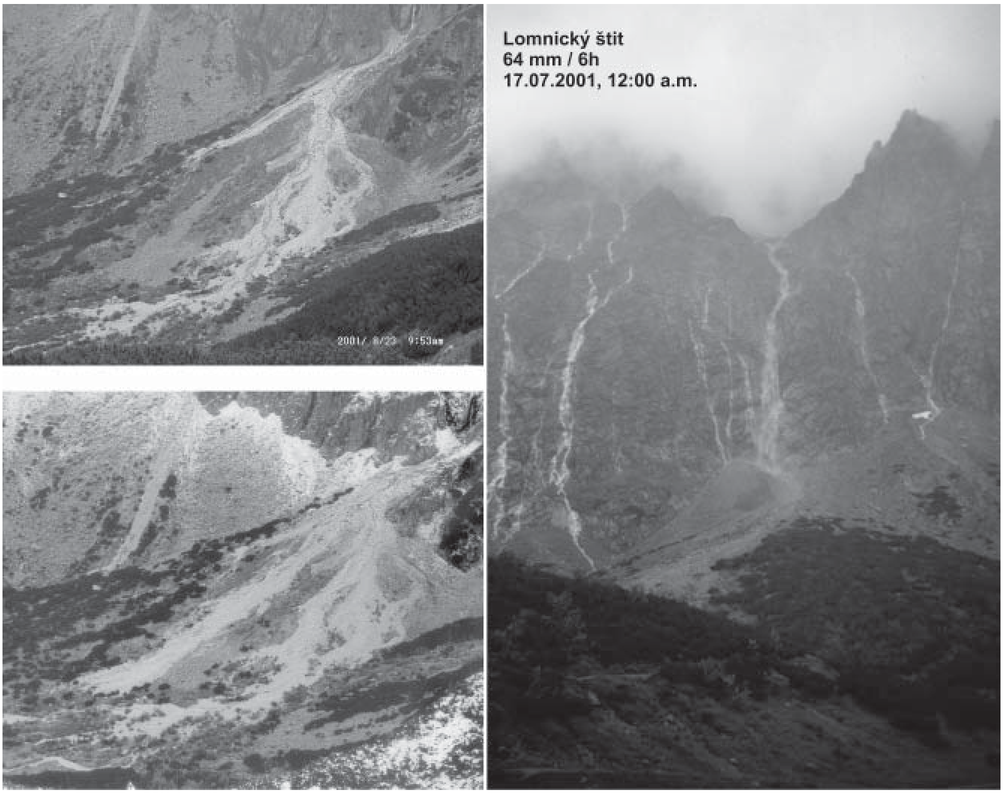

Photo 1. Debris flows on alluvial cone in Dolina Zeleného Plesa (Slovakia) triggered in 2001 and 2002, and photo centred on rockwall Maly Kežmarsky štit after 6-hour lasting rainfall (17.07. 2001, photo taken by G. Bugár)

glaciers to higher locations, permafrost wastes and areas prone to accelerated degradation by denudation processes expand, because the covers are being soaked with water originating from permafrost thawing. During the last several dozen years, under conditions of accelerated melting of glaciers in all mountains, paraglacial areas have been expanding. This denotes a territorial expansion of accelerated degradation of mountains by fast mass movements, including debris flows, in a transitional zone between glaciarised and non-glaciarised zones (*haute montagne alpine and haute montagne pyrénéene zones*). An example of a catastrophic debris flow in the paraglacial area of the Alps is the event which took place in the Aosta valley on the Mont Blanc massif in July 2003. During a dry period without precipitation, at the direct foreland of the Frébourge glacier (the Ferret valley) a debris flow was triggered by an outburst flood from an ice avalanched dammed lake formed in the zone of the retreating glacier. In the proglacial alluvial cone a volume of 30,000 m^3 of debris was transferred at a speed of 5–8 m/s. The whole event occurred in 3 surges (Deline *et al.* 2004). Phenomena of this type are not rare in the paraglacial zone of the Alps. The lack of glaciers in the Tatras explains why such processes are unknown in the environment of our mountains, nevertheless, on the microscale, paraglacial processes do occur in the highest parts of the High Tatras, particularly in the most immediate vicinity of perennial snow patches (Rączkowska 2005). The geomorphological hazards of debris flows in European mountains have been discussed, and results of different studies published (e.g. Pasuto and Soldati 2004, Glade 2005, Jakob and Hungr 2005, Luino 2005, Hürlimann *et al.* 2006).

DEBRIS FLOWS IN THE TATRA MOUNTAINS

A system analysis of mountain relief evolution assumes two morphodynamic subsystems which function independently under average hydrometeorological conditions. These are slope and channel subsystems (Kotarba *et al.* 1987). Under such conditions, there is no link between the two subsystems, so products of weathering and of denudation as broadly understood are not transferred from one to the other subsystem. Changes in slope relief are local, and material triggered during slope formation stays in the given subsystem. A similar situation occurs in channel subsystems on valley floors. The above is observed in the Tatras when short-lasting rains fall with an intensity over 1 mm/min and reach 40 mm in the course of an hour. The debris flows which form under such conditions on scree slopes and rock-debris mantled slopes of the High and Western Tatras do not descend to the valley bottoms and have no influence on the dynamics of channels (situation A). Long-lasting summer precipitation of duration above 3 days and intensity $<<$ 1 mm/min cause a linear erosion and mud flows, mainly in a timber vertical zone of the Tatras, while a lateral erosion by flood water in the valley channels results in erosional undercuts, landslides and scars formed near the bases of slopes, at the contact part between slope and channel subsystems (situation B). The most intensive geomorphological work is done in the mountains during rapid floods, when a precipitation of a few day's duration (situation B) is boosted by precipitation characteristic of situation A. Then, both subsystems join together and threshold values determining the stability of slopes and valley floors are exceeded in the entire system (Rebetz *et al.* 1997, Kotarba 2002). After the weathering-soil covers on the slopes have been saturated with water, they become liquefied, and earth-debris flows and landslides occur in particular geoecological belts. During the catastrophic flood of July 1997 in the Tatras, an unusual phenomenon was observed. The phenomenon might be called a ‘wash-out’ of entire slope covers, together with trees. In the floors of small valleys, which dissect the slopes in the timber vertical zones, bare bedrock has exposed locally. The wood-mineral material was deposited as cones at the outlets of side valleys, while on the floors of main valleys this material formed dams.

In consequence, the river/stream channels were altered, those which had earlier been stable for tens of years were dissected, and river load (including boulders up to 2 m in diameter) was transported over a distance of a 30 m while finer material was transported out of the Tatras altogether (Kotarba 1998).

A cartographic analysis of the trails of debris flows in the Slovak High and Western Tatras attests to a height differentiation of the forms (Fig. 1). They are most numerous in the height interval of 1400–1900 m a.s.l. This is the alpine meadow zone and, simultaneously, the zone in which precipitation totals are highest.

In geomorphological studies in the Tatras, the determination of the conditions necessary to trigger fast mass movements has been attempted for a long time. The threshold values which should be determined are the lowest precipitation totals for events of brief duration that are directly responsible for the fast transfer of rock masses in the form of debris- and mud-debris flows on the slopes, with a sufficient amount of loose weathered material, and which give rise to new forms that modify the circulation system of water and mineral substances that formerly existed on the slope. The threshold values have to differ in various mountain areas because the same precipitation does not always generate similar geomorphological results. Substratum resistance to an external impulse is controlled by lithology and tectonics, morphometric parameters and morphographic features of a given area (i.e. the gradient and length of slopes, the network density of slope dissection) and by types of vegetation cover (coverage with high-mountain meadows and dwarf pine patches). Observations of talus slopes carried out since the 1960s in the Sucha Woda and Pańszczyca Valleys, by the Research Station of the Institute of Geography and Spatial Organization, Polish Academy of Sciences (IGSO PAS) at Hala Gąsienicowa allowed it to be assumed that hourly precipitation totals exceeding 25 mm are the threshold values that can give rise to a debris flow. Hourly precipitation of just 35–40 mm is sufficient to trigger flows affecting entire slopes. The probability of such precipitation at Hala Gąsienicowa is 10% (Niedźwiedź 2003). However, tremendous debris flows can sometimes happen at lower threshold values. Lukniš (1973), after Zaruba and Mencel (1954), cites the description of the enormous debris flow at Slavkovsky štít in the Slovak Tatras which formed during a 26 mm hourly precipitation event taking place on 15 July 1933. The corresponding diurnal total was ‘only’ 62 mm. The aforementioned threshold value might be underestimated because the precipitation attributed to the discussed event has been measured from the meteorological station in Starý Smokovec, which is rather distant from the site at which the flow was triggered. Midriak (1984) in his synthesis for the Tatras and the neighbouring areas concluded that the largest volumes of debris masses transported by single flows are up to 25,000 m^3. Janáčik (1971) presented the description of the huge debris flow of volume 22,000 m^3 formed at the Osobitá summit in the Western Tatras in August 1970. It can be accepted that the flows in the Polish part of the Tatras transport smaller amounts of debris. In the Polish part of the High Tatras the material transferred in individual hillslope flows reached only a few thousands cubic meters in total volume (Kotarba 1992), while in the Western Tatras the figure is smaller–often of an order of a few hundred cubic meters (Krzemień 1988). The collected data on recorded precipitation and masses of material transferred in debris flows triggered by such precipitation suggest that the sizes of forms generated by debris flows are mainly conditioned by local topography, sometimes called ‘relief energy’. Precipitation of similar intensity and efficiency can generate flows differing significantly as to size. The length of slopes, their dissection by the valley systems of the first and second orders, the spatial extent of precipitation, type of slope covers and, especially, their consolidation decides on sizes of generated forms.

The analysis of the tracks of the debris flows in the Slovak High and Western Tatras, performed by Midriak (1984) showed, that despite similar hydrometeorological conditions generating the valley confined debris flows, the length of these forms differ (Table 1). In the Western Tatras 250–500 m long flows predominate (51.4%), while in the Western Tatras those 500–1000 m long are the most common (55.2%). The relief type decides upon lengths of the flow tracks. In the relief of the High Tatras, in the areas located above the upper timber line, glacial cirques predominate, these being arranged in a stairway pattern, separated by rocky sills and, most often, each cirque has a bipartite slope/slope sequence; rockwall–talus slope. Therefore, debris flows which form on talus slopes, flow down an open hillslope, and are not topographically constrained (*hillslope flows* according to Brunsden classification, 1979). In contrast to such topographic conditions, in the Western Tatras glacial cirques are not overdeepened, and continuous *valley confined flows* are the most common. Thus their length and vertical distribution is greater. They often follow gullies cut in drift, talus or regolith by previous flow events.

Table 1. Length of valley-confined debris flow tracks in the High and Western Tatra, Slovakia

Length of debris flow tracks (in meters)	High Tatras (%)	Western Tatras (%)
≤ 250	2.8	3.9
250–500	51.4	35.9
500–1,000	36.5	55.2
≥ 1,000	9.3	5.0

Source: R.Midriak 1984

COMPARISON OF DEBRIS FLOWS IN THE TATRA MOUNTAINS AND OTHER EUROPEAN MOUNTAINS

Comparison of geomorphologic events of types A + B in the Tatras to similar situations in other European mountains is difficult, due to the small size of our mountains. Floods in the Alps and Tatras are often characterised by hydrometeorological parameter which are alike, yet their outcomes are not comparable. The last huge flood in the Alps which occurred on 21–23 August 2005, affected an area of 6,500 km^2. Precipitation of 200 mm falling in 48 hours, with an instantaneous intensity reaching 20 mm/hour resulted in floods in central Switzerland, western Austria and southern Bavaria, as well as partially in the Romanian eastern Carpathians and in Transylvania. According to calculations, floods of such a territorial extent occur once every 100 years (Tropeano and Turconi 2005). In 2000, a huge flood of smaller extent yet higher precipitation occurred in the Pennine Alps. On 11–15 October, the Swiss meteorological service recorded maximum precipitation totals of 700–800 mm during 12 hours in Piemonte-Aosta valley at the Swiss-Italian boundary. In the Alps, extreme diurnal precipitation reaching 400 mm can happen. For example, in the Locarno-Magadino region precipitation of 414 mm was recorded on 10 September 1983. Much higher values (840 mm/23hrs) were observed in the Eastern Pyrenees during the catastrophic flood in October 1940 (Soutadé 1969). Fig. 2 presents the recurrence of maximum diurnal precipitation in the Tatras and the Alps.

During the last tremendous flood in the Tatras on 4–8 July 1997 the sum of precipitation at Hala Gąsienicowa was 330.3 mm, while diurnal precipitation of 223.5 mm and an hourly intensity of 39 mm were recorded on 8 July. According to the data compiled by Niedźwiedź (2003), it is believed that the extreme precipitation at Hala Gąsienicowa recorded in 1927–2002 were similar to those recorded in the Alps: one-day precipitation—300.0 mm (30.06.1973), three-day precipitation—422.4 mm (16–18. 07.1934) and five-day precipitation—462.3 mm (14–18.07.1934). The above precipitation is comparable with the alpine, although the geomorphologic effects were small, on the scale of particular Tatra drainage basins.

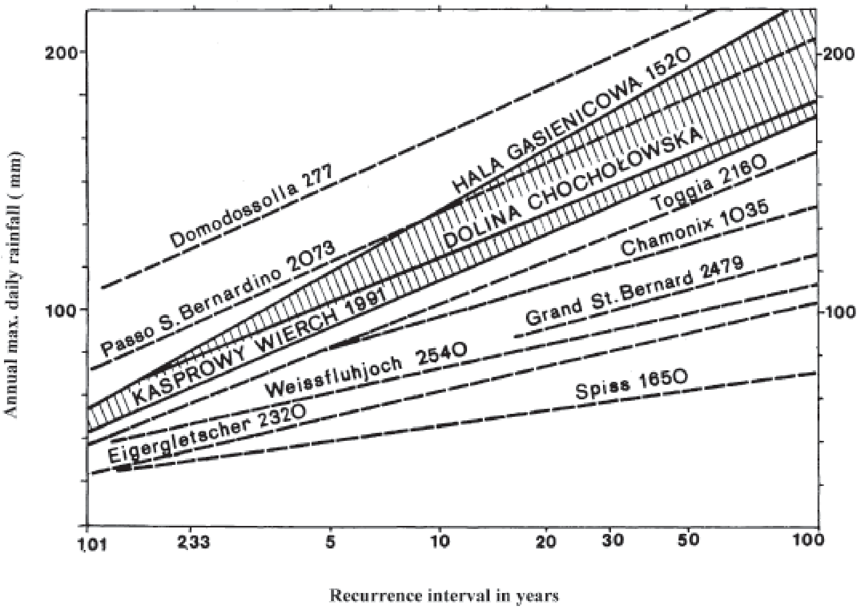

Figure 2. Recurrence intervals (in years) of annual maximum daily rainfall for high-mountain part of the Tatra Mts compared with selected Alpine stations.
Source: Zeller, J., Geiger, H. and Röthlisberger, F. (1976–1984) and Anselmo,V. (1979)

Examination of air circulation patterns in the Tatras has offered a background for determination of the genesis and intensity of atmospheric precipitation in various synoptic situations (Niedźwiedź 1981, Cebulak 1983). The origin and magnitude of precipitation triggering fast mass movements on the Tatras slopes have been identified. Knowing hydrometeorological parameters for the Alps and the Tatras, one can attempt to determine their role in the present-day modelling and transformation of the high-mountain slopes of these mountains, however, with respect to the slope subsystem only and only under the influence of short-lasting storm and intensive convection precipitation (situation A). Under the influence of such events, the most spectacular changes in slope relief take place. Following statistical calculations, maximum hourly precipitation in the Tatras, reaching 60–80 mm, occurred with a 1% probability (once per 100 years) while precipitation reaching 40 mm occurred with a 10% probability (once per 10 years) (Cebulak *et al.* 1986, Niedźwiedź 1992). On the other hand, a number of extreme precipitation events increased during the last 7 years when compared with the period of 76 years analysed by Niedźwiedź (2003). Since 1995 a transition to a moister climatic phase has been observed. This finding is crucial for considering the present-day evolution of the slope relief under the influence of fast mass movements above the upper timber line both in the Tatras and the Alps.

An intensified activity of debris flows is also observed in many mountain areas of Europe. Both the magnitude and frequency of precipitation have increased in the recent decades. The above is substantiated by the records from historical documents combined with other methods (Jomelli *et al.* 2004, Marchi and Tecca 2006). Jomelli *et al.* (2004) have evidenced that the influence of climatic changes on the dynamics of debris flows in the French Alps is visible in the scale of the recent 50 years. Twelve sets of aerial photographs taken in two test areas (Massif des Ecrin and Massif du Dévoluy), located at 1,600 (1,900 m) to 2,400 m a.s.l., in 1948–2000 have been analysed. In these study areas, there are talus slopes not covered by glaciers since the Little Ice Age. The importance of spatial and temporal overlap between heavy rainfall and debris flow activity was analysed, making use of data from meteorological stations located in these areas. The increase in temperature at high altitudes and an upward shift of the isotherm 0°C provoke a degradation of the permafrost in rockwalls, as well as reducing snow cover duration. The slopes elevated above 2,200 m are nowadays exposed to greater temperature variations and intensified physical weathering. A significant increase in summer rain, higher than 30 mm/day, has also been observed in high elevated areas since 1975. As a consequence, a shift of triggering zones of debris flows towards higher elevations has occurred during the period 1976–2000 (Jomelli *et al.* 2004). Similar tendencies have been recognized in other areas in the Alps (Zimmermann and Haeberli 1992).

The above finding is confirmed when we compare mountains differing in their sizes–the Tatras to the Alps (Fig. 3). Similar diurnal and instantaneous precipitation can result in the debris and mud-debris flows of the volume of 400,000 m^3 (Aulitzky 1970), or even of 500,000 m^3 in the Alps (Govi 1984). The debris flow in Tirol, described in details by Aulitzky, was formed in Inzing by convection precipitation amounting to 39.4 mm/24 hrs, on 26.07.1969. The recorded instantaneous intensities reached 2.1–2.5 mm/min. This precipitation fell on a summer day in a 12.2 km^2 tributary valley joining the Inn Valley. The material triggered in a hanging valley was transferred to the Inn Valley and resulted in catastrophic damage in Inzing village located on the alluvial fan. The volume of material mobilised in the hanging valley and deposited on the fan in the Inn valley was 404,000 m^3. Where the grain size composition was concerned, there was a predominance of fine particles (150,000 m^3), fine particles with coarser chunks of 0.25 m^3 (80,000 m^3) and rocky blocks exceeding 1 m^3 (70,000 m^3).

Measurements of the volume of material transferred by debris flows has been made in other massifs of the Alps, and in the mountains of Scotland, Scandinavia and Spitsbergen. The results of the above examination, compiled by Van Steijn (1996), are shown in Fig. 3. The Tatra data refer to all forms of debris flows mapped and described in the Slovak and Polish Tatras. The Tatra flows occupy a central position with respect to other mountain groups and are closest to the forms described in the French Alps in the Bachelard massif belonging to the Southern Alps which are not glaciarized nowadays and in which the highest summits reach 2,600–2,800 m (le Grand Cheval de Bois—2,839 m). In terms of the sizes of ridges and valleys they are similar to the Tatras. However, the highest non-glaciarized alpine ridges are subjected to intensive modelling by debris flows (e.g.. Ariège, Arve, Zillertal and Zell on Fig. 3).

