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# Climate change impact on hydrological processes in Lithuanian Nemunas river basin

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**Abstract** Climate change impact on hydrological processes in the largest Nemunas river basin of Lithuania has been estimated through combination of results from A1B, A2 and B1 emission scenarios and global climate models (ECHAM5 and HadCM3). Temperature and precipitation simulations from regional climate model were transferred to meteorological station sites using the delta change approach method. These climate scenarios were used as input data for HBV hydrological model. Projections of climate change impacts on hydrological processes were calculated with HBV for the periods 2011-2020, 2031-2040, 2051-2060, 2071-2080, and 2091-2100. The results were compared with baseline period 1975-1984. Projected changes in Nemunas river runoff are linked to changes of temperature and precipitation.

**Key words** *Climate change, hydrological modelling, the Nemunas River, discharge changes.*

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## INTRODUCTION

Water resources play significant role for most important economy sectors (water supply, agriculture, hydropower, tourism and transport) in Lithuania. The Nemunas river catchment covers a large part of Lithuania territory. The runoff of this river flows into the Curonian Lagoon and through the Klaipeda Strait into the Baltic Sea. Therefore changes in the distribution of the Nemunas runoff will have significant impacts on the state of these water bodies and Lithuania economy in general.

Some climate change impacts on hydrological processes have been observed already and further changes are projected. The main factors of climate influencing to the river runoff are temperature and precipitation. Global warming of the temperature by approximately 0.75 °C has been observed over the last 100 years (Trenberth *et al.* 2007) and in Lithuania – by 0.4-0.5 °C (Bukantis 2007). The impact of climate change on river discharge has been identified in the Nordic countries as well (Bergstrom *et al.* 2001; Hisdal *et al.* 2003; Lindström, Bergstrom 2004). The changes of river runoff of the Baltic States also have been investigated in general (Reihan *et al.* 2007) and also in individual national studies in Estonia and Latvia (Jaagus 1998; Klavins, Rodinov 2008). In Nordic and Baltic countries general stream flow changes show the redistribution of runoff throughout the year: a significant increase of winter discharge and a tendency for decreasing spring floods. More significant changes of river runoff have been forecasted in future because different emission scenarios project a further increase of global temperature of 1-6 °C (Meehl et al., 2007). Air temperature will rise in 21st century by 2-5 °C in Lithuania too (Rimkus *et al.* 2007).

River runoff is projected to increase in some regions and to decrease in others, exaggerating water resources problems in some catchments and alleviating them in others (Kundzewicz *et al.* 2008). On purpose to evaluate runoff changes are forecasted by modelling of hydrological processes according to different climate scenarios. Projected changes of runoff are described by many scientists (Beldring *et al.* 2008; Bergstrom *et al.* 2001; Hay *et al.* 2000; Lawrence *et al.* 2008; Rogozov, 2006). A shift in winter precipitation from snow to rain and temperature rise leads to change in timing of the peaks of stream flow in many regions (Kundzewicz *et al.* 2008). The spring snowmelt peak is brought forward and winter flows increase. Changes in flood and drought frequency and intensity are projected. Modelling the impact of climate change to river runoff was done by Lithuanian scientists too (Kilkus *et al.* 2006). In this research the time step of the model was one month, therefore it was impossible to project changes in runoff extremes (maximal and minimal discharge). Furthermore, new climate scenarios presented in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (Carter *et al.* 2007) give opportunities to evaluate the river runoff changes more exactly.

The aim of the present study is to assess the climate change impact on hydrological processes in the Nemunas river catchment and to compare projected runoff changes with results of Nordic and Baltic countries.

## METHODOLOGY

Climate change impact on hydrological processes has been evaluated using Global Climate Models (GCM), greenhouse gas emission scenarios, and hydrological modelling (Fig. 1). Projected changes in river runoff are linked to changes in the temperature and precipitations according to different climate scenarios in long-term perspective.

### Climate models

According to the latest IPCC Fourth Assessment Report (AR4) issues and GCM output data climate change predictions were done for the territory of Lithuanian. Max Planck Institute atmosphere-ocean general circulation model ECHAM5 (Roeckner et al. 2004) and the Hadley Predictions Centre model HadCM3 (Gordon et al. 2000) have been used for assessment of climate change impact on water resources in Lithuania. IPCC presented four narrative storylines (labeled A1, A2, B1, and B2) representing different demographic, social, economic, technological, and environmental developments that diverge in increasingly irreversible ways and result in different levels of green house gases emissions. Assumptions about future greenhouse gas emissions in Lithuania are based on A1B, A2, B1 greenhouse gas emission scenarios. The A1B marker scenario group assumes a balanced mix of technologies and supply sources, with technology improvements and resource assumptions such that no single source of energy is overly dominant. The A2 scenario family represents a differentiated world. Self-reliance in terms of resources and less emphasis on economic, social, and cultural interactions between regions are characteristic for this future. The central elements of the B1 future are a high level of environmental and social consciousness combined with a globally coherent approach to more sustainable development. In the B1 storyline, governments, businesses, the media, and the public pay increased attention to the environmental and social aspects of development. Technological change plays an important role (Carter *et al.* 2007; Nakicenovic *et al.* 2000).

