Response of mountainous catchments to global climate change

M. Lenartowicz and M. Gutry-Korycka

Abflussreaktion gebirgiger Einzugsgebiete auf die globale Klimaänderung

Introduction

Explanations as to global warming influences on flood formation in catchments towards the end of the 21st century are often contradictory. The controversies result from the accuracy of long-term precipitation projections and the temporal and spatial resolution of applied General Circulation Models and hydrological models. An important element in climate change modelling is the selection of an appropriate economic transformation scenario for determining emission of greenhouse gases affecting global warming (NAKIĆENOVIČ and SWART, 2000; IPCC, 2007). Coupled GCMs and hydrological models allow the projections of climate change impact on flood formation in the numerical form.

The most important is the question whether global climate change will affect the frequency of extreme floods in

Zusammenfassung

Die vorgestellte Studie befasst sich mit der Erforschung des Einflusses der Klimaänderung auf die Hochwasserentstehung in kleinen Einzugsgebieten. Das Hauptziel war die Abschätzung der Abflussentstehung bei extremen Niederschlagsereignissen mit Hilfe des Niederschlags-Abfluss-Modells MIKE SHE 2004. Es wurden die Einzugsgebiete Biała Tarnowska/Grybów und Solinka/Terka in den südpolnischen Karpaten ausgewählt. Beobachtete und generierte Extremniederschlagsereignisse wurden für die Kalibrierung und Validierung des Modells herangezogen. Eine weitere Betrachtung befasst sich mit Prognosedaten des Niederschlags für das Ende dieses Jahrhunderts auf Basis des ECHAM4 Klimamodells. Dabei wurde das SRES1b Szenario zugrunde gelegt. Diese Ergebnisse deuten auf ein Ansteigen der Intensitäten extremer Niederschlagsereignisse in der zweiten Hälfte des Jahrhunderts in den Karpaten hin. Die berechneten Abflussscheitelwerte zeigen eine Abnahme für den Zeitraum 2046–2065 und einen Anstieg für 2081–2100. Für zukünftige Arbeiten sollte der Unterschied in der räumlichen Auflösung der Klimamodelle und der hydrologischen Modelle stärker berücksichtigt werden.

Schlagwörter: Einzugsgebiete in den Karpaten, Hydrologisches Modell MIKE SHE, Abflussänderungen.

Summary

The influence of global climate change on flood formation in small basins has been investigated in this study. The main goal has been the estimation of catchment response to extreme rainfall events using the rainfall-runoff model in MIKE SHE 2004. Two Carpathian river catchments located in south Poland: Biała Tarnowska/Grybów and Solinka/Terka were selected for modelling. Real and theoretical extreme rainfall data generated from archival datasets have been used to calibrate and validate the model. An important task of the study is determining projected extreme rainfall events towards the end of the 21st century, based on data from the General Circulation Model. GCM ECHAM4 rainfall projections using the sustainable SRES1b scenario have been applied to estimate predicted probable extreme rainfall totals. Modelling results indicate that the Carpathian catchments will be exposed to an increased intensity of extreme rainfall events in the second half of the 21st century. However predicted extreme peak flows will be lower for the 2046–2065 period compared to current levels, but higher for the 2081–2100 time period. Future solutions will need to be found for the problematic difference in resolution between the R–R model and the GCMs.

Key words: Global climate change, ECHAM 4, GCMs, SRES scenario, MIKE SHE, rainfall-runoff modelling, simulation of flood.

the future. Increase of flood frequency has been already proved by many authors (e.g. MIDDELKOOP and PARMET, 1998; MILLY et al., 2002; HIRABAYASHI et al., 2008; KUNDZEWICZ, 2008). According to them global climate change will cause flooding intensity in Europe to increase.

The goal of this study is an estimation of a catchment's response to extreme rainfall events and evaluation of the global climate warming influence on rainfall-driven flood events with a low probability in two Carpathian catchments in Poland: Biała Tarnowska and Solinka. A physically based rainfall-runoff model with spatially distributed parameters included in standard MIKE SHE 2004 package has been applied. Coupling of rainfall-runoff model input data with GCM ECHAM4 output data seems to be an appropriate research tool that allows projection of likely extreme floods over the next 90 years.