The fast mass movements in the mountains of Scotland and Spitsbergen produce forms smaller by an order of magnitude than those generated in the Tatras, although the threshold values are much smaller there. According to Larsson (1982), precipitation of intensity 2 mm/hr can generate debris flows in northern Scandinavia, if preceded by diurnal precipitation of 30–50 mm. According to Rapp and Nyberg (1981), the weathering covers in these mountains are thin and permafrost is present there. The active layer is thin in summer and saturated with water originating from thawing of permafrost, so the debris flows are triggered even by a tiny precipitation impulse and affect only a thin active layer. In the case of the Scottish mountains it is evidenced that the magnitude of relief changes is controlled by the amount of loose weathered material which can be transferred. In numerous areas sheep pasturage and deer husbandry which have lasted for at least 200 years , as well as grass

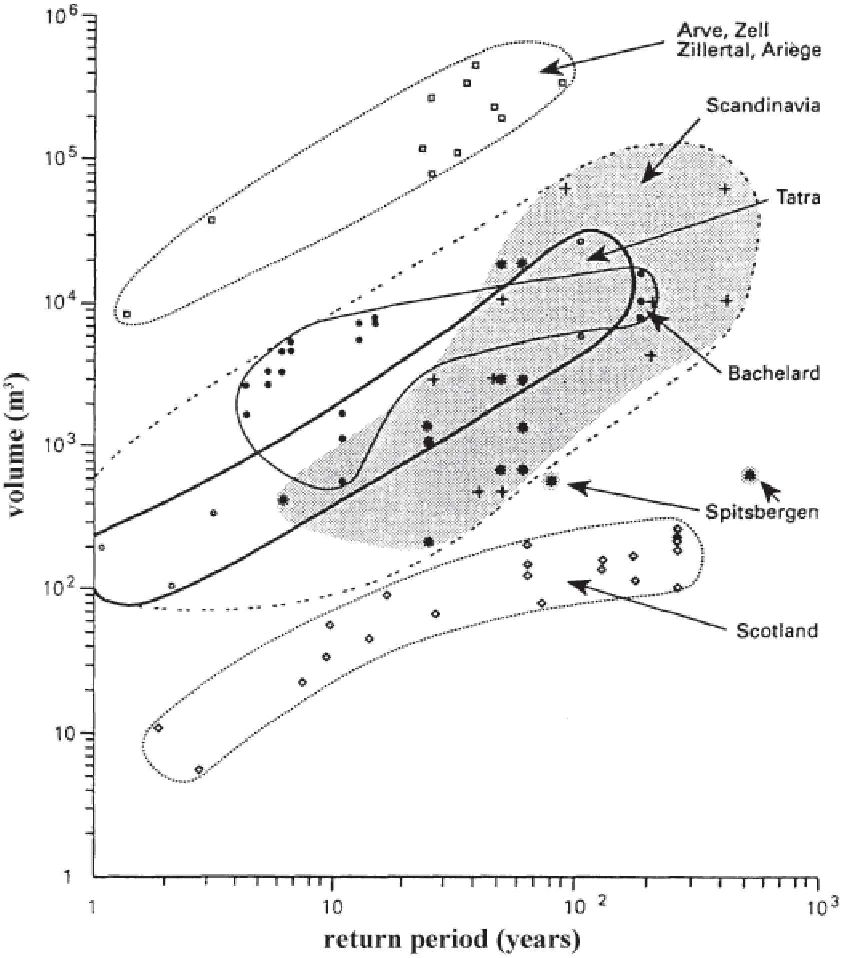

Figure 3. Debris flow magnitude-frequency relationshops in European mountains.
Source: reprinted from Van Steijn, *Geomorphology,* (1996), vol. 15, p. 267.

burning, have resulted in accelerated degradation of slope covers in the past few centuries. The present-day debris flows are of limited extent and size, as they form within those thin, degraded covers (Innes 1985). The form sizes are thus small, notwithstanding the Scottish climate favouring convectional precipitation. Addison (1987) provided evidence that precipitation of 40 mm during an hour is the threshold value triggering debris flows in Snowdonia in northern Wales. Innes (1985) compiled the features of over 900 debris flows in the mountains of Scotland and Norway. The average volume (arithmetic mean) of the forms in Scotland is 10–50 m^3, compared with 100–350 m^3 in Norway.

Icelandic debris flows are of small to medium size (from less than 100 m^3 to about 3,000 m^3, and are triggered mainly by rapid snowmelt (27%) or snowmelt associated with rain (21%), long-lasting rainfall (27%) and intense rainfall (only 13%) (Decaulne and Saemundsson 2006). The above data suggest that the grading of hydrometeorological factors triggering debris flows is different in Iceland. Under conditions of a subpolar-oceanic climate rapid snowmelt is responsible for transforming both the fine and coarse material on hillslopes, while intense rainfall is of minor importance.

FINAL CONCLUSIONS

Debris flows are among geomorphological processes occurring commonly in different climatic zones, though, they play a particular relief-forming role in mountain areas due to the large amount of water originating from rain, snow melting and the thawing of glaciers. Simultaneously, water is a factor which triggers a flow process, and is a carrier of mineral and organic matter during a flow event. Rainwater, as the factor initiating the process, has to be supplied fast, even rapidly. Water of other origins can only add to the relief-forming effects. An abundance of loose weathered material is also a necessary condition for debris flow formation. Therefore, high-mountain areas and polar regions are prone to strong modelling, yet the scale of impacts on the existing relief is conditioned, to a significant degree, by a series of other environmental factors. As these factors can overlap or cancel each other out their combined effect is a tremendous differentiation of the manner and rate of slope relief transformation on the scale of the European mountains.

Considering the size of the debris flows on the global scale, the European debris flows are among the small and medium ones. L. Innes (1983) graded debris flows in four sizes; large-scale (>10^5 m^3), medium-scale (10^3–10^5 m^3), small-scale (1–10^3 m^3) and micro-scale (<1 m^3). In the 10-grade classification of M. Jakob (2005) the Tatra debris flows belong to grade 4 (10^4–10^5 m^3), while the alpine flows are assigned to grade 5 (10^5-10^6 m^3). The largest debris flows of grade 10 (> 10^9 m^3) refer to the transfer of volcanic material in non-European regions and do not transport material of block sizes.

Based on the extensive array of results from field studies performed in non-European mountains, it is unambiguously concluded that substrate properties and topography determine erosion and type of slope transformation. According to Hovius *et al.* (2004), finding a decisive factor remains a challenge. The Tatra massif is characterised by a moderate rate, yet the results are catastrophic for people in exceptional cases only and on a small scale. The alpine debris flows result in dramatic, catastrophic damage to the infrastructure of towns and villages, and are hazardous for people dwelling in those mountains. In this domain, the Tatras are definitely different from the Alps, though since the early 1980s high-magnitude debris-flow activity has become more frequent in the Tatras also. This tendency is visible in many localities, both in the Polish and Slovak parts of the mountains. This circumstance supports the need for a comprehensive study of debris flow activity, even if the debris flow hazard is very low and limited to the local scale only. Systematic precipitation records, mainly regarding the frequency of heavy rain, and the triggering of debris flows would seem very appropriate from the geomorphological and practical points of view. The analysis of such data will provide a better understanding of debris flow initiation in the context of global climate change also.

ACKNOWLEDGEMENTS

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EXTREME RAINFALLS AND THEIR IMPACT ON SLOPES —EVALUATION BASED ON SOIL EROSION MEASUREMENTS (AS EXEMPLIFIED BY THE SUWAŁKI LAKELAND, POLAND)

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Abstract: Monitoring of soil erosion on selected slopes of the Suwałki Lakeland (NE Poland) was conducted in the years 1987–1989 and 1998–1999. The extreme rainfall was characterised by an efficiency of 35.7 mm and an average intensity of 0.5 mm per minute. This rainfall caused erosion along the entire length of the slopes, and its volume was equal to the average annual value. Almost 75% of the material deposited in the lower, concave section of the slopes during the 5-year period of measurements was transferred beyond the slope base. Some of the slopes of length over 100 m was cut by networks of rills up to 50 cm deep, and the rate of soil loss was 30 t ha^{-1}. This rainstorm was most important in respect to the intensity and transfer of eroded soil material, and was a decisive factor in soil loss and in the redistribution of soils on the slopes over the entire period of measurement.

Key words: rainfall, extreme events, soil loss, soil erosion and deposition, NE Poland.

INTRODUCTION

In research on soil erosion by water, lakelands play a special role as compared with other lowland areas, on account of their complex relief. Where the share of cultivated slopes inclined over 9° is large a high intensity of soil erosion may take place (Niewiadomski and Skrodzki 1964, Chudecki and Niedźwiecki 1983, Uggla *et al.* 1968, 1998). The important role of brief storms occurring in June and July has been emphasized by several researchers (Uggla *et al.* 1967, 1968, Niewiadomski 1968, 1998, Smolska et al. 1995, Smolska 2002). According to Józefaciuk (1991), such areas are threatened by erosion of the soil due to water to a limited, locally a moderate degree. A similar situation applies in Germany, where areas of post-glacial relief are threatened by water-induced soil erosion to a lesser degree than loess or upland terrain (Auerswald 2006). During rainfall of average intensity, local environmental conditions are more important where soil erosion is concerned. However, rainfall of high intensity sees threshold values for overland flow exceeded, erosion then depending mainly on rainfall intensity and runoff magnitude. Runoff increases from a divide toward lower parts of slopes, providing material for valley floors and river channels (Carson and Kirbky 1972, Froehlich 1982, Selby 1982, Teisseyre 1994, Bryan 2000).

The aim of research carried out in the periods 1987–1989 and 1998–1999 was thus to assess the intensity of soil erosion on selected slopes in the Suwałki Lakeland (Smolska 2002, 2005). The work described in this paper focused on the role of extreme rainfall on soil erosion and redeposition.

STUDY AREA

The relief of the Suwałki Lakeland is typical of the last glaciation. It lies within the range of the Pomeranian phase of the Leszczyńsko-Pomorski stadial (Ber 2000). A landscape of hilly and undulating morainic plain prevails in this area. There are also hills and mounds of end moraine or of dead-ice moraine origin. Other typical relief features are extensive glacial depressions with forms of aerial deglaciation on their floors. There are numerous tunnel valleys in the area. Elevations are limited, usually of 15–30 m, only locally exceeding 50 m. Slopes are usually inclined by 6° to 18° and have a convex-concave or a straight shapes. Occasional dry bowl-shaped valleys and gullies add variety to the slopes.

Soil erosion was studied on slopes typical for the area and lying within the basin of the upper Szeszupa (Fig. 1). A detailed description of the studied slopes is presented in previous papers of Smolska *et al*. (1995) and Smolska (2002, 2005). Selected parameters of the slopes are as shown in the Table 1, while longitudinal profiles of the slopes are presented in Fig. 2. Measurements of interrill erosion were conducted on short slopes which were several dozen meters to about 100 meters long, and 10–15 meters high. Rill erosion was observed sporadically on short slopes during field survey (Smolska *et al*. 1995), so this process was measured on longer slopes of the Szeszupa depression, which were 125–280 m long with a high elevation (30–70 m).

CLIMATE OF THE STUDY AREA AND METEOROLOGICAL CONDITIONS OF THE STUDY PERIOD

The temperate climate of the Suwałki Lakeland also has continental features. Mean annual air temperature is 6.1°C and mean

Table 1. Selected characteristics of investigated slope and slopewash rates

Wash	Slope	Lendth [m]	Hight [m]	Inclination [°]	Lithology	Average annual soil erosion or deposition (+) [kg ha^{-1}]		Extreme soil loss [kg ha^{-1}]	
						Convex and straight segment	Concave segment	Convex and straight segment	Concave segment
Interrill	Udziejek I	67	15	2–6	sandy loam	49.4	35.4	38.9	55.1
	Udziejek II	46	11	4–22	loam	23.7	+69.82	29.6	121.3
	Udziejek Górny	105	10	3–7	silty sand	390.0	+79.4	488.9	819.2
	Łopuchowo	66	12	3–11	sand	7,255.6	+720.7	10 320.0	16 512.5
Rill	Smolniki	280	45	4–17	sand and clay	3,775.0	0	4 729.5	0
	Krejwelek	155	32	3–12	loamy sand	2,356.9	+9 247.9	31 097.7	18 742.3
	Snołda	120	27	2–10	loamy sand	470.2	+2 044.4	9 611.6	6 805.0
	Gulbin	175	45	4–15	sandy loam	601.5	+3 624.4	6 458.1	8 922.5

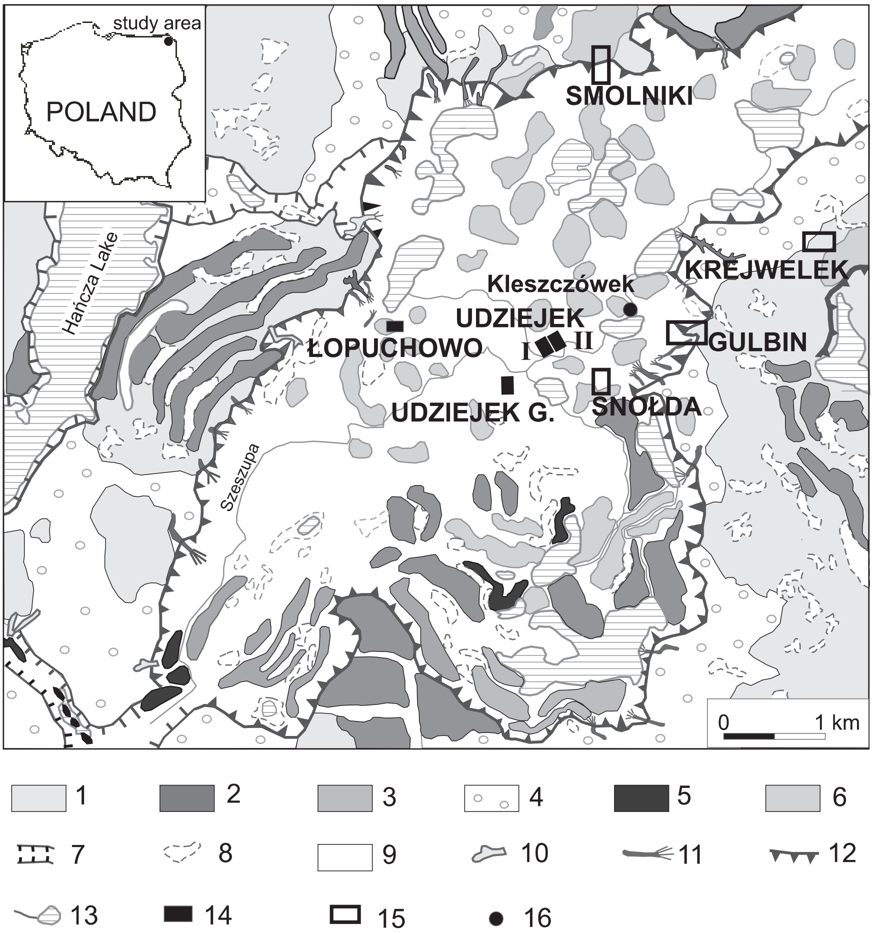

Figure 1. Geomorphological sketch (according to Ber 2000) of study area and location of soil erosion measurements:
1—morainic plateau, 2—end moraines, 3—dead-ice moraines, 4—outwash plains, 5—eskers, 6—kames, 7—tunnel valleys, 8—kettle holes, 9—bottom of depression, 10—dray valleys, 11—gullies and fans, 12—ice-contact slopes, 13—rivers and lakes, 14—slopes of interrill erosion measurements, 15—slopes of rill erosion measurements, 16—precipitation station.

annual rainfall 576 mm. Rainfall in excess of 30 mm occurs once every 2 or 3 years, and rainfall events exceeding 70 mm occur approximately once every 50 years (Stopa-Boryczka and Martyn 1985). Rainfall intensity is limited. In Suwałki, the rainfall erosivity (R_e) (according to the formula used in USLE) is 43Je ($N\ h^{-1}\ yr^{-1}$) on average annually, one of the lowest in Poland (Banasik and Górski 1993).

Both periods of field research (1987–89 and 1998–99) were relatively warm and humid in comparison with the multi-year period 1951–65 analysed by Stopa-Boryczka and Martyn (1985). Mean annual air temperature was between 6.8°C and 7.5°C, and

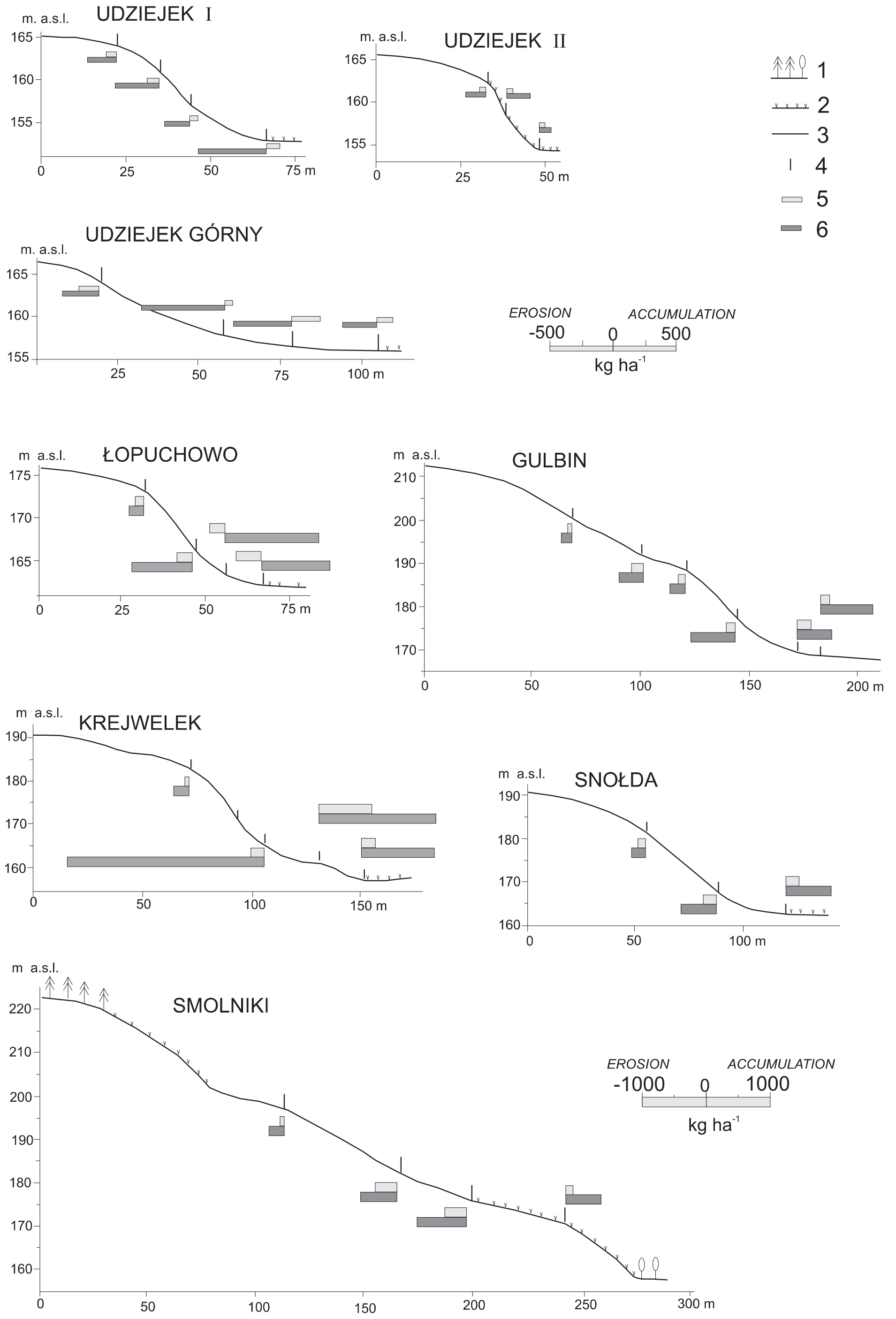

Figure 2. Profiles of investigated slope with marked mean and extreme soil redistribution: 1—forest, 2—meadows and pastures, 3—arable land, 4—measurement sites, 5—mean annual values for erosion or accumulation, 6—extreme values for erosion or accumulation

annual rainfall was between 541 mm and 716 mm (the Sidory-Kleszczówek meteorological station). There were two rainfall episodes of considerable intensity, one in each research period. This events were extreme due to rainfall intensity, exceptional for the Suwałki Lakeland region. This is clearly visible when values are set against the intensity of other rainfall events (Fig. 3). The heaviest rainfalls occur in June and July. They usually amount to only 25–30 mm and are only of significant intensity during first 10 to 15 minutes. Their erosivity according to the USLE formulae, is within a dozen or so erosivity units (Je). The heavy rainfall with an efficiency of 35.7 mm detected on June, 22, 1999 was exceptional as regards its very high intensity of 0.5 mmmin^{-1}. Its erosivity amounted to 35.2 Je, which equalled the average erosivity of all summer rainfall.