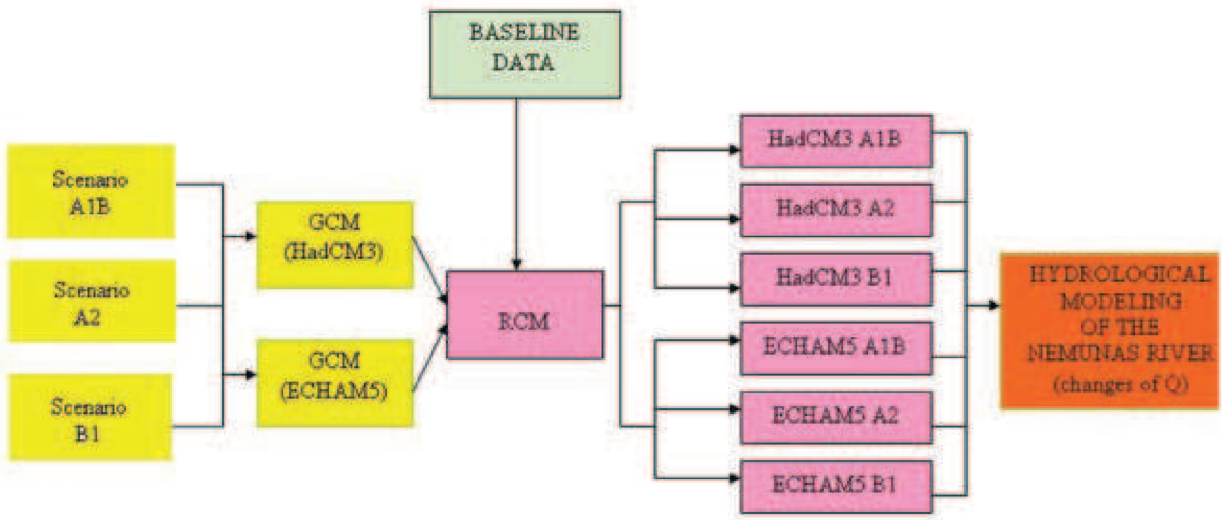


Fig. 1. Scheme of the evaluation of climate change impact on the river hydrological processes.

Primary dataset of predicted meteorological variables from general circulations models were formed from monthly means for the year from 2001 to 2100. Predictions of meteorological variables in 21st century are made for 16 meteorological stations across Lithuania. The prognostic values of variables (zonal (u) and meridional (v) wind component, air temperature, sea level pressure, precipitation) were derived from CERA database. Seasonal (for every season) algorithms were made by using the basic period from 1971 to 2000. Grid point data information (monthly means) was obtained from the NCEP / NCAR database (Kalnay *et al.* 1996). The scheme of the nearest grid points of Global Climate Models ECHAM5 and HadCM3 to Lithuanian territory is presented (Fig. 2). Resolution of HadCM3 is 2.5×3.75° of grid size and of ECHAM5 – 1.865×1.875°. On purpose to estimate the climate changes at Lithuanian territory downscaling is necessary from global models to local scale. A linear and multiple regression downscaling procedure made in order to get local scale of predictions. The linear regression method was used for air temperature forecast because data from meteorological stations and NCEP / NCAR data were very similar for all seasons and at all stations (correlation coefficient more than 0.95). Multiple regression algorithms were used for precipitation. Predictions of air temperature and precipitation were made using these relations for the years 2001 to 2100 for all 16 meteorological stations across the country.

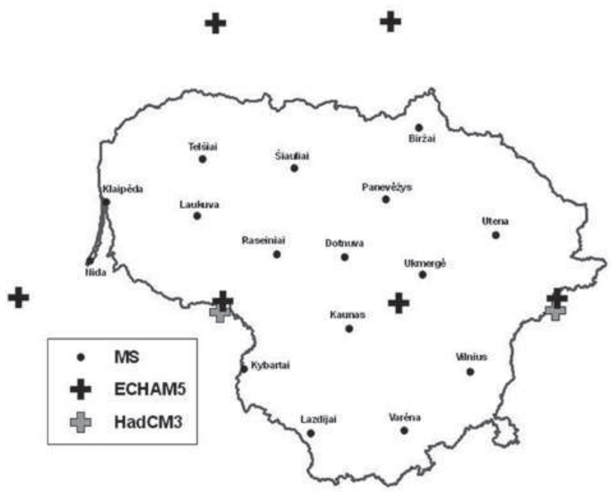


Fig. 2. Scheme of the nearest grid points of Global Climate Models ECHAM5 and HadCM3 to Lithuanian meteorological stations used in investigation.

Daily values of temperature and precipitation at measurement sites (meteorological stations) are traditionally used as input data to hydrological models. A common method for determination of climate change input to hydrological models is the delta change approach (Hay *et al.* 2000). Observed data from meteorological stations were used as background for prediction of daily meteorological data by climate scenarios. Monthly relative precipitation and temperature changes predicted by regional climate model were used to modify the observed daily meteorological data for baseline period. The predicted daily climate parameters for different scenarios are calculated according to:

$$T_{scen,d}(t) = T_{his,d}(t) + (\overline{T}_{scen,m} - \overline{T}_{his,m}),$$

$$P_{scen,d}(t) = P_{his,d}(t)\frac{\overline{P}_{scen,m}}{\overline{P}_{his,m}}.$$

Where: $P_{his,d}$, $T_{his,d}$ – historical daily data of precipitation and temperature in the baseline period, $P_{scen,d}$, $T_{scen,d}$ – predicted daily data of precipitation and temperature according to climate scenarios in the future period, $\overline{P}_{his,m}$, $\overline{T}_{his,m}$ – historical monthly data of precipitation and temperature in the baseline period, $\overline{P}_{scen,m}$, $\overline{T}_{scen,m}$ – predicted monthly data of precipitation and temperature according to climate scenarios in the future period.