Methods

Selected modules of MIKE SHE package (REFSGAARD and STORM, 1995) describing input precipitation field, interception of vegetation cover, detention of catchment's surface and surface runoff have been applied (Figure 1A). Assumed model is physically based with spatially distributed parameters. Spatial resolution of the model is 100 m and temporal resolution is 24 hours. All the parameters are identified in sub-catchments. Analyses have considered only rainfall-runoff relationship, therefore snow cover melting processes are omitted and the modelling is limited to summer half-year. Net rainfall formation has been estimated using SCS method (US Department …, 1972). It has been modelled for sub-catchments, taking into account the following physiographic parameters: slope of the main watercourse, average length of the slope and vegetation cover affecting Manning's *n* coefficient. Estimation of CN parameter enables in consequence evaluation of so-called net rainfall fraction parameter required by MIKE SHE 2004 package. Since mostly impervious sandstones are dominant on the surface of the catchments, the most important considered process has been overland flow formation (Figure 1B), described by the continuity equation:

$$D_2 = D_1 + (\bar{q}_s - \bar{q}) \cdot \Delta_t$$

where: D_1, D_2 – volume of water detained on the surface at the beginning and the end of the time-step Δt ($m^3\ m^{-1}$),
q_s – increase in specific discharge in time-step t ($m^2 \cdot s^{-1}$),
q – specific discharge ($m^2 \cdot s^{-1}$):

$$q = M \cdot \sqrt{\alpha} \cdot \left[\frac{D}{L} \left(1 + 3/5 \cdot \left(\frac{D}{D_e} \right)^3 \right) \right]^{5/3}$$

where:
M – Manning's M ($m^{1/3} \cdot s^{-1}$) – inverse of Manning's n,
D – volume of water detained on the surface ($m^3\ m^{-1}$),
D_e – volume of water detained on the surface at *equilibrium* ($m^3\ m^{-1}$).

Input precipitation data has been generated using historical time-series included in the databases of the Institute of Meteorology and Water Management, Warsaw, Poland and published in the meteorological yearbooks. Reconstruction of precipitation spatial distribution has been conducted using the IDW (Inverse Distance Weighted) interpolation procedure and spatial resolution of 100 m. The number of considered raingauges located within or close to modelled catchments is specified in Table 1. Daily precipitation totals projected by ECHAM4 GCM (assuming SRES1b scenario) for years 2046–2065 and 2081–2100 have been obtained from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset (MEEHL et al., 2007).

Sources of spatial data used for determining the model parameters are the following:

- Digital Elevation Model (90 m resolution) based on *Shuttle Radar Topography Mission* (*SRTM*) recorded in year 2000 during NASA mission of Endeavour space shuttle,
- Digital Hydrographic Map of Poland (2004) prepared by IMWM,
- Land cover map of Corine Land Cover 2000 project,
- Geological maps prepared by Polish Geological Institute.

The modelling procedure consisted of four phases. Estimated physical parameters of the model (Table 1, Table 2) have been assumed as invariable in all four phases.

First phase

The following steps have been undertaken in the first phase: selection of an integrated mathematical model of the catchment with spatially distributed parameters, selection of investigated catchments and identification of parameters, calibration and validation of the model using archive

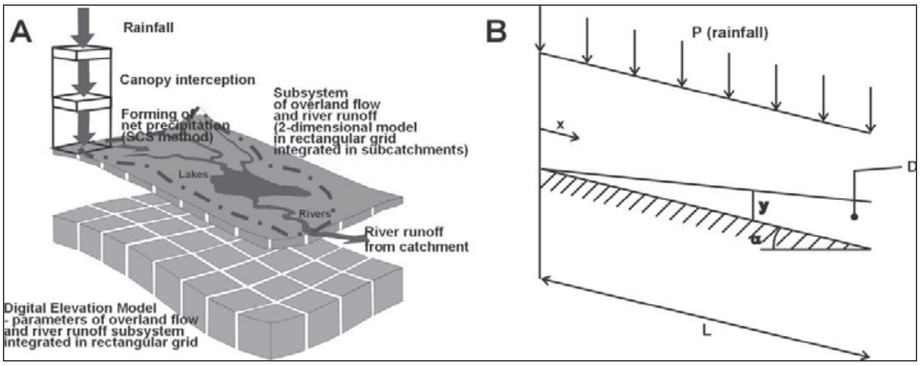

Figure 1: Structure of integrated MIKE-SHE 2004 hydrological modelling system in configuration applied in investigated catchments (A) and subsystem of overland flow (B) where: L – length of the slope, D – volume of water flowing down the slope, α – the slope, x – distance measured down the slope, y – depth of water on the surface at any point along the surface, P – rainfall (based on Mike SHE …, 2004)