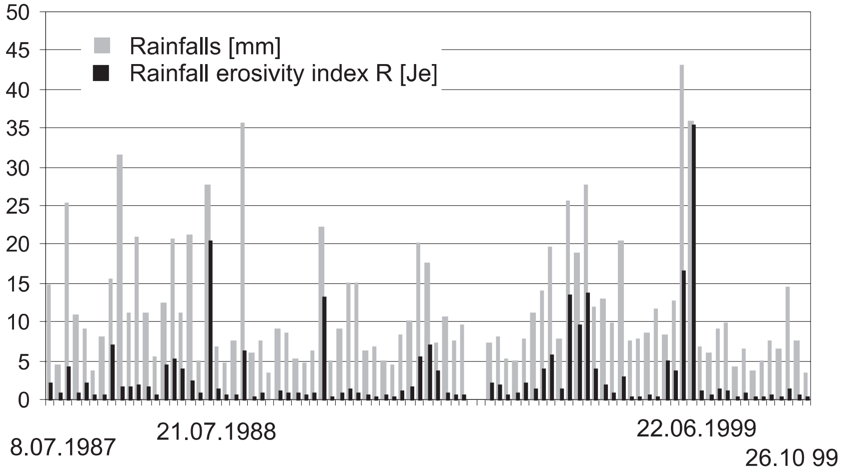

Figure 3. Daily precipitation and its erosivity in the study periods 1987–1989 and 1998–1999.

METHODS

Measurements of interrill erosion were conducted using Słupik's collectors (Słupik 1973) modified slightly (Smolska 1993). Measurement stand design was after Gerlach (1976), i.e. in places where the slope changed its shape and inclination. Each collector collected water and eroded soil for a strip of ground stretching from the water divide to the measurement stand. Depending on slope morphology, measurements were based around 3 or 4 stands, the lowermost being located at the base of the slope. Every stand consisted of 3 collectors, each with a 50 cm-wide entrance. The collectors were emptied once every 4 to 6 weeks, and additionally after each intensive rainfall.

Determination of the magnitude of rill erosion was based on the volume of rills as calculated after Klimczak (1988). Similarly, the amount of accumulated material was determined as the volume of fans or covers deposited at slope bases. Measurements were conducted seasonally with regard to changing meteorological conditions, usually 4 time per year.

RESULTS

SOIL EROSION

During rainfall of moderate intensity, sheet wash causes erosion of upper and middle segments of short slopes, and deposition takes place in lower segments of straight and convex-concave slopes (in their concave segments)(Fig. 2). Only a limited amount of material is transported beyond slopes and accumulated near their bases. Many studies of the lakeland area indicate a similar course for this process (Niewiadomski and Skrodzki 1964, Niewiadomski 1968, Uggla *et al*. 1968, 1998, Chudecki and Niedźwiecki 1983, Klimczak 1993, Niewiarowski *et al*. 1993, Szpikowski 2002). In the Suwałki Lakeland, erosion at the top of hills ranges from 24 to 400 kg ha^{-1}, while in the convex and middle segments it is of 40 kg to over 7 t ha^{-1} (Smolska 2005).

The heavy rainfall of June 22,1999 was especially significant, due to the magnitude of the erosion it caused relative to that over the entire research period. Seasonal evaluations of interrill erosion on the short loamy-sandy slope of Udziejek I (Fig. 4) illustrate the aforementioned event well. During the rainstorm, erosion in the upper and middle parts of the slope reached the mean annual value. Strong sheet wash occurred in the lower part of the slope. Rills developed in the middle and lower parts of the slope. Almost 75% of the mass of soil material that had accumulated on the concave segment of the slope over the 5-year period of measurement was rapidly transferred beyond the base of the slope.

Depending on the effectiveness and force of rainfall, the mechanics of the process and its intensity, and in consequence,

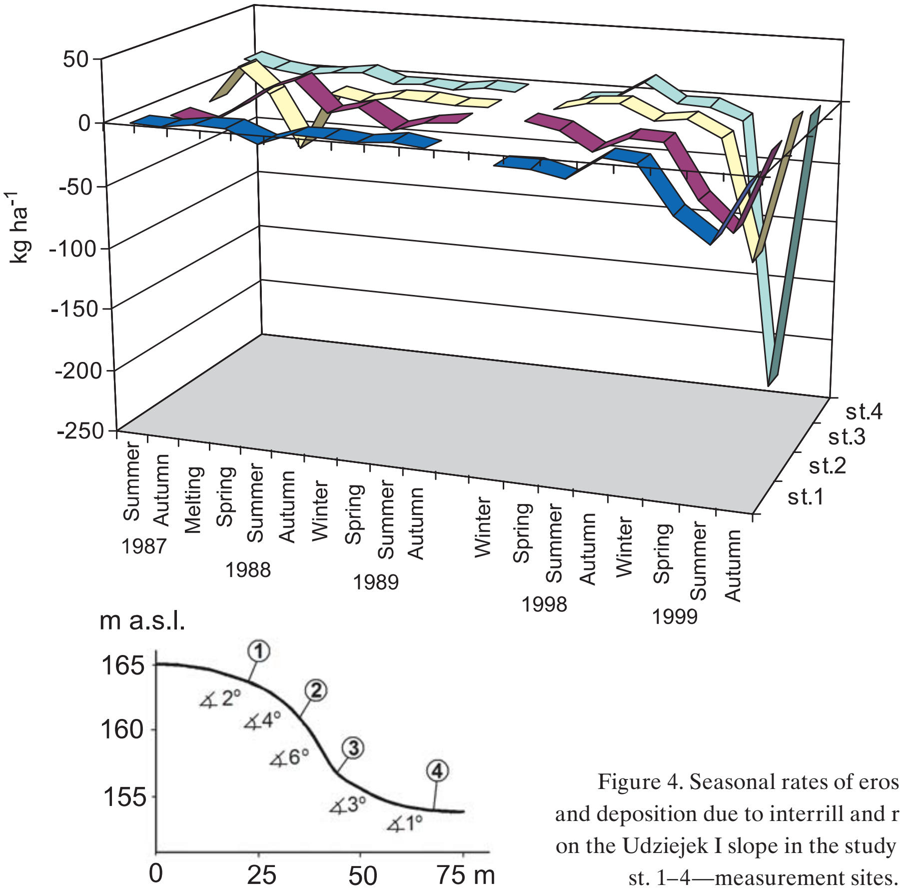

Figure 4. Seasonal rates of erosion and deposition due to interrill and rill wash on the Udziejek I slope in the study period: st. 1–4—measurement sites.

soil re-deposition differed on particular slope fragments. This differentiation is well illustrated by the wash on the Udziejek I slope during 3 rainfall events of differing erosivity (Table 2). Erosion in the upper part of the slope and deposition in the middle and lower parts occurred during brief (30 min) storms of significant intensity but a low efficiency of 8 to 15 mm (Figure 5—18.07.1988). Strong splash occurred during brief storms. While intensity of the rainfall exceeded infiltration capacity of the ground, the short duration made it possible for almost all the water to be retained in the soil's upper layers (Gil and Słupik 1972, Froehlich and Słupik 1980, Słupik 1981, Bryan 2000, Parsons and Stone 2006). Overland flow diminishes during its initial stage of formation or slightly later (Froehlich 1982, Parsons *et al.* 1998, Gil 1999). Much more material becomes mobile due to splash than to overland flow competency. Transport of material was pulsating, and deposition occurred directly beyond a zone of strongest erosion, which is beyond the convex segment of the slope. Rainfall of similar intensity but greater persistence resulted in erosion along the entire convex and straight segments of the slope, with deposition taking place in the concave segment (Fig. 5—12.06.1998). Only heavy rainfall exceeding 30 mm caused erosion on the entire slope length, with deposition of material occurring on the Szeszupa river a flood plain (Fig. 5—22.06.1999).

Table 2. Parameters of selected rainfall events calculated using USLE formulae

Parameter	18.07.1988	12.06.1998	22.06.1999
P [mm]	11.1	18.5	35.7
I_{avg} [mm min^{-1}]	0.11	0.17	0.51
I_{30} [mm min^{-1}]	0.31	0.41	0.66
I_{15} [mm min^{-1}]	0.56	0.65	0.82
Re [Je]	3.90	9.50	35.20

On many longer (> 100 m) slopes, a network of rills has been created. These were up to 30 cm deep, locally 50 cm, and erosion in them amounted to 10–30 tha^{-1}. Distinct accumulation cover developed at the slope base, though the average thickness was only 2–3 cm, with 5–7 cm occurring locally only. The effectiveness of rill erosion was several times greater than that of interrill wash,

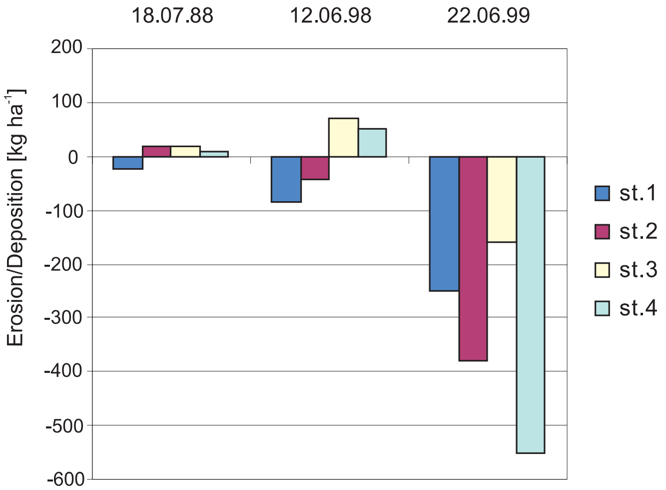

Figure 5. Sheet wash erosion and accumulation on the Udziejek I slope for selected rainstorms: st. 1–4—measurement sites; location of sites as in Figure 4.

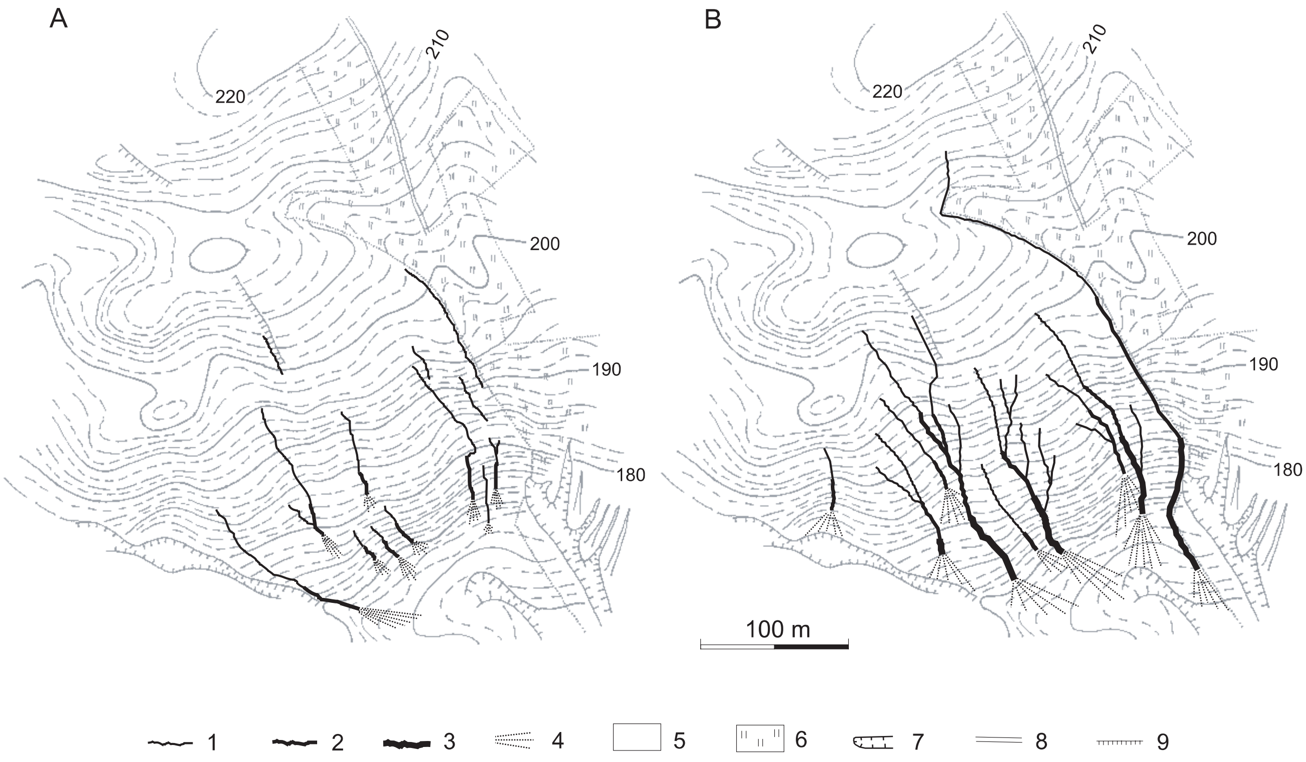

Figure 6. Rill networks and fans on the Gulbin slope formed during heavy rainfall in July 1989 (A) and June 1999 (B): 1—rills up to 10 cm deep, 2—rills of 10–20 cm deep, 3—rills deeper than 20 cm, 4—fans, 5—arable land, 6—pastures, 7—gullies, 8—roads, 9—scarps.

but the spatial range was relatively limited. The rills developed in lower parts of slopes, clearly occurring where vegetation cover is poorly developed. The impact of extreme rainfall events on slopes with different vegetation is well illustrated by the network of rills and fans on the Gulbin slope (Fig. 6). Only single rills were observed after extreme rainfall taking place in the middle of the vegetation period (Fig. 6A). However, when vegetation cover was less dense, rills created a network of density up to 180 m per 100 m^2 (Fig. 6B).

THE SIGNIFICANCE OF EXTREME EVENTS

In terms of both intensity and the transportation of eroded material, the extreme rainfall of June 22, 1999 had a decisive impact on total soil loss during the research period, and on soil loss calculated per unit area. Its importance for soil redeposition on cultivated slopes is clearly visible when compared with average annual values of soil loss on the slopes studied (Table 1). The event was responsible for a soil loss of from 300 kg ha^{-1} to 10 t ha^{-1} in the upper and lower parts of the slope due to interrill erosion, and up to 30 t ha^{-1} due to rill erosion, which equaled 25% to 40% of total soil loss during the 5-year period of measurements.

Slope cover studies show that maximal thickness is present on the lower, concave segment of the slope (Smolska 2005). An important role of topographic and vegetation barriers in the downward transportation of material is emphasized by Froehlich (1982), Teisseyre (1994), Govers et al. (1996) and Święchowicz (2002). During the research period, the concave segments of slopes played an significant role as a topographic barrier. Measurements showed that nearly all soil eroded in the upper and middle segments of slopes was deposited here (Smolska 2003). During the extreme rainfall under analysis, erosion also occurred in lower, concave, aggradational parts of slopes. Soil loss ranged from ca. 100 kg ha^{-1} to 7 t ha^{-1}. From 50% to 75% of colluvium accumulated over 5 years was transported away.

Eroded soil material transferred beyond the slope bases as a results of occasional extreme rainfalls events caused significant changes in soil redistribution on the Suwałki Lakeland slopes. This process is necessary to preserve the steepness of slopes. Only such extreme events result in intensive erosion along the entire length of slopes, and especially in their middle and lower parts. The role of barrier limiting material transport for longer distances beyond the slope base is assumed by vegetation growing on the valley floor and in depressions.

The influence of extreme events on soil redeposition is as yet only poorly recognized, most of all because data from experimental fields are insufficient (Boardman 2006). Measurements made on plots or on whole-slope scale are limited. It often happens that rainfall of maximum intensity falls not on an experimental plot but on neighbouring slopes (e.g. Niewiadomski 1968, Kostrzewski *et al.* 1989, Evans 2005). The detection and temporal and spatial understanding of heavy rain episodes therefore demands further research (Boardman 2006).

Mean and extreme values for soil erosion on cultivated slopes in selected Polish lakelands are as shown in Table 3. In the lakeland belt, continentality of climate increases in an easterly direction. Despite differentiation of local conditions such as slope inclination and lithology, soil erosion is generally of lesser intensity in climates of lesser humidity. Extreme rainfall and soil losses are thus much rarer further to the east.

Soil erosion in the area researched, as located in the eastern part of the lakeland belt, amounts to 0.2–12.9 t ha^{-1}yr^{-1}. In the western part (in northern Germany), mean soil erosion on cultivated slopes is at twice the rate, ranging from 0.4 up to about 20 t ha^{-1}yr^{-1} or even 35.2 t ha^{-1}yr^{-1} (Auerswald 2006). Mean annual precipitation in northern Germany and north-west Poland (at 500–800 mm) is only slightly greater than in north-eastern Poland (500–750 mm),

Table 3. Mean annual and maximum values for soil loss on selected lakeland areas in Poland

Location of lakeland and study period	Average and (max.) soil loss [t ha^{-1}]	Relief energy		Methods	Rainfall [mm yr^{-1}] (max. daily rainfall) [mm]	References
		Elevation [m]	Inclination [°]			
Western Pomerania						
1987–89	0.2–10.3	6–12	<16	plots, Gerlach's method	574–823	Klimczak (1993)
1994–96	1.1–19.2 (80)	6	4–5	plots volume of rills	561–801 (130)	Szpikowski (1998, 2002)
1995–99	0.5–2. 2 (51.6)			volume of rills and deposits	(28)	Kostrzewski *et al.* (1992) Koćmit *et al*. (2006)
Eastern Pomerania						
1967–70	0.5–24.8 (50.5)	5–30	8–20	Gerlach's method volume of rills	443–739	Lankauf (1975)
Mazury						
1955–64	1.6–11.5 (50.3)	12	<16	plots volume of rills	623 (72)	Niewiadomski, Skrodzki (1964) Niewiadomski (1968)
Suwałki						
1987–89 1998–99	0.2–12.9 (30.0)	7–50	<15	Gerlach's method, volume of rills	541–717 (43)	Smolska *et al*. (1995), Smolska (2002)

but the erosivity is markedly different. The mean annual erosivity index in the western part of the lakeland belt is 40–60 Je (Auerswald 2006, Szpikowski 1998, Koćmit *et al*. 2006), reaching even 100 Je in some years. Such high values have not so far been detected in the area studied (Banasik and Górski 1993), where mean annual rainfall erosivity is of only 35–50 Je, with a maximum of 75 Je (at the Suwałki and Kleszczówek stations). This explains the short distances of soil translocation and deposition on lower parts of slopes.

CONCLUSIONS

Conducted over 5 years, measurements of interrill and rill erosion on cultivated slopes reveal the dependency of the process upon the intensity and efficiency of rainfall events. Short storms of efficiency seldom exceeding 20 mm are characteristic of the Suwałki Lakeland. Their 15-minute intensity is significant; but, as the average intensity is rather low, the erosivity of such rainfall is limited, and generally ranges from 6 to 16 erosivity units (Je), using the USLE formula. Such rainfall is responsible for erosion in the upper and middle parts of slopes, and for the deposition of nearly all eroded soil in concave parts of slopes. Only 30 mm rainfall with an average intensity of 0,5 mm min^{-1} and relatively high erosivity (>30 Je), give rise to erosion along the entire length of the short slopes, and to the development of rills along longer slopes (> 100 m). One extreme event during the study period played a significant role in redistributing soil on the cultivated slopes. A significant share of the colluvium (50% to 75%) accumulated in the concave parts of these slopes over 5 years was transferred away from the slopes during that storm.

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MODELS OF IMPACTS
OF HYDROMETEOROLOGICAL EXTREMES

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Abstract: Mathematical modelling of hydrometeorological extremes and their impacts was discussed. An introduction to the notion of modelling is proposed. Annual extremes in temperature records were examined, also on the basis of qualitative indices, when quantitative data are not available due to cost restrictions. Trends in long time series of records were studied. Concepts as regards projections of risk of extreme events (such as floods) are also discussed; including synthesis of projection models for a range of climate impacts. The facets of uncertainty are also dealt with. A conceptualization of the risk in the load-resistance framework is proposed.

Key words: mathematical modelling; climate impact; hydrometeorological extremes; curve fitting; trend.

INTRODUCTION TO MODELLING

The term “modelling” is typically interpreted as the replacing of a (possibly very complex) real object of interest by a simpler, and/or more tractable, model, in order that information about the object might be drawn by examining the model. A model is a working analogy of the real object that imitates (mimics) selected aspects thereof which are deemed important to the study at hand, while omitting aspects deemed non-essential. However, since the model can be regarded as similar, but not identical, to the object, it may give a distorted view, and lead to false conclusions.