The delta change approach reproduces the changes in monthly mean values from the control to the scenario period. The same monthly precipitation changes were used for all periods of the impact simulations. The number of precipitation days was not changed in the scenario climate. It means that there is the same number of days without precipitation in the baseline period and in the predicted periods according to scenarios.

**Hydrological model**

The observed meteorological and the regional climate model results transferred to meteorological station sites were used for the hydrological modelling. The semi-distributed conceptual HBV model developed at the Swedish Meteorological and Hydrological Institute (Bergstrom 1995) was applied to Lithuanian river catchments. The main model routines are calculation of precipitation and snow accumulation, snow fall distribution and runoff generation. These routines have components of snow accumulation, interception storage, soil moisture storage capacity, groundwater storage and runoff response, soil and lake evaporation. The HBV model is used to compute runoff from each subbasin. The inflow from each subbasin is added to flow through a river channel from the outlet of the upstream.

Calibration and validation of the HBV model were done according to observed daily discharge data series in the river catchment for baseline period. Observed daily precipitation and temperature time series from meteorological stations were used as an input data for calculations. The calibration procedure has consisted of changing the volume, snow, soil, response and damping parameters in a certain order (Integrated… 2005). The best values of calibration parameters could be selected using automatic parameter estimation routines (Lawrence *et al*. 2008).

There are some methods for evaluation of the calibration results. Calculation of the accumulated difference between the simulated and measured discharge was done according to (Integrated … 2005):

$$Accdiff = \Sigma(Q_c - Q_R) \cdot C_t,$$

Where: $Q_C$ – simulated discharge, $Q_R$ – measured discharge, C – coefficient transforming to mm over the basin, t – time.

Accumulated difference between the calculated and observed discharge could be expressed by bias (relative volume error). Bias measures the tendency of modelled values to be larger or smaller than the observed values. There is small difference between simulated and measured values when bias value approaches to zero.

Another method is calculating of variance $R^2$:

$$R^2 = \frac{\Sigma(Q_R - Q_{Rmean})^2 - \Sigma(Q_c - Q_R)^2}{\Sigma(Q_R - Q_{Rmean})^2},$$

Where: $Q_{Rmean}$ – mean observed discharge over the calibration period.

The HBV model has been calibrated normally if the $R^2$ ends up between 0.7 and 0.95. The accumulated difference between the calculated and the observed discharge has to be as less as possible. Exclusively the calibrated model could be used for hydrological modelling of river discharge according to climate scenarios.

## Study area and data

This study examined climate change impact on hydrological processes in the Nemunas River (to Kaunas cross-section). The location of the four subbasins and the sites of meteorological and hydrological stations are shown (Fig. 3). Selected subbasin characteristics are described (Table 1). According different types of rivers feeding and hydrological regime Lithuania is divided into three hydrological districts: Western, Middle and Southeastern. The Nemunas River is typical river of Southeastern region. It is natural regulated river with a prevailing subsurface feeding. The permeable sandy soils, that are widespread here, effectively absorb snowmelt and later gradually release, supplying rivers in the low water period. The annual runoff of the Nemunas is distributed rather equally – the part of the spring flood runoff is only from 20% to 30% of the total annual runoff. The variation of the Nemunas


Fig. 3. The Nemunas river catchment (to Kaunas) and the sites of meteorological (O) and hydrological stations (Δ).

Table 1. Characteristics of subbasin in the Nemunas River catchment.

| Subbasin cross–sections | Area (km²) | Subbasin land cover (%) | | | |
|---|---|---|---|---|---|
| | | Forest | Bogs | Fields | Lakes |
| Source of the Nemunas–Mosty | 24466 | 36.9 | 2.4 | 54.8 | 6.0 |
| Mosty–Druskininkai | 8712 | 37.0 | 2.5 | 54.3 | 6.2 |
| Merkys | 4293 | 35.4 | 17.7 | 38.9 | 8.0 |
| Druskininkai–Nemajūnai | 1070 | 36.2 | 0.0 | 63.8 | 0.0 |

river runoff is synchronic with the runoff of the rivers from Southeastern region (correlation coefficient R=0.71-0.87) and from Central region (R=0.60-0.90). The runoff of the Nemunas River has formed in these regions of Lithuania. The correlation with the rivers runoff from the Western region is smaller (R=0.44-0.69) (Kriauciuniene *et al.* 2006). Similar tendencies of variation of the Nemunas runoff and the rivers runoff of Central and Southeastern hydrological regions enable us to forecast the trends of the river runoff changes in the large part of Lithuanian territory according to results of the Nemunas river hydrological modeling in future.