Abbildung 1: Modellstruktur von MIKE SHE 2004 (A) und Modellbereich des Oberflächenabflusses (B)

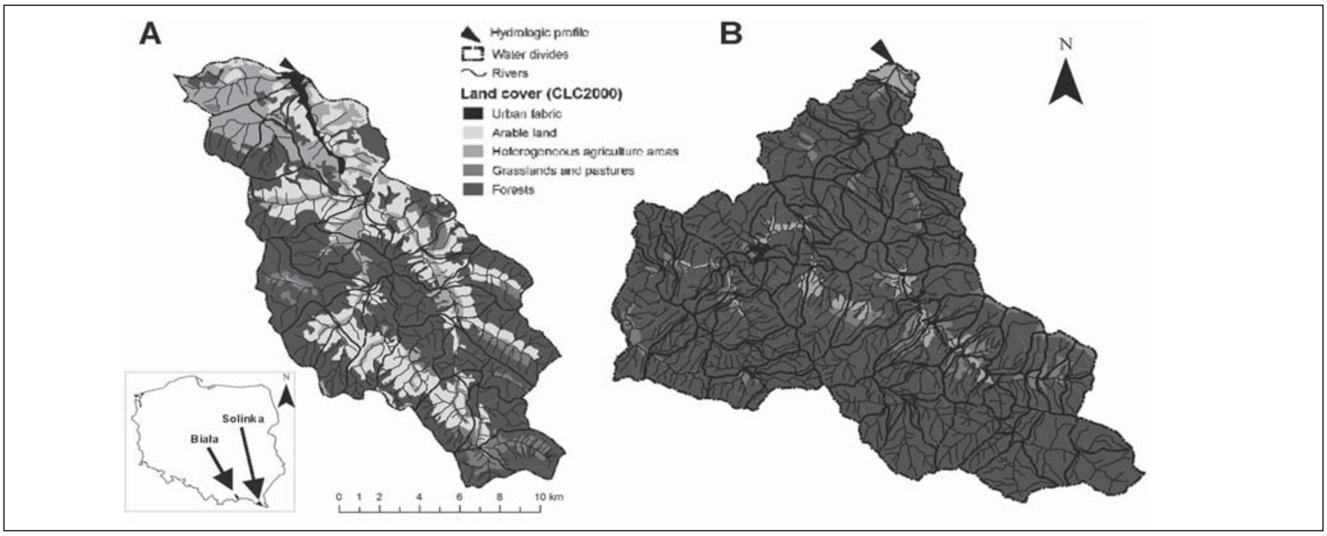

Figure 2: Investigated catchments: Biała Tarnowska/Grybów (A) and Solinka/Terka (B)

Abbildung 2: Untersuchungsgebiete: Biała Tarnowska/Grybów (A) und Solinka/Terka (B)

Table 1: Basic characteristics of modelled mountainous catchments

Tabelle 1: Eigenschaften der modellierten, alpinen Einzugsgebiete

Parameters		Biała Tarnowska / Grybów	Solinka / Terka
Catchment area	(km^2)	206.9	308.9
Max. elevation	(m a.s.l.)	990.0	1298.0
Min. elevation	(m a.s.l.)	327.0	432.0
Average slope of the main river valley	(‰)	10.0	15.0
Number of raingauges considered	(-)	8	7
Forests	(%)	53.3	91.0
Lakeness	(%)	0.0	0.0
Urban areas	(%)	1.1	0.2
Maximum discharge Q_{max}	($m^3 \cdot s^{-1}$)	369.0 (1961–1990)	418.0 (1961–1990)
Maximum specific discharge q_{max}	($dm^3 \cdot s^{-1} \cdot km^{-2}$)	1783.5	1353.2

Table 2: Physical parameters of rainfall – runoff model (as weighted average for the whole catchments) and the results of validation
Tabelle 2: Modellparameter des NA-Modells (gewichtete Mittelwerte) und Validierungsgüte