The mathematical modelling this paper deals with can be understood as the use of mathematical constructs to describe features of systems or processes. Virtually every use of a mathematical equation to represent links between variables, or to mimic a temporal or spatial structure of variable(s), can be called mathematical modelling.

One can distinguish a number of stages to the modelling process, beginning with the selection of the model structure (i.e. mathematical equations governing links between variables describing the object) for the problem at hand, and progressing via the development of an efficient algorithm, writing of a code, and testing. If a well-tested model is available, it is necessary to identify values of model parameters (parameters of mathematical equations) for the system being modelled. This can be difficult (a mathematically ill-posed, inverse problem, where by a small inaccuracy in input data may lead to a large parameter identification error). If a large number of parameters need to be identified, problems with over-parameterization may occur, hence parsimony in parameters is important. Simpler, approximate models have fewer parameters than more complete models. Once model parameters have been identified, the stage of validation is proceeded to. This implies the checking of how the selected model with identified parameter values performs on independent data. Once the model has been verified, it can be used (for simulation, hindcasting, or forecasting). If the validation fails and model performance is rated non-satisfactory, another modelling approach (e.g. one based on a different structure) is necessary.

Typically, there is a trade-off between model accuracy and complexity. Simple models produce results which are usually less accurate than those from the complex (hence more costly) and physically-based models (provided that appropriate data necessary to run such models are available). However, at times, simple models may produce results of sufficient accuracy and this is a clue that a simpler model can be chosen in this particular case.

There are many criteria for model classification; one of these being the degree of physical justification. Here one can distinguish at least three classes:

- mechanistic, process-based, techniques involving (possibly complex) systems of equations expressing rigorous physical laws and theoretical concepts;
- conceptual models consisting of simple elements, which may represent, in an approximate way, processes occurring in the basin. [Conceptual models may have physically-based parameters (cf. Kundzewicz, 1986)];
- the 'systems' approach capable of being understood as purely empirical, black-box techniques, which match the input and output signals of the system, without mimicking the internal structure.

This last class of models includes linear models (e.g. integral operator, or a time-series model) and nonlinear models, such as artificial neural networks (ANNs) and fuzzy sets; capable of representing a wide range of complex relationships. However, results of black-box models are valid only under the conditions for which they have been validated. The fuzzy sets approach provides a framework for the interpretation of any existing theoretical knowledge (also expert knowledge elicitation) and adding to it a learning process, in which way the approach becomes less of a black-box.

There may be a non-uniqueness, in the sense that several models that represent the system of interest may exist, being different in model structures.

There are a number of factors influencing the process of model selection, such as:

- the general modelling objective;
- representation of the most relevant processes (e.g. for operational forecasting, a model should contain an updating component, reacting to the so-far forecast errors, which are likely to be correlated, hence there is potentially useful information in the time series of forecast errors that can be tapped);
- the type and size of the system to be modelled;
- the variables to be modelled;
- the characteristics of the system (e.g. climate, physiography, land use);
- data (availability, type, length of record and quality/accuracy);
- the possibility of transposing model parameters for ungauged systems, i.e. transposing from a smaller object to a larger object; or from one set of conditions to another;
- model availability (whether free, i.e. in the public domain, or at a cost; user-friendliness, available know-how);
- required model simplicity (ease of application to match the available manpower);
- the availability and power of computers—a criterion for both model development and operation that has largely lost its importance with the advent of more and more powerful and inexpensive personal computers, (however, exceptions continue to exist, e. g. the „curse of dimensionality" still making it difficult to optimize the opera-

tion of multiple water storage reservoirs, by dynamic programming).

1. CLIMATE EXTREMES AND THEIR IMPACTS

It is natural that geophysical variables (and meteorological and hydrological variables therein) are subject to strong variability, at times attaining extreme values. Some of these extreme values, such as high wind speeds, extremely high (or low) temperatures, extremely high precipitation, and extremely high (or low) river discharge, may lead to substantial human and material damage. For this reason, the modelling of extremes and their impacts is of considerable importance to a better understanding of the risk past and future events may pose.

The series of global temperature anomalies available since 1850 is known to exhibit a statistically significant increase. Here, extremes can be understood as very warm or very cold years, with mean annual temperature departing greatly from the long-term central value (e.g. mean or median). The shape of the visible trend is clearly non-linear: a notable increase in recent decades is to be observed, compared with little (if any) change in the earlier decades. Numerous models that reflect such behaviour may be fitted to the available global temperature data. Here we make no claims as to the validity of the fitted models, and do not consider the possibility of long-term correlations in the residuals, treating them as independent Gaussian variables. The series of global temperature anomalies is denoted GT below. Fig. 1a shows the results of a least-squares fitting of the logistic curve with the restriction that the saddle-point be put on the last year with available data:

$$GT \sim a + b/(1 + \exp(c(year — 2006))) \quad (1)$$

The residual error is 0.1263. When the restriction on the saddle-point is relaxed, closer fits are obtained when the saddle point is placed in a distant future. This suggests that, for the time interval for which data are available, the data are better approximated by an exponential function (Fig. 1b):

$$GT \sim a + b \exp(c\ year) \quad (2)$$

Indeed, the fitting is slightly improved (residual error 0.1243). Another approach, the broken-line regression, is given by the formula:

$$GT \sim a + b\ year + c\ |year – d| \quad (3)$$

where:
d is the break-point year.

If d is fixed and the remaining parameters fitted, the residual standard error as a function of d is obtained (Fig. 1c). This function has a global minimum, corresponding to the fitted model, and another, local, minimum, only slightly higher. Such behaviour may indicate that the model is not well suited for this data, but the model performance (in terms of standard error) is similar to that of the previous two models, with the residual error of 0.1265 (Fig. 1d).

The models presented above are very different in their characteristics, especially in the rate of change outside the observed interval (bounded change, exponential change, linear change, oscillations only). This augments the well known fact that a model based on observed data alone is useless for long-term forecasting. It also shows that discriminating between different models may be difficult or impossible when the sole basis is exploration of the data, rather than a good understanding of the underlying system. While a phenomenon remains poorly understood, simple, robust conclusions (e.g. the existence of an upward trend) may still be drawn from the characteristics shared by different matching models, although the significance associated with such findings must be studied using appropriate methods allowing for long-term correlations in the data.

Long time series (1954–2005) of average values of annual mean temperatures at 16 stations in Poland (data from several Polish statistical yearbooks published by

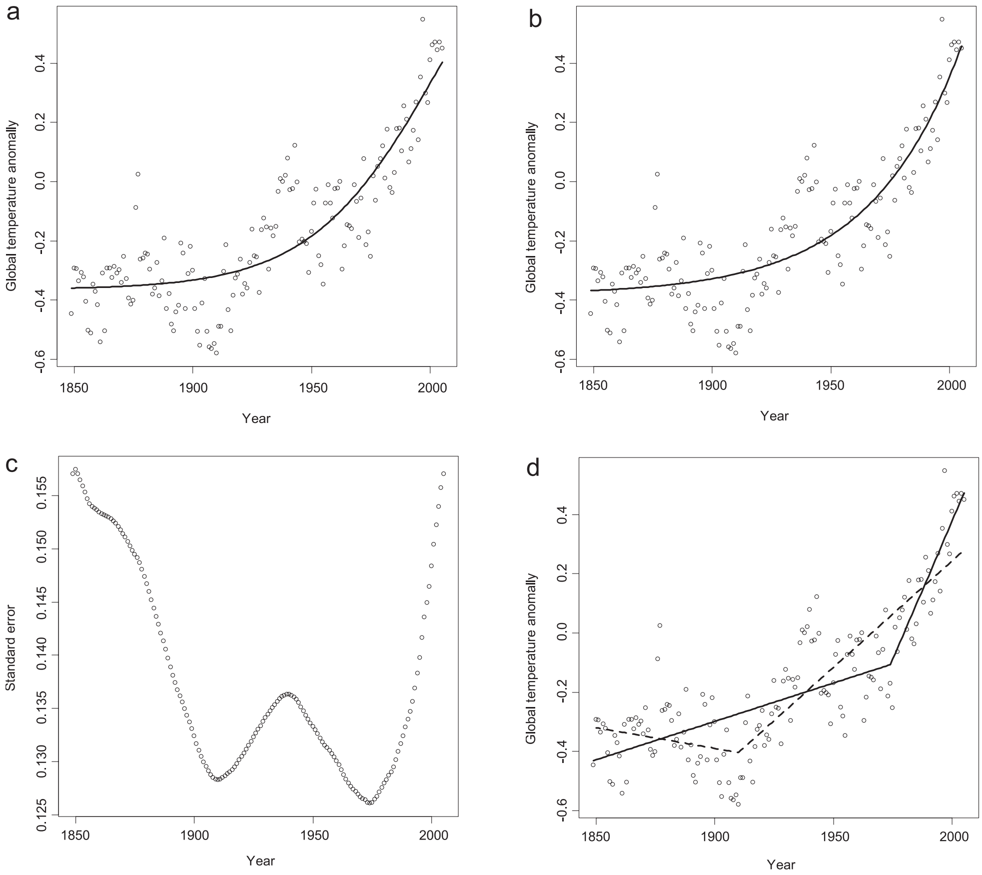

Figure 1. Least-squares fitting of different functions to global temperature data. Points: global temperature anomaly. Line: fitted function. (a) Logistic function; (b) Exponential function; (c) Residual standard error of a fitted broken line model as a function of the break-point year; (d) Broken line. Points: global temperature anomaly. Solid line: fitted model. Dashed line: model corresponding to local minimum.

GUS—Main Statistical Office), show a clear upward trend (cf. Fig. 2). Table 1, presenting the 10 coldest and 10 warmest years in the 52-year period of records, demonstrates that many entries in the list of warmest years occurred recently (six of the ten entries have been since the 1990s and only one before 1970). Only one entry in the list of 11 coldest years occurred after 1990 (in 1996) and six entries before 1970.

Since daily and monthly numerical data are available at a (rather substantial) cost only, it is tempting to use free (qualitative) data on the thermal classification of months, prepared and made available on the internet by Professor Halina Lorenc (2007) on the website of the Polish hydrometeorological service (Institute of Meteorology and Water Management). The series of information on ranges of monthly temperature for Warsaw spans the 36-year period (1971–2006). For every month, the mean temperature is classified to one of 11 categories (extremely cold, anomalously cold, very cold, cold, slightly cold, normal, slightly warm, warm, very warm, anomalously warm and extremely warm). The range marked „normal" spans the interval (m-0.5sd, m+0.5sd) where m and sd represent mean and standard deviation, respectively. Hence, the width of this interval is 1 *sd*, while the width of each of the 10 remaining categories is 0.5 *sd*.

The 36-year period of available monthly data (1971–2006) has been divided into four consecutive nine-year sub-periods. Fig. 3 compares qualitative monthly temperature indices for these sub-periods. It is evident that the mass of the pdf shifts in time towards higher temperatures. However, the cold extremes do not tend to disappear. Actually, the peak of pdf flattens, and the variability grows with time.

As can be seen in Fig. 4, the number of warm monthly extremes has been increasing with time. For example, the interpretation for 2006 reads: four warm extremes (July, September, October, December) and two cold extremes (January, March). The number of cold and warm extremes for monthly data are shown in Table 2.

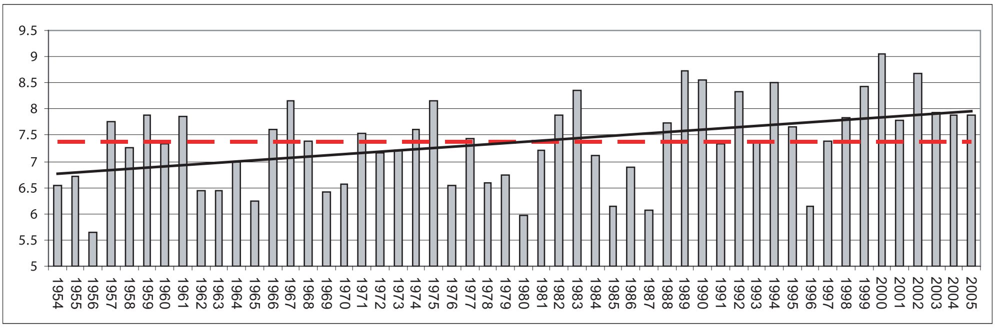

Figure 2. Average values of mean annual temperatures (in °C) at 16 stations in Poland (*data source*: GUS); $y = 0.0235x + 6.7438$, $R^2 = 0.1941$. The dashed line represents the long-term mean.

Table 1. List of the 10 coldest and 10 warmest years in Poland in the period 1954–2005 (mean for 16 stations).

Ten coldest years in 1954–2005 (mean for 16 stations)		Ten warmest years in 1954–2005 (mean for 16 stations)	
Year	Mean annual temperature [°C]	Year	Mean annual temperature [°C]
1956	5.66	2000	9.04
1980	5.96	1989	8.72
1987	6.07	2002	8.68
1985	6.15	1990	8.55
1996	6.15	1994	8.49
1965	6.24	1999	8.43
1969	6.42	1983	8.35
1962	6.43	1992	8.34
1963	6.44	1967	8.17
1954, 1976	6.53	1975	8.16

Data source: GUS.

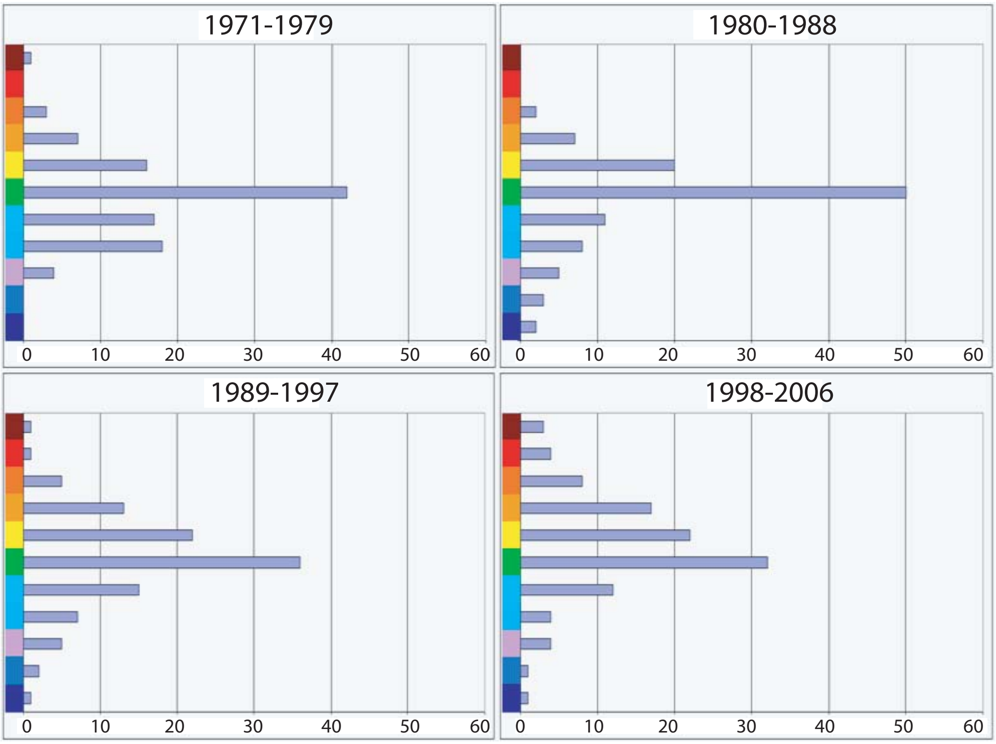

Figure 3. Comparison of qualitative temperature indices for Warsaw (Okęcie) in four nine-year periods (1971–1979, 1980–1988, 1989–1997, 1998–2006). Number of months in a particular temperature class is given on the *x*-axis, qualitative classes given on the *y*-axis. *Data source*: Lorenc (2007).

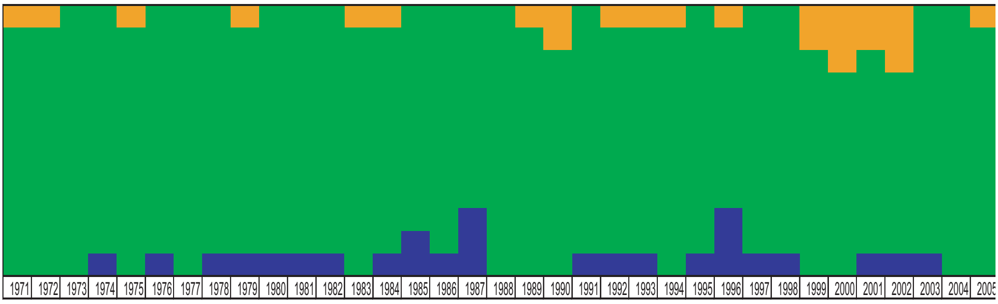

Figure 4. Cold and warm extremes in the monthly temperature data for Warsaw, 1971–2006. Notation: green denotes non-extreme months (categories: cold, slightly cold, normal, slightly warm, warm), orange—warm extremes (very warm, anomalously warm, extremely warm) and blue—cold extremes (very cold, anomalously cold, extremely cold). *Data source*: Lorenc (2007).

Table 2. Number of cold and warm extremes for monthly temperature data from Warsaw in four nine-year sub-periods. Interpretation of cold and warm extremes—see caption to Fig. 4.

Sub-period	Number of cold extremes	Number of hot extremes
1 (1971–1979)	4	4
2 (1980–1988)	10	2
3 (1989–1997)	8	7
4 (1998–2006)	6	15

Data source: Lorenc (2007).

Changes in the distribution of quantitative temperature data from Warsaw (cf. Figs 3–4 and Table 2) are illustrated in Fig. 5. Fig. 5a shows changes in means, while Fig. 5b presents changes in standard deviations. The interpretation of these changes is: towards warming and increasing variability. Quantitative classes were used to represent the categorical, qualitative data.

It is difficult to determine the frequency of meteorological or hydrological extremes, especially for events of a high return period. Under conditions of stationarity, it can be assumed that a 100-year record of high quality data should be available in order to determine, in a rigorous and reliable way, the magnitude of a 10-year event. However, attempts to draw conclusions based on very rare events (e.g. a 1,000-year event) are often made on the basis of a meagre data record (e.g. of 30 years or less, with possible gaps and missing values, and questionable

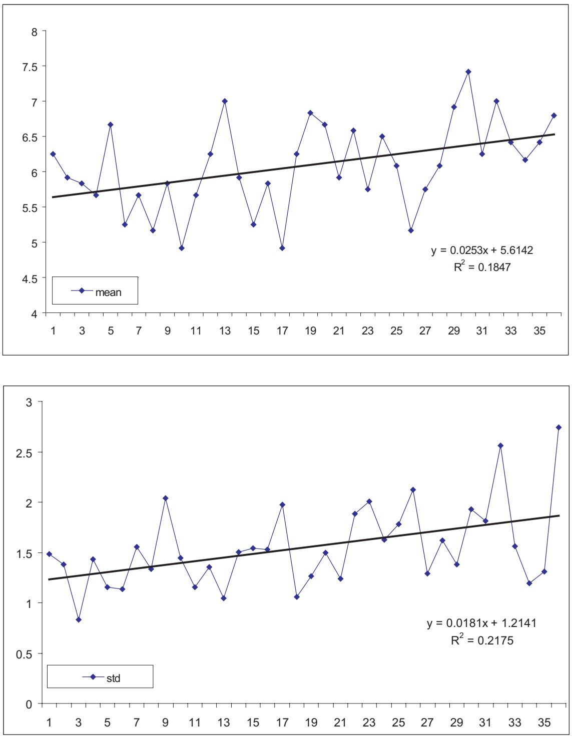

Figure 5. Changing annual temperature distributions in Warsaw;
(a) change in means—towards warming; (b) change in standard deviations—towards increasing variability. Time (in years after 1970 onwards is represented in the x-axis; i.e. $x=1$ means year 1971).
Data source: Lorenc (2007).

quality, especially in the range of extremes, where error may be very high). Moreover, the stationarity assumption is not likely to hold.

There is an obvious tautology that rare, truly extreme events do not occur frequently. Hence, there is an endemic small-sample syndrome—even a long time series may contain very few (or none) really destructive extreme events. Therefore, recourse to exterior information is indispensable. A single event (the only extreme on record), such as the summer 1997 flood on the Odra, the Vistula, and their upper tributaries—cannot guide the development of a rigorous damage-discharge relationship. Even estimation of the return period of this flood has become a subject of national debate (Kundzewicz *et al.*, 1999).