The hydrological model of the Nemunas river was calibrated for four subbasins which boundaries are the source of the Nemunas – Mosty, Mosty – Druskininkai, catchment of the Merkys River, Druskininkai – Nemajūnai the Nemunas. Calibration of models was done for the period of 1975-1979 and validation - for period of 1980-1984. Simulated discharge values of river were compared with measured discharge values in four hydrological gauging stations (Mosty, Druskininkai, Merkys, and Nemajūnai). The results of variance $R^2$ and bias statistics for calibration and validation periods are presented (Table 2). High variance values (>0.70) and small relative volume error of calibration and validation periods enable us to use hydrological model to calculate the Nemunas runoff in the conditions of climate change.

Table 2. Results of the Nemunas hydrological model calibration and validation for 1975-1984.

| Hydrological station in subbasin | Calibration | | Validation | |
|---|---|---|---|---|
| | Variance R² | Bias | Variance R² | Bias |
| Mosty | 0.79 | 0.03 | 0.71 | 0.02 |
| Druskininkai | 0.81 | 0.04 | 0.76 | 0.00 |
| Merkys | 0.71 | 0.05 | 0.62 | -0.01 |
| Nemajūnai | 0.81 | 0.04 | 0.73 | 0.00 |

## RESULTS AND DISCUSSION

Calculations of the Nemunas river runoff according to climate scenarios were done in the periods of 2011-2020, 2031-2040, 2051-2060, 2071-2080 and 2091-2100. Calculation results were compared with the runoff characteristics in the baseline period of 1975-1984. Local downscaling results (time series of temperature and precipitation) were used as an input data to the Nemunas hydrological model. The resulting time series for each climate scenario were calculated using data of all meteorological stations in the river catchment. The hydrological model modified temperature and precipitation data from the meteorological station sites according to the simplified precipitation type classification and temperature lapse rates. Average time series of temperature and precipitation within the river catchment were used to compare these data according to climate scenarios with the baseline period data. Changes in mean values and standard deviation for daily temperature and precipitation were calculated from 1975-84 to 2091-2100 (Table 3). Most increasing of temperature was forecasted according to A2 gas emission scenario (4.4 -4.9 ºC) and the least increasing (2.6 -2.7 ºC) – according to B1. Predicted temperature changes according to various global climate models (ECHAM5, HadCM3) differ not significantly. Standard deviation of temperature shows a significant decrease of variability in climate scenarios to compare with the baseline period. There are no clear tendencies in changes of precipitation time series from 1975-84 to 2091-2100. Positive standard deviations of precipitation indicate that variability of precipitation in climate scenarios is more significant compared to the baseline period.

Table 3. Changes in mean value and standard deviations of daily temperature and precipitation from 1975-1984 to 2091-2100.

| Climate change scenario | Temperature | | Precipitation | |
|---|---|---|---|---|
| | Change in mean (ºC) | Change in standard deviation (ºC) | Change in mean (mm) | Change in standard deviation (mm) |
| HadCM3 A2 | 4.4 | -1.3 | 0.2 | 0.7 |
| HadCM3 A1B | 3.9 | -0.6 | -0.1 | 0.1 |
| HadCM3 B1 | 2.6 | -0.7 | 0.1 | 0.6 |
| ECHAM5 A2 | 4.9 | -1.4 | 0.2 | 0.6 |
| ECHAM5 A1B | 4.1 | -0.6 | -0.2 | 0.0 |
| ECHAM5 B1 | 2.7 | -0.7 | 0.1 | 0.6 |

The air temperature in the territory of the Nemunas catchment will rise intensively in the whole calculated period in comparison with the baseline period: in 2011-2020 - 0,8-1.2 °C, in 2031-2040 – 0.9-1.9 °C, in 2051-2060 – 1.6-2.5 °C, in 2071-2080 – 2.8-3.9 °C and in 2091-2100 – 2.6-4.8 °C (Fig. 4). The average air temperature will rise about 0.4 ºC in every 10-year period. The largest increase of the average temperature should be seen between the 2051-2060 and 2071-2080 periods (from the average temperature of 8.1 °C to 9.3 °C). It is forecasted that the average and minimal air temperatures will only have a tendency of rising in the 21st century and the maximal temperature will have the tendency of rising in the 2051-2060 and 2091-2100 periods. The tendencies in the other periods will be inconsistent. According to the HadCM3 A2 climate scenario, the highest maximal air temperature will be in the 2071-2080 period, meaning that the maximal temperature will rise 6.0 °C comparing to the maximal temperature of the baseline period.

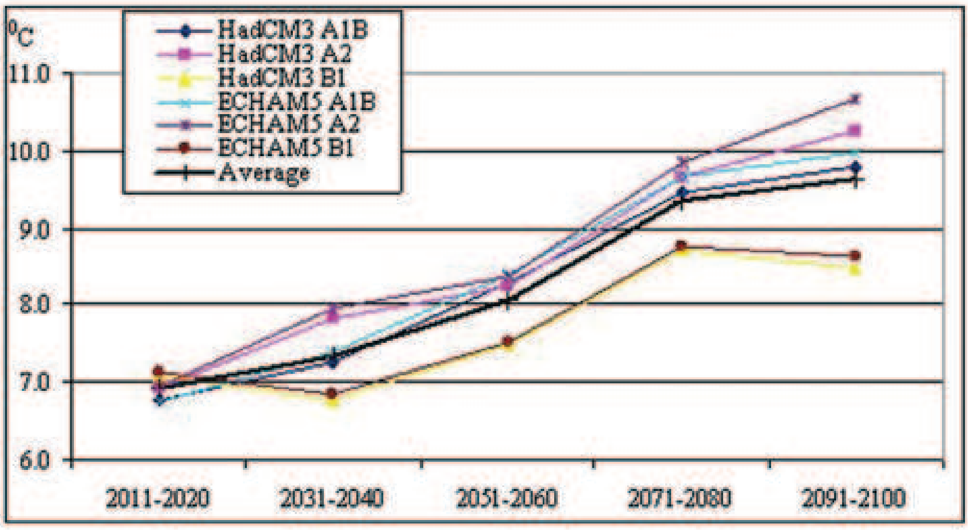

Fig. 4. Distribution of forecasted average annual temperature according to different climate scenarios in 21st century.