Parameter		**Biała Tarnowska / Grybów**	**Solinka / Terka**
Manning's – *M* 1)	$(m^{1/3}\cdot s^{-1})$	15	20
CN 2)	(-)	90	80
Number of subcatchments		34	97
Simulation period (calibration)		14.07.2001 – 20.07.2001	14.07.2001 – 20.07.2001
Simulation period (validation)		21.07.2001 – 30.07.2001	14.11.1992 – 25.11.1992
Linear correlation coefficient (R)	(-)	0.948	0.989
Root Mean Square Error (RMSE)	(-)	17.828	26.434

1) Reversed Manning's *n*
2) Coefficient *CN* according to SCS method (US Department …, 1972)

data.

In the model calibration process archival extreme precipitation episodes generating a flood wave of a low occurrence probability have been selected. As a rule, rainfall events producing the highest observed peak discharges have been taken into consideration. Spatially distributed precipitation input has been reconstructed using GIS (ESRI ArcGIS Desktop®). Modelling results have been evaluated on the base of real data using simple criteria such as correlation coefficient *R* and root mean square error *RMSE* (Table 2).

Second phase

In the second phase, real precipitation input has been replaced by synthetic data generated from 25 year (1956–1980) historical time-series (Stach, 2007), corresponding to the centroid of the catchment. Input, equal to daily precipitation total of 1% occurrence probability has been assumed (Figure 3). This has allowed the evaluation of runoff responses to theoretical extreme precipitation episodes in the case of both investigated catchments.

Third and fourth phases

Further analyses have considered projected daily precipitation totals in the next 90 year period, being a product of ECHAM4 GCM (extracted from the CMIP3 multi-model dataset). Adopted input data have been generated applying

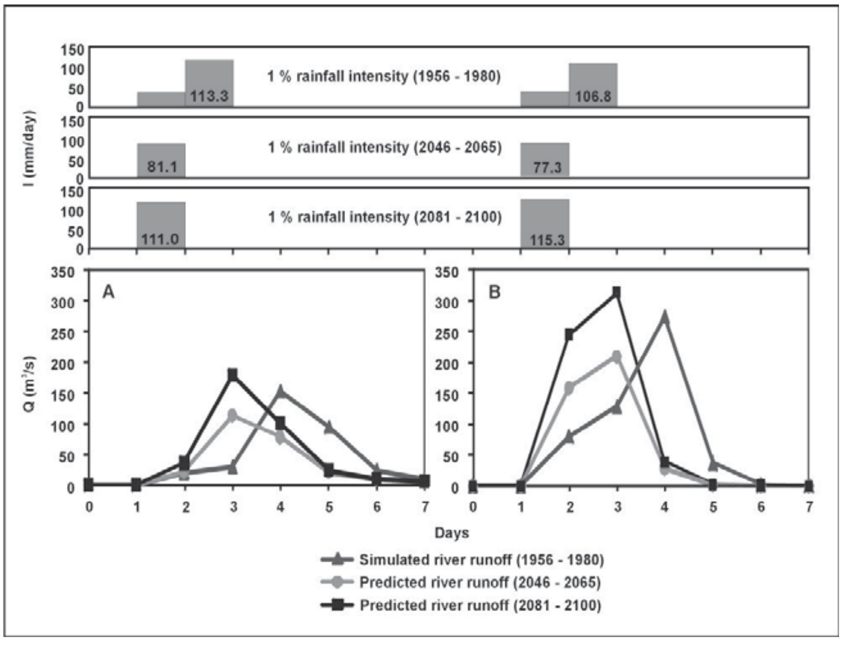

Figure 3: Simulation of river runoff after 1% rainfall total based at estimation for 1956–1980 and prediction of ECHAM4 GCM for 2046–2065 and 2081–2100 in the catchments: Biała Tarnowska at Grybów (A) and Solinka at Terka (B)
Abbildung 3: Abflussberechnung bei Niederschlägen mit 1% Auftrittswahrscheinlichkeit für die Zeitspannen 1956–1980, 2046–2065 und 2081–2100 für die Gebiete Biała Tarnowska/Grybów (A) und Solinka bei Terka (B)

the sustainable scenario of socio-economic development SRES1b that assumes stabilization of greenhouse gases concentration in the atmosphere at 720 p.p.m. (Nakičenovič and Swart, 2000; IPCC, 2007). On the base of ECHAM4 projections, daily precipitation totals of 1% occurrence probability, corresponding at the centroid of the investigated catchments have been estimated. This has enabled the evaluation of the catchment's response to theoretical extreme precipitation episodes produced by changing climate conditions in years 2046–2065 (IIIrd phase) and 2081–2100 (IVth phase).