Analysis of climate extremes, such as temperature, is less difficult than study of the impacts of climate extremes. This is so for several reasons, such as: the complex structure of the climate-impact system and the lack of necessary data. In the global system, everything is connected with everything else, so that a pragmatic decision of simplification is needed. Fig. 6 illustrates a simplified structure of interconnected components of the global super-system. Only first-order impacts are noted in the simplified scheme, but in fact, Fig. 6 could contain many more arrows linking individual components, in both directions. One can postulate mathematical forms of relationship between components.

Data scarcity is a commonplace. If data are collected, they typically refer to a small number of variables, e.g. precipitation and water stage, while understanding of the flood phenomena and their impacts in a holistic context would require collection of a comprehensive dataset embracing long time series of environmental and socio-economic variables (cf. Kundzewicz and Schellnhuber, 2004). Even in the developed world, such data are not readily available.

2. PROJECTIONS FOR THE FUTURE

The convenient assumption of stationarity does not hold in a changing world. Many aspects of the system change over time,

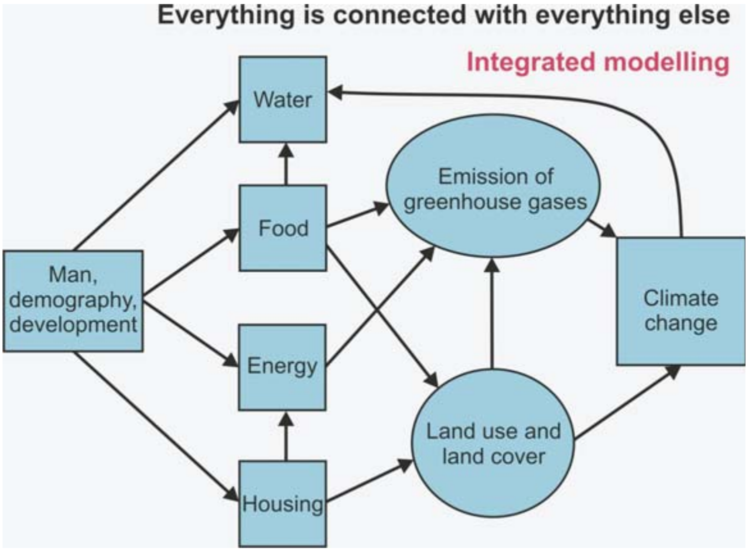

Figure 6. Simplified structure of the global super-system.

either for natural reasons (such as changes in solar activity, Earth orbit, volcanic activity) or anthropogenic reasons (e.g. land use, land cover). There is increasingly strong evidence to support the hypothesis that recent climate changes are largely of anthropogenic origin. We are indeed observing an induced global warming caused by the enhanced greenhouse effect, and resulting from increasing emissions of greenhouse gases into the atmosphere (burning fossil fuels and methane emission from agriculture and animal husbandry), as well as a reduction of carbon sequestration via land-use change (e.g. deforestation and urbanization). Hence, the properties of the system observed in the past may change considerably in the future.

Human societies adapt to the changing environment—climate changes trigger the need for a (possibly costly) change in adaptation. One needs models to project the future situation in the changing world, in order to plan appropriate adaptation measures, whose implementation may take a long time. In the case of structural water-engineering measures, the adaptation (from concept to the start of operations) may take several decades.

Projections for the near future, called forecasts, are among the routine activities of meteorological and hydrological services. For instance, forecasting high river discharge and stage allows for the issuance of warnings early enough for a response (e.g. evacuation) to be mounted. An early flood warning is information that water is likely to rise (a flood is likely to occur) in a defined time point in the near future. Hence, the forecast of river discharge, $Q_{\mathrm{forecast}}(t + T \mid t)$ is made in the current time instant, t, for the forecast horizon (small time scale), T, i. e. up to the time instant $t + T$. Loss reduction depends on the forecast horizon (T) and accuracy (error in amplitude and timing).

In the present paper, a projection is understood in a long time scale. For example, in reference to floods, it could be called a flood risk warning; indicating that the flood risk is likely to change (typically rise) on the long time scale T. That is:

$$\mathrm{P}_{t+T}\,(Q \geq Q_{\mathrm{I}}) \neq \mathrm{P}_{\mathrm{t}}\,(Q \geq Q_{\mathrm{I}}) \tag{4}$$

where:

P_t is the probability in the time instant t;

Q is the river discharge;

Q_{I} is the minimum river discharge causing flood damage.

Projection for a long time horizon, e.g. $T = 50$ years allows the flood preparedness system to be adapted, including by implementing structural measures (reservoirs, polders, dikes and relief channels).

In order to understand a system, it is important to observe it, by measuring the relevant variables over a long time and to carry out interpretations of collected data and search for trends. Yet, in order to project the reaction of the system to an arbitrary forcing (e.g. a future forcing corresponding to a changed climate), one needs models. Mathematical models (calibrated for past-to-present conditions) are the principal way to study future situations. Although purely empirical and black-box relationships continue to prove beneficial under certain circumstances in global change studies (with validity typically limited to the range of situations encompassed in the validation process), they may be subject to serious errors when applied under conditions not previously experienced. Hence, physically-based models, founded on theoretical background, and conceptual models, whose parameters have a quasi-physical sense are expected to be more trustworthy under such conditions. They are based on a more plausible assumption that the physical laws are not changing, i.e. the present laws would also hold in the future.

The process of modelling of the past and present behaviour of systems of interest is different from modelling for future climate. In the former, validation is an indispensable phase, while in the latter, it is not possible. In the classical approach, the available data record is split into two parts (the split-sample approach). One is used for the identification of parameters and the other—for validation. They check how the model performs on independent observation material. In future projection studies, direct validation is not possible. One can assume that a (physically-based) model that worked well for past data is likely to perform satisfactorily for future conditions. In particular, if a model can reconstruct the past, it is expected to hold promise for future projections. A known input signal (past observation data) and known output signal (past observation data) serve in the determination and identification of parameters of the climate impact model (e.g. from climate, via water, extreme indices to environmental and socio-economic impacts).

If there are no observation data (e.g. because ungauged areas or future conditions are under study), use of methods not requiring the availability of a long time series is necessitated. If among many similar and adjacent areas, some are gauged, and others are not, one can try to establish regionally valid laws. Models for gauged catchments can be developed and their parameters linked to physical characteristics (e.g. by linear regression). Once this is done, the regional approach can be applied to ungauged basins, whose physical characteristics can be determined (at least approximately). This holds for prediction (e.g. flood frequency analysis–regionalization of annual maximum flood, and then determination of floods with the return period of interest, such as a 100-year flood, Q_{100}, etc):

$$Q_{100} = f(\underline{p}_1, t) \quad (5)$$

where:

$\underline{p}_1$ is a vector of parameters.

The projecting of future flood damage, flood risk, and vulnerability requires evaluation of future load (river flow / stage / inundation area) and damage potential (Fig. 7).

2.1 SYNTHESIS OF PROJECTION MODELS

As stated in Stern (2007), physical and biological principles indicate that impacts in many sectors will become disproportionately more severe with rising temperatures, but there is little empirical support for specific quantitative relationships, which remain rather speculative (largely based on common

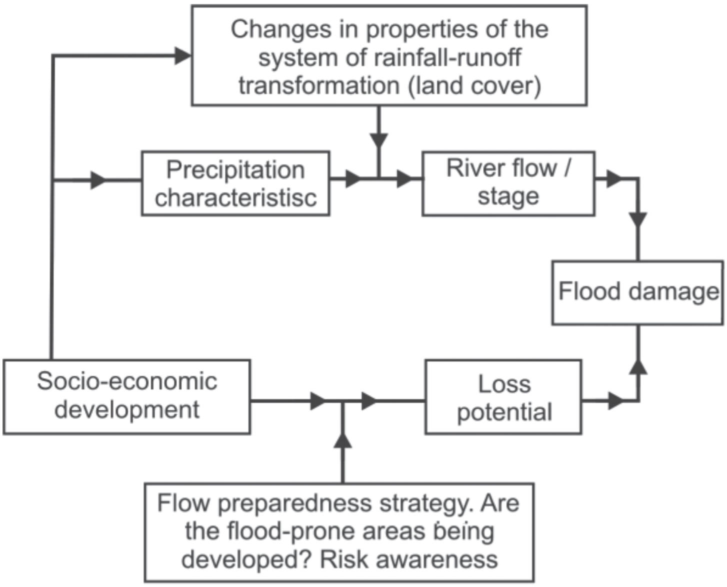

Figure 7. A conceptual sketch linking factors controlling future flood damage.

sense or expert judgment). Hitz and Smith (2004) reviewed results of published studies examining the nature of the relationship between global impacts and the amplitude of global warming. They found increasingly adverse impacts for several climate-sensitive sectors, though others gave no consistent relationships with temperature. A few illustrating examples are given below, for orientation.

The Clausius-Clapeyron equation shows that the water holding capacity of the atmosphere increases exponentially with temperature, in line with the equation:

$$de_s(T) / e_s(T) = L\, dT / (R\, T^2) \qquad (6)$$

where:

$e_s(T)$ is the saturation vapor pressure at temperature T,

L the latent heat of vaporization,

R the gas constant.

When linearizing the above equation for the present conditions, one may find that every 1°C increase in temperature corresponds to a 6–7% increase in the mean water holding capacity of the atmosphere. This means that the water cycle will intensify, leading to more severe intense precipitation (and, in consequence, floods). Mills *et al.* (2001) estimated that a 25% increase in 30 min. precipitation may reduce the flooding return period from 100-year to 17-year. There will be more energy to drive storms and hurricanes. According to an approximate assessment reported in Mills *et al.* (2001), a 2.2°C mean temperature increase leads to a 5–10% increase in hurricane wind speed, while a 1°C mean summer temperature increase may correspond to a 17–28% increase in wildfires.

The agricultural production systems follow the inverse parabolic (“hill function”) relation with temperature. In cooler regions, low levels of warming may improve conditions for crop growth (lengthening the growing season and increasing the area under agricultural production), but further warming will have increasingly negative impacts as critical temperature thresholds are crossed more often. It is likely that the tropical regions may already have passed the peak. The shape and location of the “hill” curve depends on the crop. However, regionally, e.g. in Poland, temperature rise itself is not the only important factor—impacts on agricultural production systems will depend on water availability (soil moisture, as result of precipitation), which may become more scarce in the growing season.

Available data show that the link between the heat-related human mortality and temperature is U-shaped (the bathtub pattern). A sharp increase in mortality can be observed once human temperature tolerances are exceeded, both on the side of the minimum and maximum thresholds (cold spells and heat waves). Rising temperatures cause a decrease in cold-related mortality and increase in heat-related mortality. In some temperate countries, such as Poland, cold spells are still the weather extremes causing the most fatalities, exceeding 200 during colder winters in the (warm) 2000s.

Storm damage is over-proportionally related to wind speed and a cubic relation (infrastructure damage increases as a cube of wind-speed) is often postulated. Mills *et al.* (2001) proposed a quadratic relationship whereby a doubling of wind speed is translated into a four-fold increase in damage. Grace (2007) cited Insurance Australia Group’s experience, showing that an increase in peak wind gust strength from 40–50 to 50–60 knots can generate a 6.5-fold increase in building claims.

Hitz and Smith (2004) report on parabolic relations found for temperature rising impacts on sectoral damage in agriculture, terrestrial ecosystems, productivity, and forestry. Increasingly adverse effects are expected in coastal and marine ecosystems, biodiversity as well as health. A parabolic relation with temperature was postulated for additional numbers of people in the coastal hazard zone (e.g. living below the 1000-year storm surge elevation), under the assumption that adaptation is based on observed practice. However, by adaptation one can considerably improve the situation.

The insurance industry requires capital for an extreme year (now ca \$120bn). Climate change is likely to shift the distribution towards higher values. Extreme losses are likely to increase more than average losses, cf. Stern (2007). Storm intensity growth by 6% (for doubling CO_2 and 3°C warming) may increase the need for insurance capital in Japan and the US by 80–90%.

2.2 UNCERTAINTY

Future projections cannot be deterministic. Indeed, they are only possible in a statistical sense, loaded by strong uncertainty. Uncertainty of projections cannot be eliminated. Among sources are different possible scenarios for the future (socio-economic development and new technologies; emissions of greenhouse gases and land use, adaptation and mitigation). Uncertainty in regard to the models is also marked; there is a scarcity of reliable, rigorously tested models. Model uncertainty (in structure, parameters and data) results from the simplification of land-surface processes, and mismatches in spatial and temporal scales, between the climate model (large grid cells and daily data made commonly available) and the hydrological (catchment and event) scale. Hence, disaggregation of information from climate models is needed. Since different models produce largely varying results, one may consider an ensemble of model-based projections, allowing one to grasp the range of possible futures.

Future input signals to hydrological models (climatical input—temperature and precipitation) differ very much for various climate models and various assumptions about future socio-economic developments driving greenhouse-gas emissions. It is not uncommon that different climate scenarios or models produce projections differing in the sign of changes for a given variable, area and time horizon. Projections may range from a substantial increase according to one model to a substantial decrease for another. This strong uncertainty augments the "traditional uncertainty" in hydrological models, such as model structure uncertainty, model parameter uncertainty, and uncertainty involved in the input data (due to measurement errors, a lack of representativeness of the measurement site, or problems in aggregating or disaggregating data, in order to cover areas of concern). Thorough sensitivity studies help in assessing uncertainty.

Even if our understanding of uncertainties and their interpretation has improved, and new methods (e.g. ensemble-based approaches) are being developed for their characterization, quantitative projections of changes in precipitation, river flows and water levels at the river-basin scale remain uncertain (Kundzewicz *et al*., 2007).

Uncertainties to climate change projections increase with the length of the time horizon. In the near-term (e.g. 2020s), climate model uncertainties play the most important role, while over longer time horizons, uncertainties due to the selection of emission scenarios become increasingly significant (Jenkins and Lowe, 2003).

Most GCMs have difficulty in producing consistent precipitation simulations, while temperature simulations are well correlated with observations. These uncertainties, in turn, induce biases in the simulation of river flows when using direct GCM-output representative of a current time-horizon.

For precipitation changes to the end of the 21st century, the multi-model ensemble mean exceeds the inter-model standard deviation at high latitudes only. Over several regions, e.g. in Poland, models disagree on the sign of the seasonal precipitation change (forecasting decreased or increased future summer precipitation).

Uncertainties in climate change impacts on water resources are mainly due to the uncertainty in precipitation inputs, only to a lesser extent uncertainties over greenhouse gas emissions (Döll *et al.,* 2003), climate sensitivities (Prudhomme *et al., 200*3), or hydrological models themselves (Kaspar, 2003). Comparison of different sources of uncertainty in flood statistics in two UK catchments (Kay *et al*., 2006) led to the conclusion that GCM structure is the largest source of uncertainty, larger than emission scenarios and hydrological modelling.

It is difficult to evaluate the credibility of individual scenarios. Multi-model probabilistic approaches are preferable to using the output of one climate model only, when assessing uncertainty in the climate-change impacts on water resources.

The large range for different climate model-based scenarios suggests that adaptive planning should not be based on only a few scenarios, since there is no guarantee that the range simulated represents the full one.

3. CONCLUDING REMARKS

If informed decisions on building the preparedness system for meteorological and hydrological extremes are to be made, mathematical models are needed, enabling the analyst to convert the measured (or postulated) values of some variables into values of other variables of interest. In order to simulate systemic behaviour, time series of observations (e.g. precipitation over a basin area and river flow in a terminating cross-section) are first used to identify the system's model (an impulse response in the linear case). Once this has been done and the system's response is identified, one can model the response of the system corresponding to any input. In ungauged basins, where precipitation or river flow, or both, are not measured, the models have to be developed without access to a long time series of gauge records. Yet, urgent practical problems need to be solved in both gauged and ungauged basins. This drives the search for universal hydrological laws, utilisable in ungauged basins.

It is not necessary to measure the mass, force and acceleration of every moving object, since the formulation of the general Newtonian law allows us to understand any motion. Does one have general hydrological laws of comparably universal validity, which could be of use in ungauged basins or for future climate? One could say that drainage basins are so very different from each other. Yet so are the objects obeying Newton's laws of dynamics. Certainly, one obvious and essential law ruling hydrological systems is the principle of the conservation of mass (the continuity rule), valid over spatial and temporal scale (Kundzewicz, 2007).

Fig. 8 illustrates the impacts of heat wave effects on the Polish population in the load-resistance framework, stemming from mechanics, but useful in multiple system studies. This conceptual sketch shows that the load (summer heat) is likely to grow with time, while the resistance is likely to decrease with time in the ageing society, despite possible developments in public healthcare.

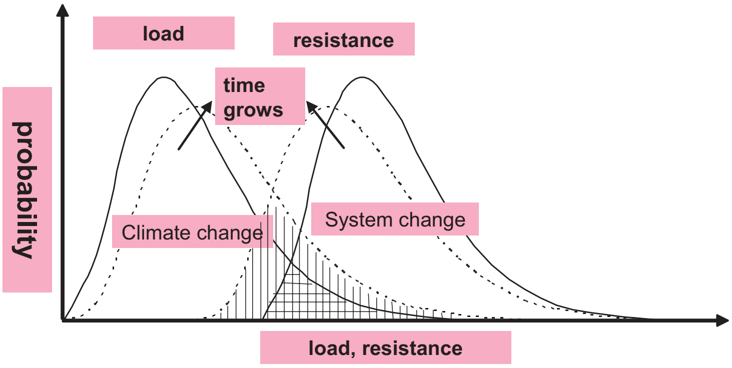

Figure 8. Increasing risk of adverse heat wave effects on the Polish population in the load-resistance framework. A conceptual sketch.

Since life span is likely to grow, there will be a larger proportion of older people, sensitive to excess summer heat. Heat wave impacts depend on age structure, the health status of the nation, and adaptation (e.g. air conditioning, establishing cooling areas in old-people's homes and hospitals).

Difficulties in modelling future impacts of climate extremes are immense. Rather than a general theory, there are fragmented and restricted studies, whose generalization is not easy. The modelling is in its infancy, with models being largely simplistic and speculative. Trustworthy models tested in a range of conditions are in short supply. An important bottleneck is data availability for past-to-present. Hence, while mathematical models are deployable to assess some problems, recourse is often made to soliciting more qualitative expert opinions, including subjective probabilities.

According to IPCC (2001), "[t]he analysis of extreme events in both observations and coupled models is underdeveloped" and this is true on the global scale. Change detection in data and projections referring to hydrometeorological extremes and their impacts remain an exciting scientific challenge.

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APPLICATION OF HYDRODYNAMIC MODEL OF THE BALTIC SEA TO STORM SURGE REPRESENTATION ALONG THE POLISH BALTIC COAST

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Abstract: A hydrodynamic model of the Baltic Sea based on the Princeton Ocean Model was applied in analyses of extreme storm surges along the Polish Baltic coast. When the applicability of the model in cases of high-amplitude and rapid water level fluctuations, such as those observed at the beginning of November 2006, was tested a good fit was obtained between observed and computed data. The model correctly predicted the hydrodynamic situation; it also generated relatively good simulations of water-level variations. The best fit between the numerical calculations and readings from the sea-level gauges was obtained for Gdańsk Nowy Port, while only slightly worse agreement characterized Świnoujscie and Ustka.

Key words: numerical modelling, storm surges, low-pressure systems, southern Baltic Sea.

INTRODUCTION

Extreme storm surges along the Polish Baltic coast occur as a result of the passage of a deep and intensive depression over the southern Baltic Sea. They produce flooding of coastal areas, polders, and areas adjacent to rivers; impact upon shore and beach stability; result in coastal erosion; affect port operations and navigation negatively; and impinge upon coastal zone infrastructure. It should be mentioned that the flood risk is anticipated to increase in the future as a result of sea-level rise and an increased frequency of severe storms.