The changes of forecasted seasonal air temperature according to the climate scenarios are described (Table 4). The most significant changes of temperature will occur in winter season. During this season, the average temperature should rise for 3.4-6.9 °C in comparison with the baseline period. The changes of temperature in the spring season will not be so significant – it will only rise for 0.7-4.1 °C. March will be the month with the most significant changes in temperature. According to the ECHAM5 A2 climate scenario, the air temperature of March in the 2091-2100 period will rise for 6.1 °C in comparison with the baseline period. The temperature of summer will increase even less (1.1-3.4 °C). According to the ECHAM5 A1B climate scenario, July should be the month with the largest temperature (increasing for 4.1 °C in comparison with the temperature of the baseline period). The changes in the autumn season should be similar to those of the spring season – 1.6-4.0 °C. According to the A1B and B1 emission scenarios, the month with the most significant increase of temperature will be November. According to the A2 emission scenario, it will be October.

In the period of 2011-2100, it is forecasted that the air temperature will rise in all seasons of the year. The increase of air temperature will be the most intense in the winter season, and if the forecasts of the temperature being above zero come true, the probability of snowfall will decrease. The lowest forecasted changes of the temperature will be in the summer season. Quite considerable increase of air temperatures in spring and autumn seasons are likely. The largest changes of the average air temperature are given out according to A2 emission scenario. And the lowest changes are

Table 4. Changes of seasonal temperatures according to climate scenarios in fight periods comparing with the baseline period in 1975-1984, $^{0}$C.

| Period | Winter, $^{0}$C | Spring, $^{0}$C | Summer, $^{0}$C | Autumn, $^{0}$C |
|---|---|---|---|---|
| 2011-2020 | 1,9-4,5 | 0,0-1,2 | 0,5-1,1 | 0,7-1,6 |
| 2031-2040 | 3,5-5,9 | 0,5-0,7 | 0,0-1,2 | 1,6-2,1 |
| 2051-2060 | 2,9-4,8 | 1,2-2,5 | 1,5-2,5 | 0,6-1,7 |
| 2071-2080 | 5,5-8,3 | 1,3-3,3 | 0,0-3,0 | 2,0-4,0 |
| 2091-2100 | 4,4-8,1 | 2,0-4,1 | 2,1-3,4 | 2,0-3,4 |

possible according to B1 scenario. Meanwhile A1B stays intermediate.

When forecasting the change of river runoff, the amount and duration of precipitation are very important. Therefore, an analysis of six forecasted precipitation time series (composed according to the ECHAM5 and HadCM3 models and A1B, A2 and B1 emission scenarios) for the 2011-2020, the 2031-2040, the 2051-2060, the 2071-2080 and the 2091-2100 periods was made. Attained forecasts are compared to the precipitation values of the baseline (1975-1984) period.

Forecasted annual precipitation amount has various tendencies in five periods. The A2 emission scenario forecasts an increase of average annual precipitation amount by 77-98 mm and the B1 scenario – by 41-42 mm (Fig. 5). The largest changes of precipitation are forecasted by the HadCM3 model and A2 emission scenario. Meanwhile, according to the A1B emission scenario, a decrease of precipitation is forecasted by 55 mm. According to this scenario, the precipitation amount should intensively decrease in summer and autumn. Therefore, there will be an increased aridity in Lithuania in the second half of summer and in the beginning of autumn.

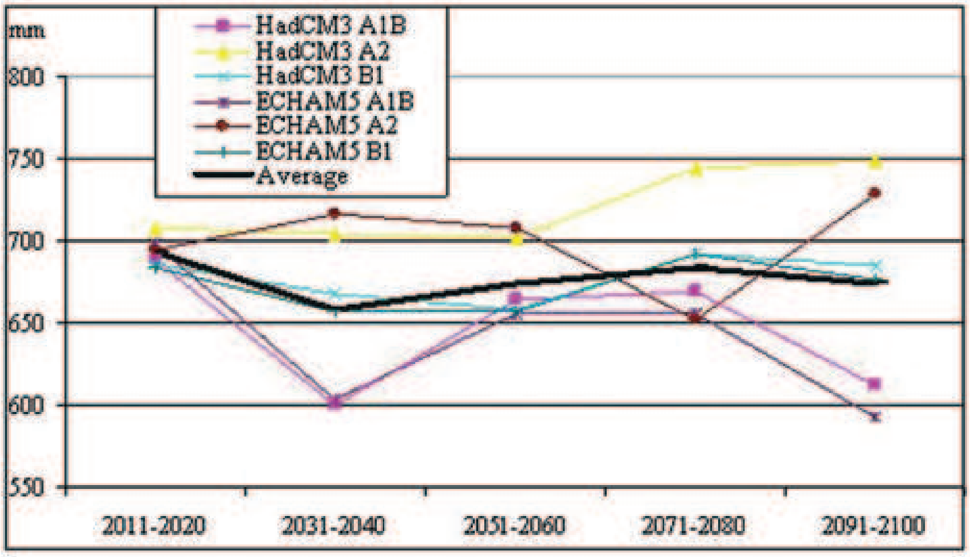


Fig. 5. Distribution of forecasted average annual precipitation according to different climate scenarios in 21st century.