Results

In the first phase detailed calibration of the physical model MIKE SHE has been performed. Validation using an independent dataset has confirmed that the model properly describes flood formation processes, reflects the shape of the flood hydrograph and estimates peak flow Q_{max} in the investigated catchments. Only the initial segments of the rising limbs in the simulated hydrographs seem to be underestimated due to an omission of groundwater runoff that forms the base flow.

In the second phase daily precipitation totals of 1% occurrence probability estimated on the base of 1956–1980 time-series have been assumed. According to the simulation results, precipitation inputs are transformed in the catchments into the floods with peak flows of slightly lower probability of occurrence. Hydrograph results from the simulations show that main factors controlling extreme flood formation currently are precipitation intensity and topography. The floods are more intense in the Solinka river catchment (A = 309 km^2), characterised by higher slopes and altitude. Moreover, daily precipitation totals with assumed probability of occurrence are always higher in this catchment than in the Biała Tarnowska river catchment (A = 207 km^2). Time of concentration is very short and comparable in both mountainous catchments, however the recession time in the Biała Tarnowska river catchment is longer.

In the third and fourth phases only precipitation input has been changed. According to ECHAM4 projections daily precipitation totals with 1% probability of occurrence will be significantly lower in years 2046–2065 and slightly higher in years 2081–2100 than in present. Over the next 90 years greater variability is predicted in the Solinka river catchment. In both cases predicted peak flows Q_{max} are higher for 2081–2100 and lower for 2046–2065 in comparison to the results of simulations for present conditions (IInd phase), however the time of concentration is still very short. Such projections show strong instability in the precipitation distribution and subsequent flood frequency in the coming decades.

Conclusion and remarks

If global warming is still increasing, the hydrological cycle will be significantly accelerated. In the next 80–90 years a stronger response of the investigated Carpathian catchments to the extreme rainfall events should be expected.

Table 3: Comparison of peak river discharge Q_{max} simulations in modeled catchments
Tabelle 3: Vergleich der berechneten Abflussscheitelwerte Q_{max} der Testgebiete

River peak discharge $(m^3 \cdot s^{-1})$	Biała Tarnowska / Grybów	Solinka / Terka
Q_{maxr}	129.00	254.00
Q_{maxsym}	84.50	176.80
Q_{max0} (1956–1980)	124.00	288.20
Q_{maxsym} / Q_{max0}	**0.68**	**0.61**
Q_{max1} (2046–2065)	111.30	208.60
Q_{max1} / Q_{max0}	**0.90**	**0.72**
Q_{max2} (2081–2100)	176.90	311.10
Q_{max2} / Q_{max0}	**1.43**	**1.08**

Q_{maxr} – measured river peak discharge used for validation of the model,
Q_{maxsym} – simulated river peak discharge obtained during validation of the model,
Q_{max0} – peak river discharge simulated as catchment's response for 1% rainfall generated using 1956–1980 data,
Q_{max1} – peak river discharge simulated as catchment's response for 1% rainfall generated using GCM ECHAM4 projection for years 2046–2065 (assuming SRES1b scenario),
Q_{max2} – peak river discharge simulated as catchment's response for 1% rainfall generated using GCM ECHAM4 projection for years 2081–2100 (assuming SRES1b scenario).

Higher variability and intensity of predicted precipitation will generate floods with higher peak discharges and shorter time of concentration by the end of 21st century, compared with events observed over the past years. Similar conclusions are confirmed by other authors (Hirabayashi et. al., 2008). An important question is the uncertainty and quality of applied models. In most cases the more processes and sub-catchments included in the hydrological model, the higher the quality of flood prediction. On the other hand, the use of a more "aggressive" scenario and efficient GCMs or a scenario-neutral approach (Prudhomme et al., 2010) may reveal even faster changes in extreme precipitations and flood frequencies, especially in mountainous catchments. More catchments, especially in lowlands, should be investigated in the future to compare expected hydrological response of various physiographic conditions to the projected climate change.

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