In the Baltic Sea, the water level varies substantially as a result of an overlap of various types of periodic and non-periodic oscillations. It is also influenced by a number of meteorological and hydrological factors. The main ones affecting sea level are wind and sea-level pressure patterns over the Baltic Sea, weather systems over the North

Atlantic, the water exchange between the North and Baltic Seas and the inflow of fresh river water. Precipitation, evaporation, seasonal water density changes, seiches (standing waves) as well as bathymetry of the body of water are other factors influencing the sea level (Dziadziuszko and Jednorał 1987, Wiśniewski 1978, Heyen *et. al* 1996, Carlsson 1998, Wiśniewski *et al*. 2000, Lehmann and Hinrichsen 2001). As reported by Jasińska and Massel (2007), tidal effects on sea level are negligible along the Baltic Sea coast (tidal amplitudes range from 0.02 m to 0.1 m).

Prolonged stationary weather systems over the Baltic Sea are important factors determining its water volume and sea level. During prolonged periods of domination by westerly winds an inflow from the North Sea into the Baltic Sea takes place, causing an increase in sea level. On the other hand, the prolonged domination of easterlies reduces in sea level, due to the outflow from the Baltic Sea into the North Sea (Łomniewski *et al*. 1975, Dziadziuszko and Jednorał 1987).

A storm surge, as a type of non-periodic oscillation, is a rapid increase in sea level associated with the passage of a deep and intense low-pressure weather system. Fluctuations in sea level result from the combined effects of persistent wind over a shallow body of water and changes in atmospheric pressure on the sea surface; such effects generate a sea surface deformation, the so-called baric wave, with its positive phase inside the low and its negative phases outside it. The wave is like a cushion of water under a depression that moves together with it. Effects of the wind and the baric wave may be additive, i.e., both factors act in concert to increase or to decrease the sea level at the shore, or they may be non-additive, i.e., one factor increases the sea level and the other decreases it (Wiśniewski *et al*. 2005, Wiśniewski and Kowalewska-Kalkowska 2007).

Over recent years, numerical modelling has become an essential tool in water level forecasting within the Baltic Sea region. The High Resolution Operational Model for the Baltic Sea (HIROMB) was developed at the Bundesamt für Seeschifffahrt und Hydrographie (BSH) in Hamburg (Germany) and subsequently extended in cooperation with the Swedish Meteorological and Hydrological Institute (SMHI) in Norrköping (Sweden) (Kleine 1994, Eigenheer 1999, Funkquist 2001). It is now run operationally by the SMHI (http://www.smhi.se/oceanografi/oce_info_data/models/hiromb.htm). The Maritime Institute in Gdańsk (Poland) verified the model for the Polish zone of the Baltic (Kałas and Szefler 1999, Kowalska *et al*. 2001). At present, the Maritime Branch of the Institute of Meteorology and Water Management (IMWM) in Gdynia (Poland) issues, i.a., an online daily water level forecast for the southern Baltic Sea (http://baltyk.imgw.gdynia.pl/hiromb/). In Denmark, the Danish Meteorological Institute (DMI) (http://ocean.dmi.dk/models/index.html) issues storm surge predictions using Mike 21 (supplied to the DMI by the Danish Hydraulic Institute for Water and Environment, i.e. DHI Water & Environment). Marine forecasts concerning, i.a., water level, produced by the DHI Water & Environment are available at http://www.waterforecast.com and http://www.bsh.de/.

This paper discusses the applicability of a 3D pre-operational hydrodynamic model of the Baltic Sea (M3D_UG), developed at the Institute of Oceanography, University of Gdańsk to analyses of storm surges along the southern Baltic coast.

MODEL DESCRIPTION

The three-dimensional, pre-operational hydrodynamic model of the Baltic Sea (M3D_UG), developed at the Institute of

Oceanography, University of Gdańsk, is a baroclinic model that describes water circulation, with due consideration given to advection and diffusion processes. The model is based on the Princeton Ocean Model (POM), described in detail by Blumberg and Mellor (1987). Adapting the model to the Baltic Sea required certain changes in the numerical calculation algorithm, as described in detail by Kowalewski (1997). The open boundary was located between the Kattegat and the Skagerrak to parameterise water exchange between the North and Baltic Seas. A radiation boundary condition for the vertically averaged flows was applied. A monthly averaged vertical distribution of salinity and the temperature gradient normal to the border equal to zero were assumed at the open boundary as well (Ołdakowski *et al*. 2005). The solar energy input was calculated based on astronomical data and meteorological conditions (Krężel 1997). Other components of the heat budget at the sea surface were derived from meteorological data and simulated sea surface temperatures (Jędrasik 1997). The model takes 153 riverine discharge events into account. Because of wind-driven water back-flow in the River Odra's downstream reaches, a simplified operational model of the Odra discharge based on water budget in a stream channel was developed (Kowalewska-Kalkowska and Kowalewski 2006). Meteorological data (wind field, air temperature, atmospheric pressure, and water vapour pressure) were taken from the Unified Model for Poland Area (UMPL) mesoscale operational weather forecast model that generates 60-h weather forecasts with 1 hour steps (Herman-Iżycki *et al*. 2002). Contiguous tensions related to wind and the direct stress of atmospheric pressure on the sea surface (the baric wave) are factored into the hydrodynamic model as well. The initial conditions for the hydrodynamic fields were adopted in accordance with their climatic distributions based on the Baltic Environmental Database (http://data.ecology.su.se/models/bed.htm).

The model is valid for three areas with different spatial grid resolutions: 5 nautical miles (NM) for the Baltic Sea, 1 NM for the Gulf of Gdańsk, and 0.5 NM for the Pomeranian Bay and Szczecin Lagoon (Fig. 1). A numerical grid with sigma-transformation allows for a vertical profile at any point in the sea, irrespective of depth, to be divided into 18 layers (Kowalewska-Kalkowska and Kowalewski 2005, Kowalewski and Ostrowski 2005).

Evaluation of the model's performance for both the eastern and western parts of the southern Baltic coast showed the results of the model calculations to be of the same quality. The model correctly reflected hydrodynamic conditions and seasonal variability in sea level; it also generated relatively good simulations. The results showed a significant correlation between calculated and measured distributions of water levels. As described by Kowalewski (2002), correlation coefficients for the relationships between modelled water levels and those measured by the IMWM gauges in August 1999 in Władysławowo, Hel, and Gdańsk-Port Północny were 0.91, 0.89 and 0.87 respectively. In the model validation reported by Jędrasik (2005), correlation coefficients for relationships between numerical simulations and readings from tide-gauges located along the southern Baltic coast in 1995 and 2000 ranged from 0.69 in Ustka to 0.85 in Władysławowo. Finally, a good fit was obtained for the Pomeranian Bay and Szczecin Lagoon stations, with correlation coefficients ranging from 0.81 for Świnoujście (a 60-h forecast) to 0.93 for Trzebież (a 0-h forecast), as reported by Kowalewska-Kalkowska and Kowalewski (2005, 2006). It should be mentioned that the numerical data are relative only, that is, due to the imperfection of the boundary conditions

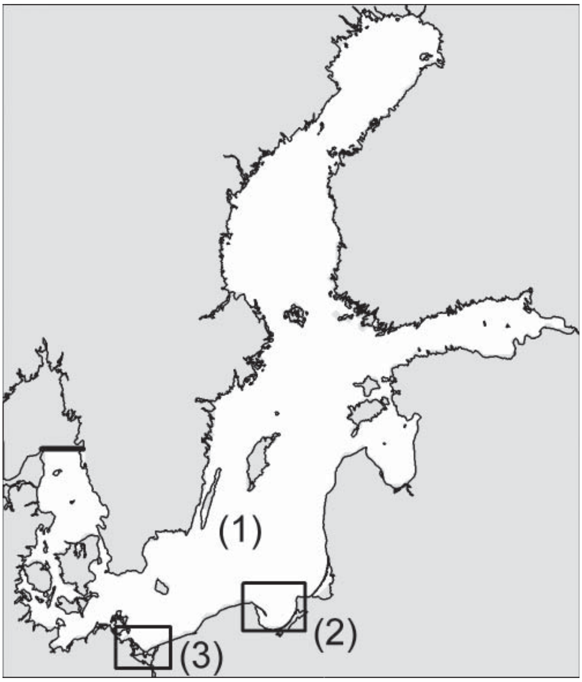

Figure 1. Regions modelled: Baltic Sea (1), Gulf of Gdańsk (2), Pomeranian Bay and Szczecin Lagoon (3).

applied to the open border in the Skagerrak and Kattegat, it is difficult to render them comparable to the average sea level, and to calculate the absolute sea levels (Kowalewski 2002, Kowalewska-Kalkowska and Kowalewski 2005). Hence, when the modelled and observed values are compared, a certain constant is added to render the initial forecast and observed values identical.

APPLICATION OF THE MODEL TO STORM SURGE REPRESENTATION

The good fit between simulations and readings of sea level from gauges located on the southern Baltic coast was an incentive for testing the applicability of the model to storm surge representation. Temporal sea-level variations in the region, as approximated by the model, may be visualised for a case involving a heavy storm surge that occurred in the beginning of November 2006. This was the result of the passage of a deep and intensive low-pressure system over the Baltic Sea. Initially, a decrease in water level at coastal stations was observed on 31 October, as a result of the low centre's fast shift over the North Sea (983 hPa in the centre) (Fig. 2a). The lowest sea level of 467 cm, i.e. 33 cm below the mean sea level, was recorded in Świnoujście at 11 a.m. as a result of the negative phase of the baric wave and southwesterly winds. The agreement between that empirical minimum and the forecast for 31 October in the timing and extent of the drop was very good (Fig. 3a). Subsequently, the water level along the southern Baltic coast was observed to increase rapidly as a result of the low centre's shift over the

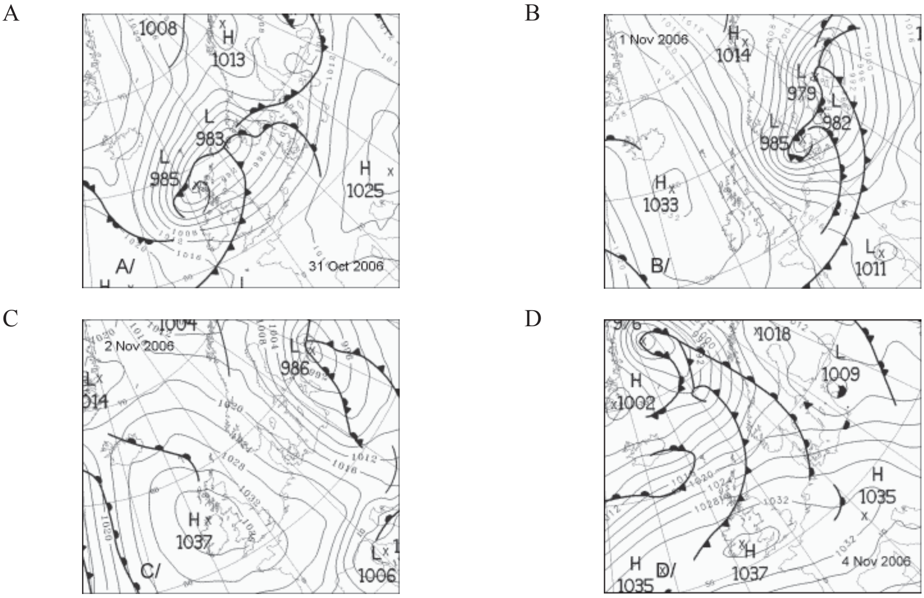

Figure 2. The synoptic situation (after http://www.wetterzentrale.de/topkarten/fsfaxsem.html) during the November 2006 storm-surge event.

southern part of Sweden and then eastward over the central Baltic (Fig. 2b). Along the southern Baltic, the maximum levels were observed on 1 November, resulting from the overlap of the positive phase of the baric wave and northerly winds. In Świnoujście the maximum level of 647 cm (147 cm above the mean sea level) was observed at 3 p.m.; in Ustka the observed level (at 6 p.m.) was 630 cm (130 cm above the mean level), while the level of 645 cm (145 above the mean level) was observed in Gdańsk at 10 p.m. (Fig. 3). The rapid increase in sea level was accurately approximated by the model. The timing and extent of maximum values as calculated by 31 October and 1 November were also predicted with high accuracy. It was only in Świnoujście that the maximum level was overestimated by the 31 October forecast and predicted to occur 3 h after the real maximum. On the other hand, the 31 October forecast underestimated the maximum levels in Ustka and Gdańsk. Over the following days, the low's centre passed over the Gulf of Finland and then moved north, resulting in the ensuing drop in sea level along the southern Baltic coast (Figs. 2c,d). The temporal variations in sea level occurring at that time were reproduced fairly accurately by the model. During those days, the best fit between the modelled and observed sea level fluctuations was obtained for Gdańsk (Fig. 3c). The sea level variations in Świnoujście were also correctly predicted by the model; however some underestimates were produced on 2 November from the 1 November forecast and some overestimates on 4 November from the 2 November prediction (Fig. 3a). On the other hand, the continuing drop in sea level on 2 November at Ustka was underestimated by the 1 November forecast, whereas the 2 November prediction generated some overestimates (Fig. 3b). Figs 4, 5 and 6 illustrate all the storm phases as predicted by the 3D numerical model.

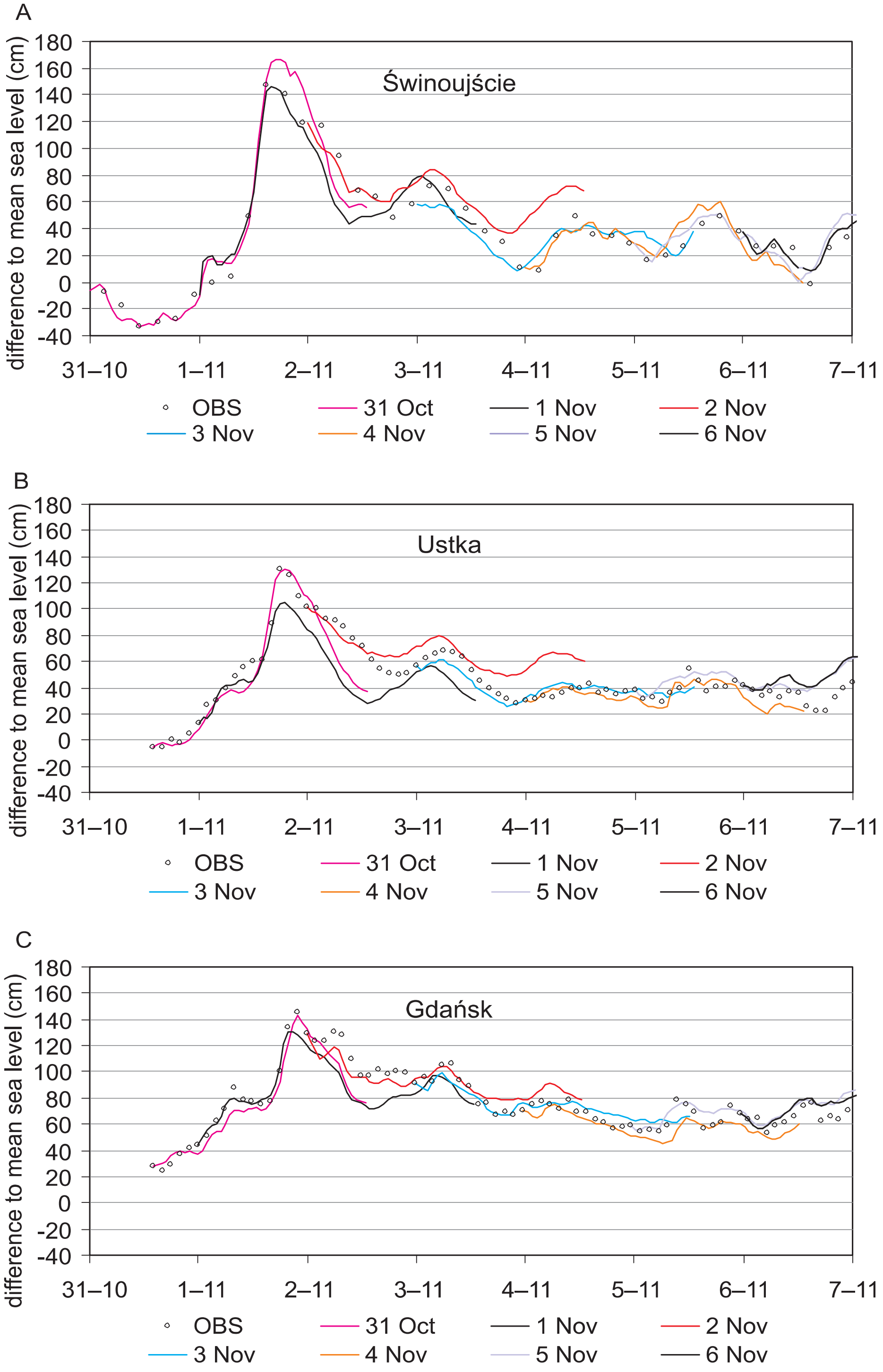

Figure 3. Observed and predicted water levels in Świnoujście (A), Ustka (B), and Gdańsk (C) during the November 2006 storm-surge event (in cm, relative to mean sea level). Legend: forecasts from 31 October, 1, 2, 3, 4, 5, and 6 November.

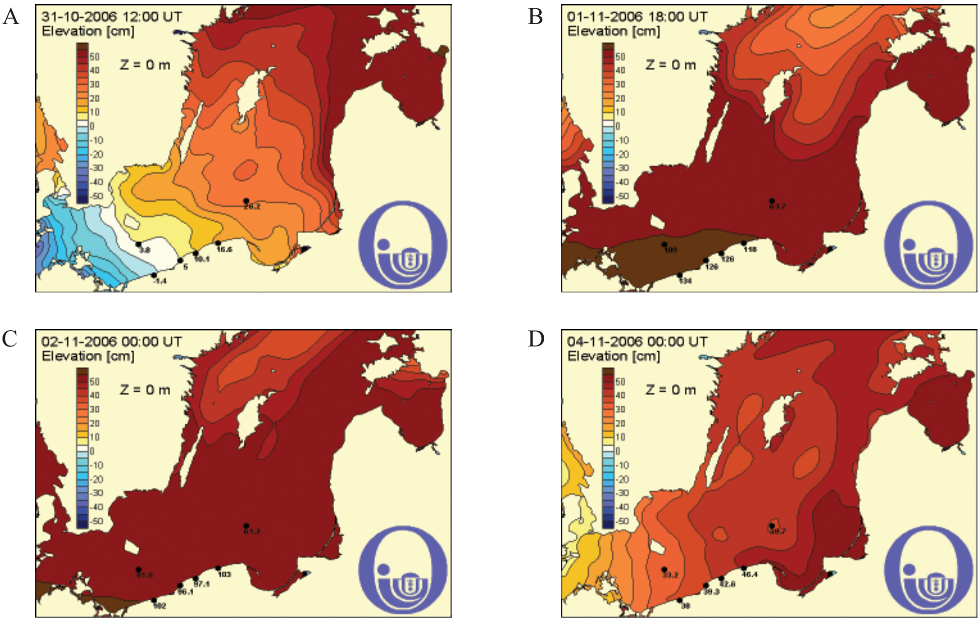

Figure 4. Spatial distribution of water levels (in cm, relative to mean water level) in the southern Baltic during the November 2006 storm-surge event, as simulated by the M3D_UG model and placed on the <http://model.ocean.univ.gda.pl> website.

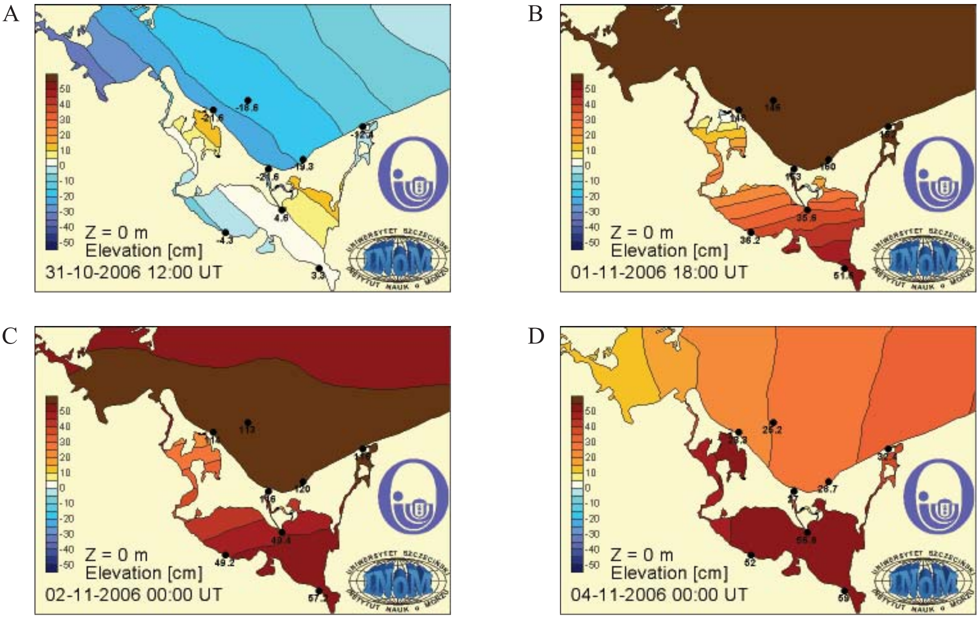

Figure 5. Spatial distribution of water levels (in cm, relative to mean water level) in the Pomeranian Bay and Szczecin Lagoon during the November 2006 storm-surge event, as simulated by the M3D_UG model and placed on the <http://model.ocean.univ.gda.pl> website.