The forecasted maximal day precipitation values have very variable tendencies of change in all seasons. In the 2011-2020 period only decreasing tendencies of maximal precipitation per day are forecasted, and in the other four periods both increasing and decreasing tendencies exist. According to the ECHAM5 A1B climate scenario, in the 2091-2100 period, the maximal precipitation amount per day should decrease by 9 mm in comparison with the baseline period. According to the ECHAM B1 scenario, it should increase by 9.3 mm.

The tendencies of precipitation change in various seasons were determined. In winter season, the precipitation amount should increase by 1-80 mm depending on the climate scenario and period. The highest increase of precipitation amount is forecasted by the HadCM3 A2 climate scenario in the 2091-2100 period. The increase precipitation should be the largest in December.

In the spring season, precipitation amount should increase too, but the increase won‘t be so significant (3-29 mm in comparison with the precipitation of baseline period). The highest precipitation amount in the spring season is forecasted by the ECHAM5 A2 climate scenario in the 2091-2100 period.

In summer season, the change of precipitation amount isn‘t so significant as in winter season. In this season, precipitation amount should decrease by 4-36 mm in comparison with the precipitation of the baseline period. According to the HadCM3 B1 climate scenario, the largest decrease of the precipitation amount is forecasted in the 2091-2100 period.

In the autumn season, there will be tendencies of both increase and decrease in the precipitation amount depending on model and emission scenario. The largest decrease of precipitation is forecasted by the A1B emission scenario in the 2091-2100 period (36-27 mm in comparison with the baseline period) and the largest decrease – by the HadCM3 A1B climate scenario in the 2051-2060 period (27 mm).

The most significant changes of precipitation are forecasted by the A2 emission scenario and the least significant changes of precipitation are given out by the B1 emission scenario. The exceptions are 2051-2060 and 2071-2080 periods. In these periods, the least significant changes of precipitation are forecasted by the A1B emission scenario. According to all of the climate scenarios, the largest increase if the precipitation amount is observed in the winter season, and not such an intensive increase - in the spring season. Also, all of the scenarios forecast the decrease of the precipitation in summer. The forecasted change of precipitation amount in autumn differs, but the average precipitation amount in the autumn season should be the one that changes the least.

Modelling of the Nemunas river runoff according to six climate scenarios was done for five periods (2011-2020, 2031-2040, 2051-2060, 2071-2080 and 2091-2100). The results of calculation show a decrease of the Nemunas river runoff (Fig. 6).

According to the HadCM3 A1B, HadCM3 A2 and ECHAM5 A2 climate scenarios in the 2011-2020 period, the spring flood will decrease and according to the ECHAM5 A1B climate scenario, the flood will not only decrease, but also occur around one month earlier. According to the ECHAM5 B1 climate scenario, the average maximal discharge of this period should be 411 $m^3/s$ and according to the HadCM3 B1 scenario - 419 $m^3/s$, when the maximal discharge of the baseline period (1975-1984) is 723 $m^3/s$.

According to two emission scenarios (A1B and B1) we forecast that in the 2031-2040 period the spring flood will decrease and according to the A2 emission scenario it will not only decrease, but occur earlier – in February. According to the A1B emission scenario, in the autumn and winter months the runoff will decrease intensely. The decreasing of maximal average discharge (381 $m^3/s$) in comparison with the baseline period is forecasted by the HadCM3 A1B climate scenario.

In the 2051-2060 period, according to all scenarios, the Nemunas river discharge decreases intensely and the spring flood not only moves to the earlier month, but also decreases greatly. The average maximal discharge will decrease the most according to the ECHAM5 A1B climate scenario, even by 415 $m^3/s$ in comparison with the baseline period.

The decrease of discharge is also forecasted in the 2071-2080 period. The largest decrease of discharge