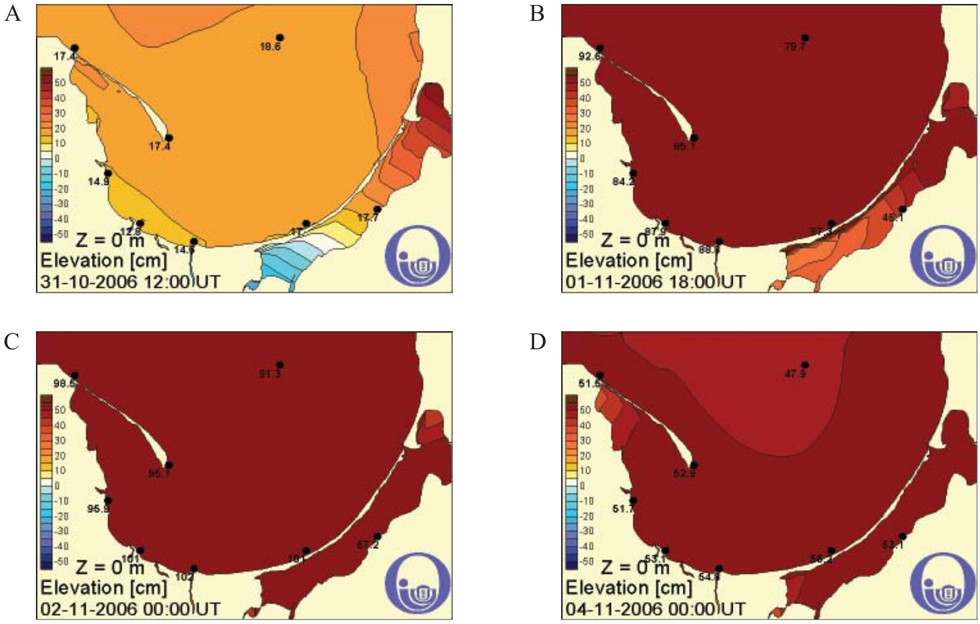

Figure 6. Spatial distribution of water levels (in cm, relative to mean water level) in the Gulf of Gdańsk during the November 2006 storm-surge event, as simulated by the M3D_UG model and placed on the <http://model.ocean.univ.gda.pl> website.

CONCLUSIONS

Evaluation of the M3D_UG model's performance showed a good fit between the modelled and observed distributions of water levels. In the cases of high-amplitude and rapid water level fluctuations, such as those observed at the beginning of November 2006, the model correctly predicted the hydrodynamic situation; it also generated relatively good simulations of water level variations. During the storm analysed, the best fit between the numerical calculations and readings from the sea-level gauges was obtained for Gdańsk Nowy Port, only a slightly worse agreement being shown for Świnoujscie and Ustka.

The adequate approximation of sea-level variations along the southern Baltic Sea coast by the model makes it a reliable tool for analysing and forecasting storm surges. Continuously updated results of the model's application are placed daily on the University of Gdańsk website (http://model.ocean.univ.gda.pl) as maps of 60-hour forecasts of water level, currents, water temperature, and salinity for the southern Baltic Sea and the Gulf of Gdańsk, as well as for the Pomeranian Bay and the Szczecin Lagoon.

Fast online access to the hydrographic forecast allows potential users to predict the day-by-day development of processes that may affect different areas of human life and activities, e.g. navigation, port operations or flood protection in coastal areas. In addition, the model may prove of assistance in studies on extreme sea level variations. Hence it is intended to fine-tune the model to improve its prognostic reliability so that a better fit between the observed and computed data is obtained.

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PROJECTIONS OF CLIMATE EXTREMES IN POLAND

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Abstract: The climate change projections for Poland are consistent in foreseeing overall temperature increase in the coming decades. Precipitation is projected to decrease in summer (though this finding is not robust, being model-dependent) and to increase in winter. It is expected that the occurrence of climate extremes over Poland may change in the future, warmer climate. In this study, daily temperature and precipitation data from the Hadley Centre HadRM3-PRECIS regional model simulations (for the SRES A2 scenario in three model experiments) in Poland were used to study temperature and precipitation extremes defined according to the specification made in the Integrated Project entitled "Extreme meteorological and hydrological events". Climate extremes in the control period, 1961–1990, were compared with those in the projection period, 2071–2100.

Key words: climate change, climate model, extremes, precipitation, temperature, Poland.

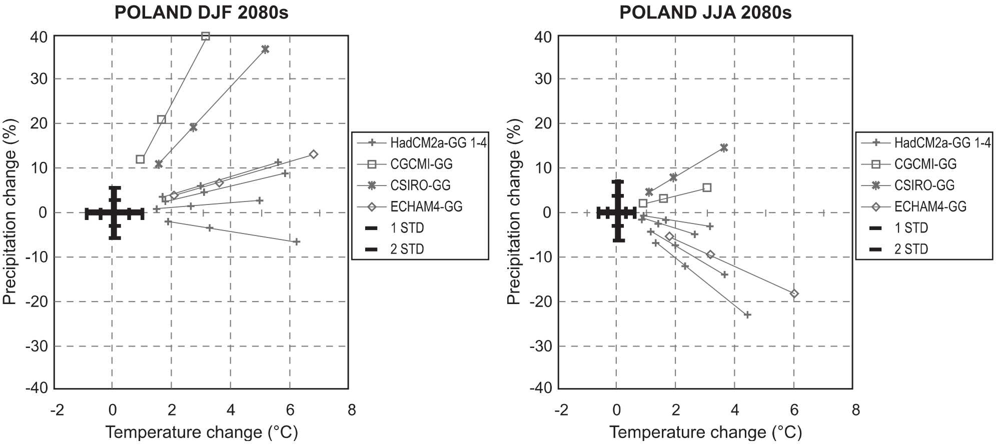
INTRODUCTION

Several episodes of temperature extremes (heat waves) and precipitation extremes (intense and/or long-lasting precipitation or long dry spells, often coincident with high air temperature) have occurred worldwide, and in Europe, in recent years. These events, leading to high-impact floods, droughts, and heat waves did not omit the territory of Poland. The Odra River flood in July 1997 was the most destructive natural event in Polish history, though floods in 1998 and 2001 also led to fatalities and severe material damage. The summer droughts in 1992 and 2006 caused a major fall in harvests and challenged water supply systems. A large number of wildfires was also observed. The heat wave in 2006 with a record hot July caused considerable damage. In this context, it is natural to ask such questions as: Is this a natural climate fluctuation superimposed on socio-economic factors, such as increasing human impact. Do these events signal climate change, and are such events likely to be more severe and to occur more frequently in the future? There have been numerous studies in Europe tackling this issue. For example, Klein Tank and Koennen (2003) analyzed a large set of station data for daily temperature and precipitation in Europe, for the years 1946–99. Indices of temperature extremes indicate that both cold and warm tails to the distributions of minimum and maximum temperature have shifted towards higher values. Klein Tank and Koennen (2003) also found that Europe-average indices of precipitation extremes had increased, even though the spatial trends were not coherent. The extreme heat wave in Europe in the summer of 2003 (not as severe as that in 2006 in Poland) was examined by Beniston (2004), on the basis of Swiss climatological data and model simulations. The observed event resembles what regional climate models are projecting for summers in the latter decades of the 21st century. Hence, one can interpret the 2003 heat wave as a proxy for a hotter future climate.

The climate-change projections for Poland are consistent in foreseeing an overall increase in temperature in the coming decades. However, the models are not consistent as regards their projections of the direction to changes in precipitation. Most models foresee a decrease in summer precipitation and an increase in winter precipitation (Parry, 2000), but there are some projecting contrary changes (Fig. 1). Based on HadRM3-PRECIS regional model simulations, this paper aims to illustrate the way in which the projected changes will influence the characteristics of climate extremes in the future.

DATA

In this paper, it is the temperature and precipitation extremes defined according to the specification made in the Integrated Project entitled ‘Extreme meteorological and hydrological events’ that have been analyzed. Daily temperature and precipitation data from the HadRM3-PRECIS regional model simulations (for the SRES A2 scenario in three model experiments) in Poland have been used to compare climate


POLAND DJF 2080s

POLAND JJA 2080s

Figure 1. Scenarios for changes in mean seasonal air temperature and precipitation for Poland in winter (DJF = December, January, February) and in summer (JJA = June, July, August); results obtained by Tim Carter as a part of the ACACIA project for time horizon of the 2080s, as compared to control period 1961–1990. Levels of one and two standard deviations are also marked (crosses passing through the centre of the coordinate systems). Symbols linked refer to results of single climate model for different SRES emission scenarios (A1, A2, B1, B2).

Source: Parry, 2000.

extremes in the 30-year periods 1961–1990 and 2071–2100, where the period 1961–1990 is the control one, while 2071–2100 is the projection one. The 1961–1990 values/characteristics are based on model simulations and not on observations.

This Regional Climate Model (RCM) has been developed by the Hadley Centre, to help address issues where resolution higher than that of the General Circulation Models (GCMs) is necessary. The RCM model covers Europe with a spatial resolution 0.44° by 0.44° (about 50 by 50 km), with 149 grid-cells over the territory of Poland. The model has been developed in the U.K. and is most accurate over Britain. Some of the inaccuracies in the RCM model have been analyzed by various authors, e.g. Holt *et al.* (2005).

In order to verify model simulations and to assess the usefulness of the HadRCM model for this research, the control period data (1961–1990) from the model have been compared with those from the European Climate Archive (ECA) for six Polish stations (Białystok, Hel, Poznań, Szczecin, Warszawa and Wrocław) for the same period.

The modelled data reconstruct the monthly distribution of mean temperature correctly, yet the values in the model are slightly overestimated, especially in the summer months. The present value for annual precipitation is also reconstructed quite correctly, but the distribution and values for the monthly precipitation for modeled data differ significantly from the observed station data. The highest precipitation in the model occurs in June and not in July, as in the observation records. Winter precipitation is too high as compared with the summer one. If a model cannot cope with reconstructing the details of the present climate, it is not a trustworthy tool to make projections for the future, yet, it has been reported in several studies that models do not perform very well in reproducing observational data over Eastern Europe. Fig. 2 presents, as an example, a comparison of the monthly distribution for mean temperature and precipitation, based on the climate model and on the observations contained in the ECA holding, for the city of Poznań and for the cell containing Poznań.

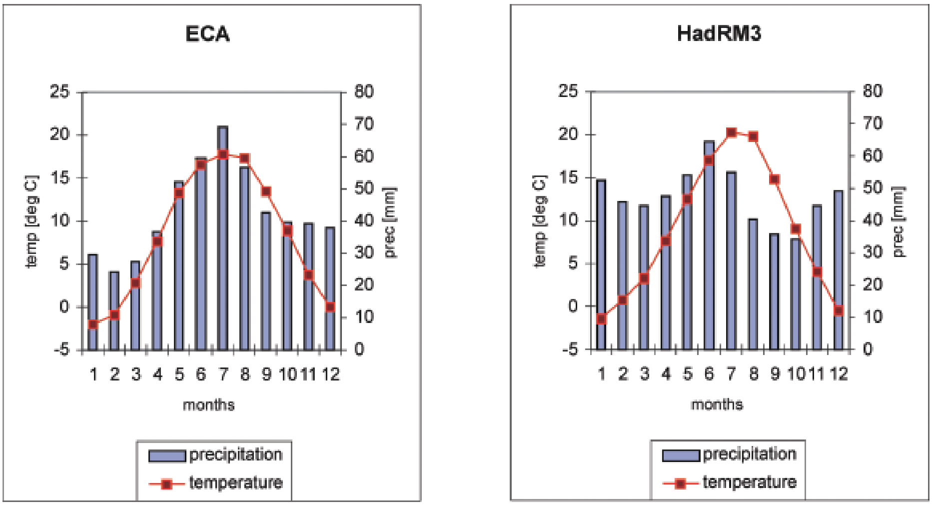


Figure 2. Mean monthly temperature and precipitation in the present (1961–1990) in Poznań.
Source: Authors' own elaboration based on ECA data and in cell with the city of Poznań, HadRM3 results.

PRECIPITATION EXTREMES

Exceptionally intense and/or long-lasting precipitation or long dry spells are among the categories of extremes defined in the specification made for the Integrated Project "Extreme meteorological and hydrological events". Among extremes related to atmospheric precipitation, the characteristics studied are:

- maximum one-month precipitation in a given year,
- maximum one-day precipitation,
- daily precipitation with a probability of exceedence of 10%,
- number of days with 24-h precipitation in excess of 10, 30, 50 and 100 mm,
- meteorological drought defined as lack of precipitation extending over at least 15 days.

Projections of maximum one-month precipitation in a given year for the future (2071–2100) range from below 100 mm at the Baltic coast to more than 400 mm for the higher mountains. In general, this precipitation characteristic is projected to decrease in the western and southern parts of Poland, and to increase in the east. The biggest decrease in the future as compared to the control period is expected for high mountains, about 30 mm and more. It is projected to exceed 20 mm in the central part of the country (Fig. 3).

For maximum one-day precipitation, the greatest increases are projected for central Poland, while the biggest decrease is likely along the Odra River, in the mountainous catchments of its tributaries (Fig. 4). The maximum one-day precipitation in a single year is projected to feature strong regional variations in the future (2071–2100), from less than 30 mm in Pomerania to more than

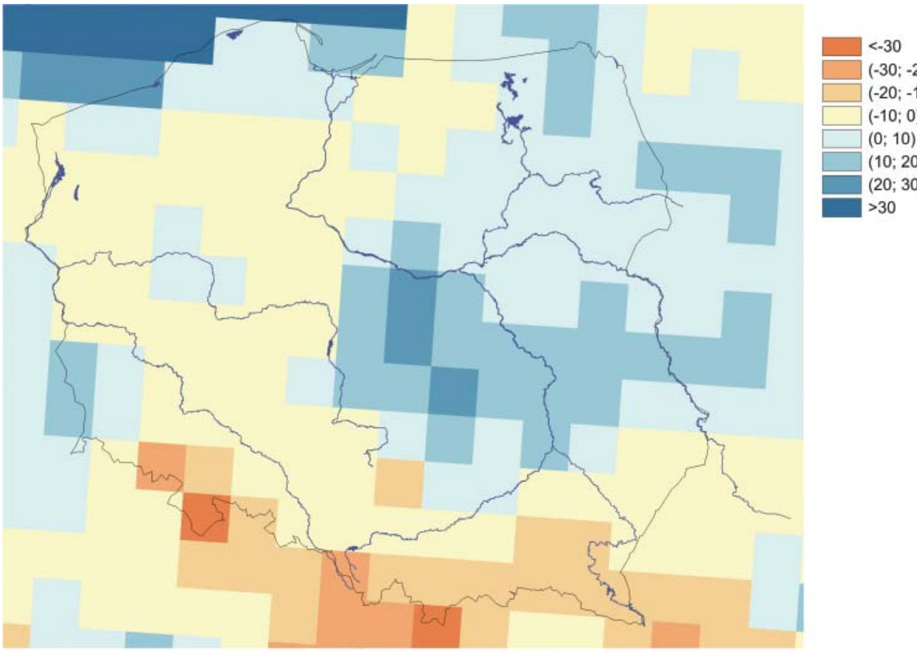


Figure 3. Difference in maximum one-month precipitation between the future (2071–2100) and the present (1961–1990)
Source: Authors' own elaboration based on HadRM3 results [in mm].

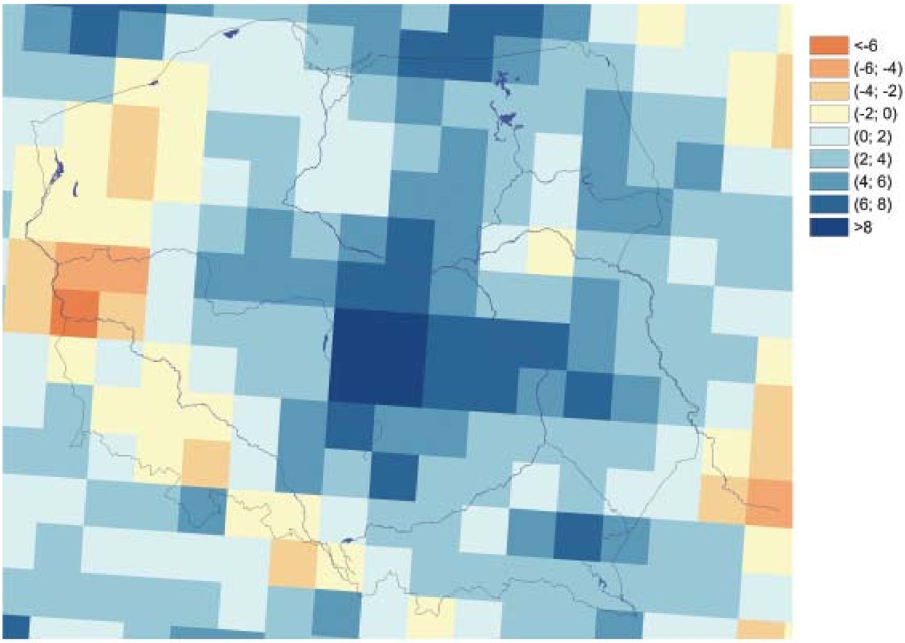


Figure 4. Difference in maximum one-day precipitation between the future (2071–2100) and the present (1961–1990)
Source: Authors' own elaboration based on HadRM3 results [in mm].

100 on the South. Appropriately, daily precipitation with a probability of exceedence of 10% is expected in the future to range from 2 mm to more than 20 mm, while for most of Poland it is projected to be about 4–6 mm.

The projections for the future indicate a decrease in the number of days with intense precipitation (defined as 10 mm over one day or more). The greatest decrease in the future (2071–2100) in comparison with the control period is projected for the mountains; over 10 days. A decrease in the West is also projected, while in the Eastern part and at the Baltic coast an increase in the number of such a days is foreseen. Yet the projected increases in the number of days with precipitation above 10 mm are not as large as the decreases, and they are to last up to 4 days (Fig. 5).

If higher thresholds of intense precipitation are adopted in analysis (e.g. above 30, 50 and 100 mm per day), it is difficult to analyze them on the basis of climatic models. That is because the values apply to the area of a large grid cell (50x50 km), rather than to a point. As a result, the climate model flattens extreme values. The only conclusion that can be drawn on this basis is the projected decrease in the number of such days in mountainous areas.

The precipitation deficit can be as severe as (or even more severe than) the surplus, especially if it occurs in the growing season. In this study, drought is defined as a period without precipitation extending over at least 15 days. The future mean drought is projected to last less time in relation to the control period, approximately by two days, in the North-East and in the mountains. In the other areas of Poland, the duration of the mean drought will be longer in the future (2071–2100) by more than four days (Fig. 6).

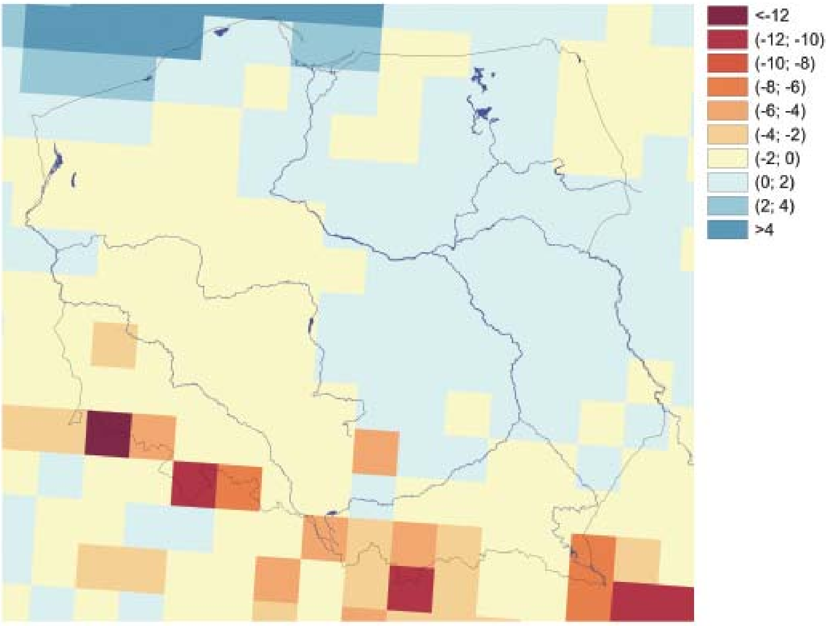


Figure 5. Difference in the number of days with precipitation P ≥10 mm between the future (2071–2100) and the present (1961–1990)
Source: Authors' own elaboration based on HadRM3 results [in days].

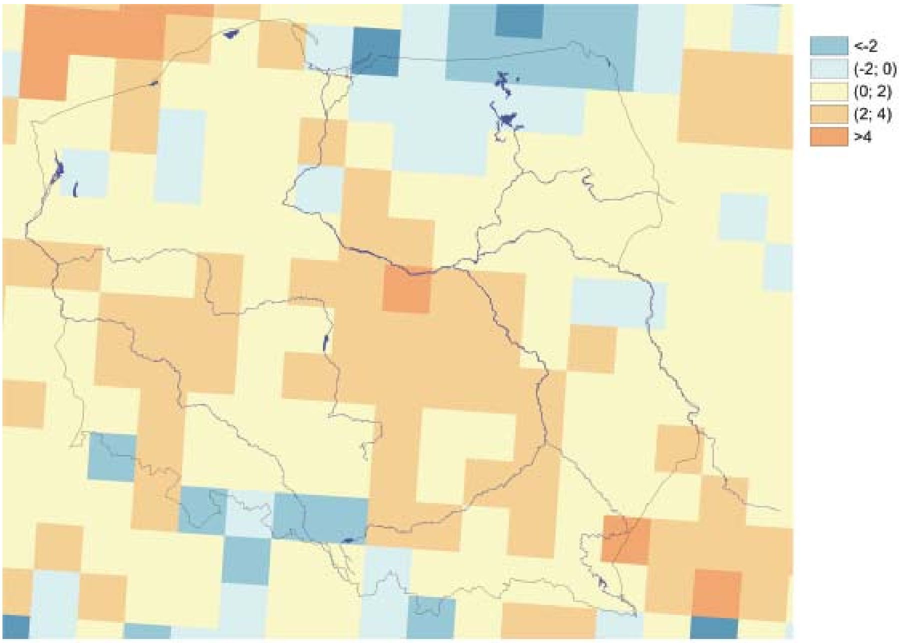


Figure 6. Difference in mean duration of dry spell (at least 15 days) in a year between the future (2071–2100) and the present (1961–1990)
Source: Authors' own elaboration based on HadRM3 results [in days].

The analysis of the longest dry spell in the year yields similar results. In the future, the longest dry spell in a year is projected to last from 20 days on the Baltic coast and Pomerania to more than 35 days in the Sandomierz Valley. Thus, only for the north-eastern part of Poland and for the higher mountains does the climate projection indicate a shortening of the longest dry spell in a year. In the other areas of Poland, the duration of drought is projected to be longer in the future (2071–2100), even by more than 20 days.

The HadRM3 model draws just one possible future (for a specific emission scenario, A2). Other models are likely to produce different results. As seen in Fig. 7 (IPCC WG1-AR4, 2007), models do not agree even on the sign of precipitation change over much of Europe, including Poland. In summer, less than 8 out of 12 models considered agree on the sign. In winter most models project increased precipitation over the territory of Poland. Best agreement of models (11 out of 12 models agree on the sign of significant precipitation change) can be observed in the north of Europe (winter precipitation increases) and in the Mediterranean (summer precipitation decreases).

TEMPERATURE EXTREMES

Climate projections indicate that the increase in mean temperature across Poland is likely to continue. A question may arise as to the behaviour of temperature extremes. In the category of extremes related to air temperature, the characteristics studied are:

- absolute minimum and maximum of temperature,
- the number of extremely warm days ($t_{max} \geq 35.0$°C),
- the number of tropical nights ($t_{min} \geq 20.0$°C),
- the length of the frost-free period with a probability of 10%,
- the number of days with severe frost in May ($t_{min} \leq -2.0$°C) and
- the number of extremely cold days ($t_{min} \leq -20.0$°C).

Absolute maximum daily temperature is projected to increase in the future (2071–2100) by 2 to even 6°C in the North-East. In absolute terms, the modeled maximum is projected to range from 30°C on the Baltic coast to more than 50°C in the Bug and Narew River basins (Fig. 8). The extreme temperature (with a probability of

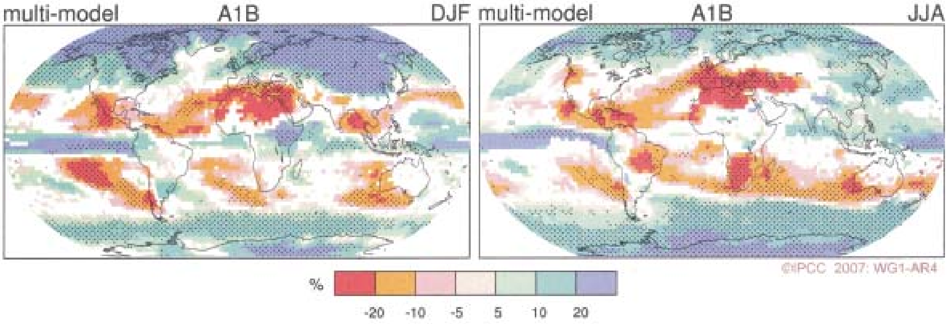


Figure 7. Projected patterns of precipitation changes. Relative changes in precipitation (in percent) for the period 2090–2099, relative to 1980 –1999. Values are multi-model averages based on the SRES A1B scenario for December to February (left) and June to August (right). White areas are where less than 66% of the models agree in the sign of the change and stippled areas are where more than 90% of the models agree in the sign of the change.
Source: IPCC, 2007.

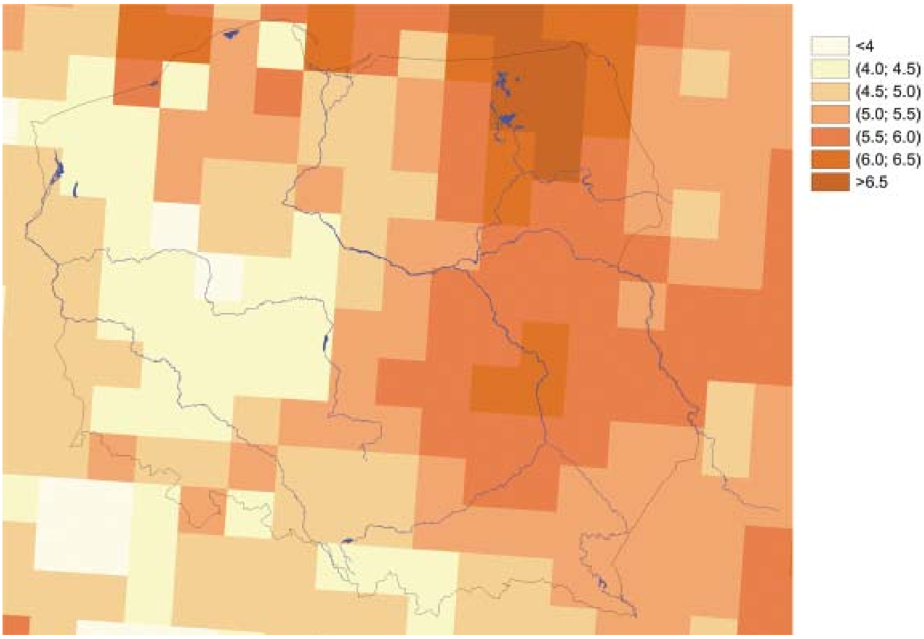


Figure 8. The increase of absolute maximum daily temperature in the future (2071–2100) versus present (1961–1990)
Source: Authors' own elaboration based on HadRM3 results [in °C].

exceedence of 10%) is also projected to be higher in the future than at present. This temperature is expected to range from 22°C on the Baltic coast to more than 34°C for the Lublin and Małopolska Uplands in the future projection horizon (2071–2100).

In the future horizon, the number of days with extreme temperature (days and/or nights) is projected to increase. The number of extremely hot days, with maximum temperature higher than or equal to 35°C is projected to increase by 5 to 30 days. In absolute terms, it is projected to range from 10 days on the Baltic coast to more than 40 days in the south, except for the high mountain areas (Fig. 9). The number of tropical nights, with minimum temperature higher than or equal to 20°C is also projected to increase in comparison to the control period. It varies from 5 nights at the Baltic coast to 45 and more in the south-east and along the upper and middle Odra River. The greatest increase in the number of hot nights is foreseen for the Sandomierz Basin (Fig. 10).

There is evidence that a high and prolonged period of raised temperature may have a dramatic impact on different fields of human activity, in particular on human health. Heat waves often turn fatal when the night-time temperature does not drop considerably below the high day-time temperature. For this reason, the numbers of days with both maximum temperature higher than or equal to 35°C and minimum temperature higher than or equal to 20°C have been analyzed. This number is projected to increase in the future. In the upper and middle Odra River basin, the Sandomierz Basin and the Lublin Upland, the longest spell of this thermal characteristic may increase by up to 10 days for the projection period 2071–2100, in comparison with the control period. The number of such days in an average year may rise in the future to more than 20 in the South of Poland.

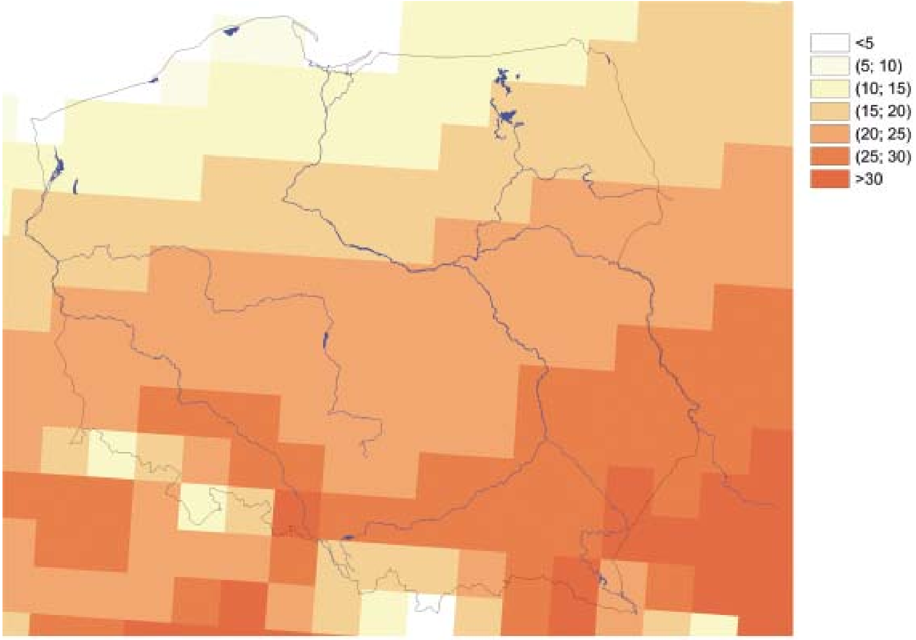


Figure 9. The increase in the number of extremely hot days (with $T_{max} \geq 35°C$) in the future (2071–2100) versus present (1961–1990)

Source: Authors' own elaboration based on HadRM3 results [in days].

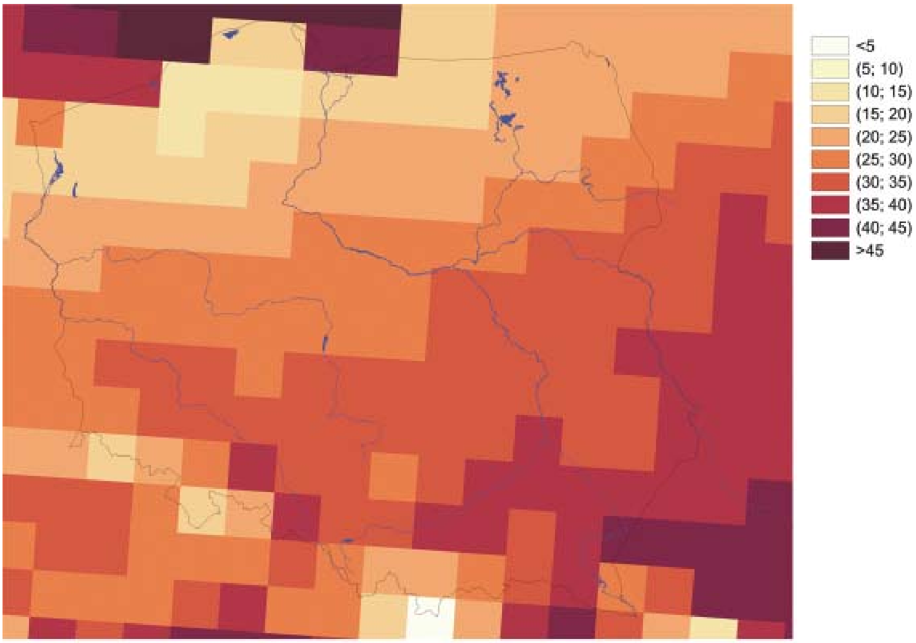


Figure 10. The increase in the number of tropical nights (with $T_{min} \geq 20°C$) in the future (2071–2100) versus present (1961–1990)

Source: Authors' own elaboration based on HadRM3 results [in days].

Based on climate projections, one can conclude that frost is expected to retreat from the territory of Poland in the future (2071–2100). The length of the frost-free period will increase markedly, and the frosts will probably be uncommon.

Absolute minimum daily temperature is projected to range from -5°C at the coast and along the Odra River to below -20°C in the Tatra Mountains, so it will higher by 6 to even 12 degrees in the East, in relation to the present (Fig. 11). The minimum temperature with a probability of exceedence of 10% is also projected to increase in the future. It will probably range from to -4°C to 0°C in the future, as compared with the range -10°C to 0°C at present. In the Lower Odra Valley, only temperatures above 0°C are expected for the future (2071–2100).

The longest frost-free period, with minimum temperature above 0°C, is projected to last longer in the period 2071–2100 by 50–60 days compared with in the present climate of Poland. The greatest increase is projected for the central part of Poland. The length of such a period with a probability of exceedence of 10%, which means that such a long frost-free period is projected to occur in only 1 out of 10 years, will vary from 210 days in the high mountains to about 270 days in Western Pomerania and along the Lower and Middle Odra River. It follows that the frost-free period is projected to increase by 40 to 75 days in the future (2071–2100) (Fig. 12). A temperature below 0°C in May is not likely to occur in an average year in the future projection horizon. Similarly, climate projections indicate a lack of very cold days (defined as those with minimum temperature below -30°C) in the future. Even the minimum temperatures of -20°C are not likely to occur in the prediction period, 2071–2100.

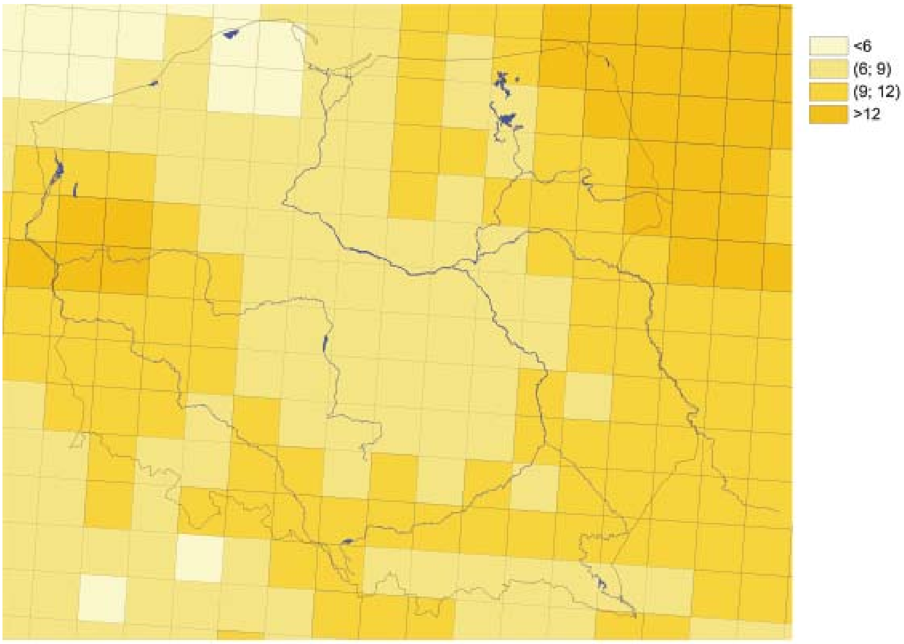


Figure 11. The increase of absolute minimum daily temperature in the future (2071–2100) versus present (1961–1990)
Source: Authors' own elaboration based on HadRM3 results [in °C].

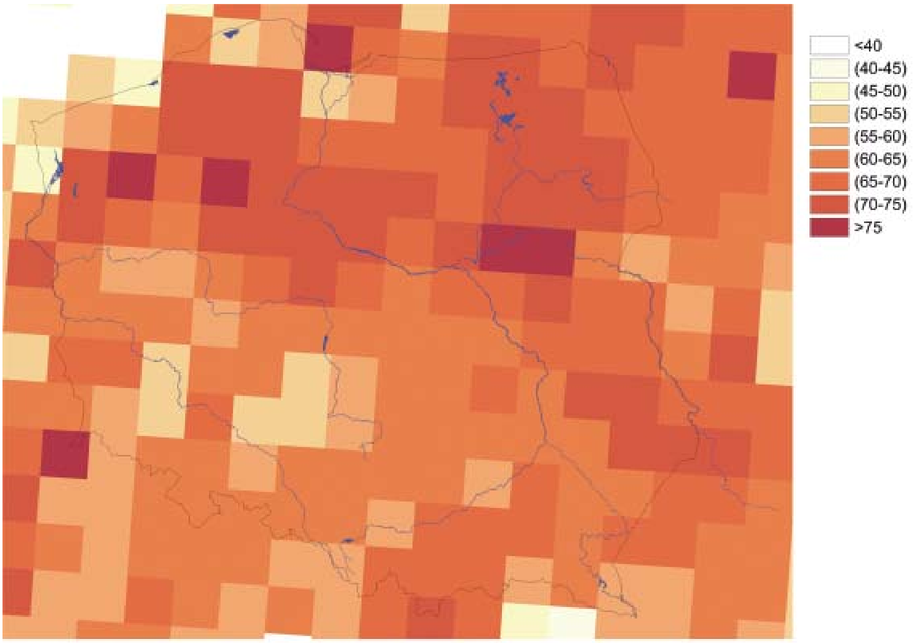


Figure 12. The increase in the length of frost-free period with probability of exceedence 10% in the future (2071–2100) versus present (1961–1990)

Source: Authors' own elaboration based on HadRM3 results [in days].

FINAL REMARKS

The projections of climate extremes for Poland, obtained for 2071–2100 with the help of the Hadley Centre Regional Climate Model (HadRM3-P) show considerable changes in comparison to the control period (1961–1990), which can be summarized as:

- an increase in mean temperature and such temperature-related indices as minimum and maximum temperature, percentiles of temperature, length of hot period, duration of a suite of tropical nights and the frost-free interval,
- intensification of the hydrological cycle; with intense precipitation and droughts becoming more extreme.

Unfortunately, there is a marked uncertainty to future projections. Results are strongly scenario- and model-dependent. Model dependence is important even for the less remote future, while for long-term effects the importance of scenarios comes into play.

ACKNOWLEDGEMENTS

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