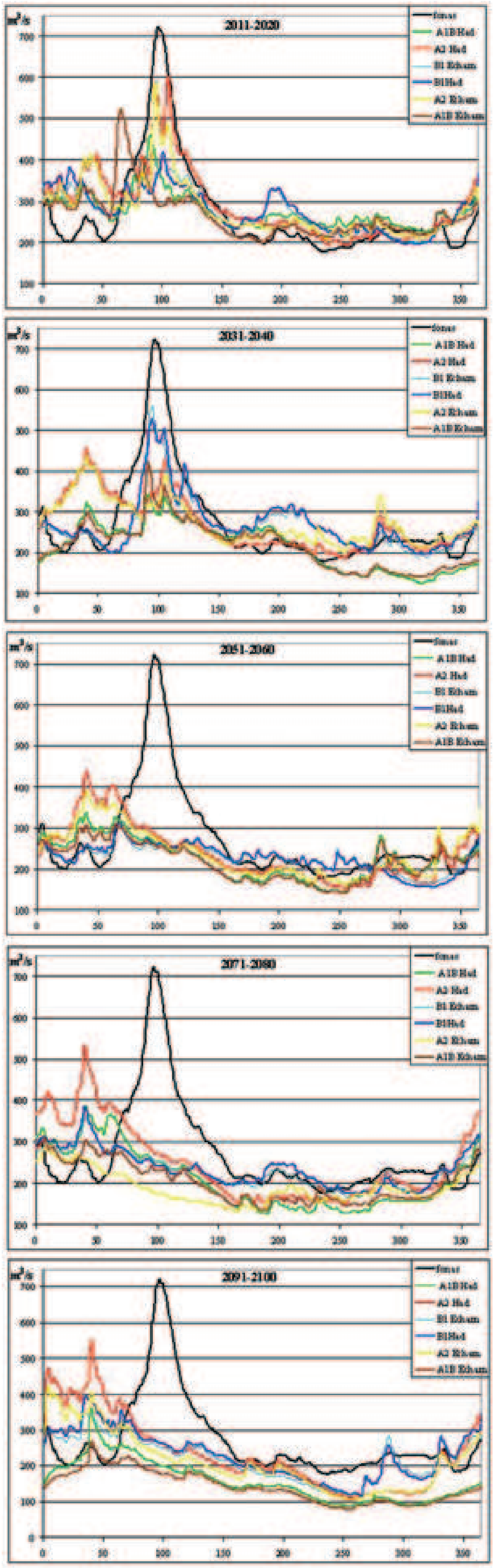


Fig. 6. Simulated mean daily discharge of the Nemunas river for periods of 2011-2120, 2031-2040, 2051-2060, 2071-2080 and 2091-2100 according to emission scenarios (A2, B1, A1B) and global climate models (HadCM3, ECHAM5) compared with discharge of baseline period of 1975-1984.

is forecasted by the HadCM3 A1B climate scenario. According to this scenario, the forecasted minimal discharge should be 125 m$^3$/s in the end of July, when the minimal discharge of the baseline period is 177 m$^3$/s in August. Also, all of the scenarios show that the flood will occur earlier and will be smaller.

In the 2091-2100 period, the largest decrease of discharge is forecasted. The minimal discharge value according to six scenarios would be 85-117 m$^3$/s (the minimal discharge value of the baseline period is 177 m$^3$/s). Also, a large difference is also seen between the maximal flood discharge values. According to various scenarios, they would range between 268 m$^3$/s and 551 m$^3$/s.

Average discharges of the Nemunas river will decrease the most according to the A1B emission scenario (Fig. 7.). The most distinct decrease of average discharges is forecasted in the 2091-2100 period. During this period, according to the ECHAM5 A1B climate scenario, discharges will decrease by 129 m$^3$/s in comparison with the baseline period and according to the HadCM3 A2 climate scenario – by 35 m$^3$/s.

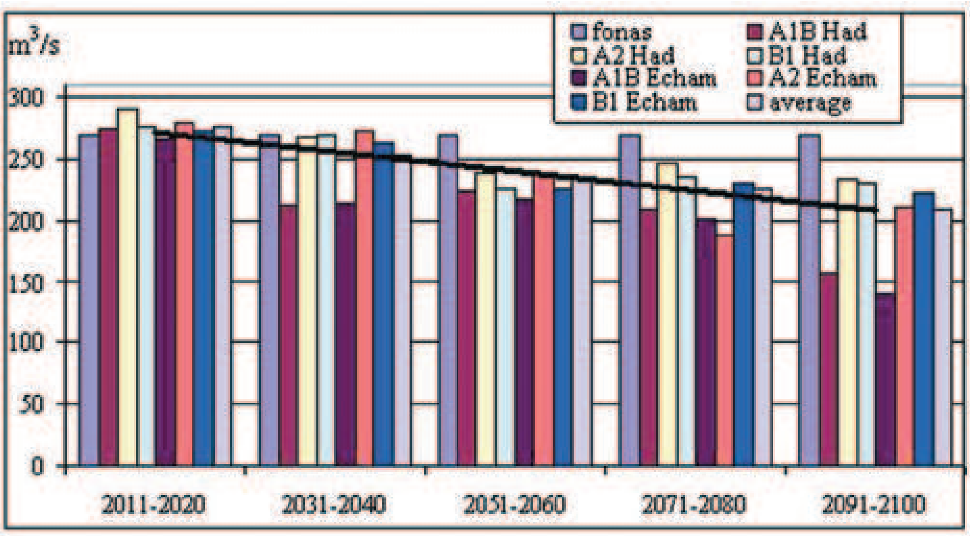


Fig. 7. Distribution of forecasted average annual Nemunas river runoff according to different climate scenarios in 21st century.

Average and extreme (maximal and minimal) river discharges will have intense decreasing tendencies depending on the emission scenario and the five forecasted periods. This proves the statement that in the 21st century the runoff of the Nemunas river in Lithuania will decrease. During all of the five forecasted periods the spring floods will occur earlier (averagely they will move to January-February). Also, the maximal flood discharge values will decrease intensely. The forecasted maximal average flood discharge values in various periods can be seen (Table 5). Minimal discharge values will decrease by 26-59 m$^3$/s. The largest decrease of average and extreme discharges should occur in the 2091-2100 period.

The changes of the Nemunas river runoff are forecasted in all seasons of the year. In the winter season, the discharges will increase by 68-100 m$^3$/s in comparison with the baseline period. The runoff will increase the most in this season in the first two periods (2011-2020 and 2031-2040). According to all of the emission scenarios, the largest increase of runoff will happen in February. In the spring season, the river discharges will decrease by 107-248 m$^3$/s in comparison with the baseline period. The largest decrease of the spring season discharges is forecasted in the 2071-2080 and 2090-2100 periods. River discharges of the spring season will decrease the most in May. In the summer season of the 2011-2020 and 2031-2040 periods, it is forecasted that the runoff will increase (by 50-66 m$^3$/s comparing with the baseline period). In the other periods (2051-2060, 2071-2080 and 2091-2100), it is forecasted that the runoff in the summer season will decrease. Discharges should decrease by 43-90 m$^3$/s in comparison with the baseline period. The largest decrease of summer season discharges is forecasted in the 2091-2100 period by the ECHAM5 A1B climate scenario. In the autumn season, the runoff tendencies are various. In this season, the river discharges of the 2011-2020 period should increase by 1-30 m$^3$/s in comparison with the baseline period. In the other periods (2031-2040, 2051-2060, 2071-2080 and 2091-2100), the discharges of the autumn season will decrease by 35-124 m$^3$/s in comparison with the baseline period.

When summarizing the forecasted changes of seasonal runoff, the fact that the largest changes are forecasted in the winter and spring seasons should be emphasized. In all the periods, the runoff of winter season will increase and the spring season runoff will have decreasing tendencies. The winter season runoff will increase the most in February and the spring season runoff will decrease the most in May. The largest changes of both seasons are forecasted by the A2 emission scenario. In summer and autumn seasons, the runoff will have both increasing and decreasing tendencies.

Modelling of climate change impact on hydrological processes in the river basins was done in Nordic and Baltic countries. The different emission scenarios and global climate models were used to forecast river discharge changes though the common patterns of changes have been described. A change in the seasonality of

Table 5. Forecasted maximal average discharges according to climate scenarios in different periods, $m^3/s$.

| Climate scenario | 2011–2020 | 2031–2040 | 2051–2060 | 2071–2080 | 2091–2100 |
|---|---|---|---|---|---|
| Baseline period | 723 | 723 | 723 | 723 | 723 |
| HadCM3 A1B | 460 | 342 | 336 | 387 | 361 |
| HadCM3 A2 | 597 | 456 | 438 | 534 | 551 |
| HadCM3 B1 | 419 | 527 | 310 | 386 | 398 |
| ECHAM5 A1B | 522 | 420 | 309 | 311 | 268 |
| ECHAM5 A2 | 587 | 437 | 392 | 286 | 422 |
| ECHAM5 B1 | 411 | 560 | 308 | 362 | 351 |

river flow, as timing and amount of snow accumulation and melt is forecasted in all countries (Climate… 2007; Beldring *et al.* 2008). The winter will be less stable which will be a reason of increasing of winter season runoff. Decreasing of spring flood will be typical for all countries too. The annual river runoff in the most river basins of Nordic countries will have the increase tendency whereas the increasing and decreasing tendencies of runoff are forecasted in Latvian river basins (Rogozova 2007). All GCMs show increase in precipitation in Nordic countries and relatively small changes of its rate in Nemunas River basin (South-eastern Baltic region). The decreasing of the annual Nemunas river runoff is predictable in future. On purpose to evaluate the runoff changes in all main river catchments of the Baltic Sea region the hydrological modeling has been done according to the same methodological conditions (emission scenarios, global climate model scenarios, the time periods, hydrological model). Only uniform methodology enables us to compare results from different countries and to reduce uncertainty in evaluation of river runoff changes.

## CONCLUSIONS

In this study the projections of climate change impacts on hydrological processes are based on scenarios from two global climate models (ECHAM5, HadCM3), three emission scenarios for greenhouse gases (A2, A1B, B1) and the delta change approach method for transferring the climate change signal to meteorological station sites. A forecast of the Nemunas river runoff in the 21st century was made with a calibrated and verified HBV hydrological model. The average annual runoff should decrease.

During the century, the runoff would decrease by 41% according to the A1B emission scenario, because according to this scenario, the air temperature would increase the most and the precipitation would stay unchanged, in comparison with the other scenarios. The decreasing of runoff should be determined by high temperatures (the chance of snowfall decreases, only minimal cover of snow is possible). Therefore, according to the A1B emission scenario, the largest decrease of the spring flood maximal discharges is forecasted.

According to the A2 emission scenario, a smaller decrease of the Nemunas river runoff is forecasted (during the century, only by 17% in comparison with the baseline period). According to the A2 emission scenario, the largest amount of precipitation is forecasted, whereas the changes of air temperature will be similar to those of the A1B emission scenario. Therefore, according to the A2 emission scenario, the river runoff will be supplemented by more precipitation and will be larger than according to the A1B emission scenario.

In the winter season, the runoff will increase and in the spring season it will decrease according to all of the emission scenarios. In the summer and autumn seasons, the runoff will have both increasing and decreasing tendencies. The emission scenarios have much bigger influence for forecasting of the Nemunas river runoff than the global climate models. In the 21st century the discharge changes in the rivers of the Central and Southeastern regions of Lithuania could have the same pattern as the modeled changes of the Nemunas river discharge according to climate scenarios.


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