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Climate change impacts on river runoff in Latvia

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ABSTRACT: In order to assess climate change impacts on river runoff patterns at the end of this century, the hydrological model METQ2007BDOPT was applied to 8 river basins and sub-basins in Latvia, which is a part of the southeast Baltic Sea basin. The climate data we used originate from the PRUDENCE project and were prepared in a separate study. Changes in hydro-climate were analysed using one control run (1961–1990) and 2 IPCC scenario runs (A2 and B2; 2071–2100). For the A2 scenario, both annual and seasonal analysis predicted the major significant changes in most cases. For both scenarios, an increase of the mean annual climate data (air temperature, precipitation and evapotranspiration) is forecast, whereas the mean annual river runoff is predicted to decrease. The seasonal runoff pattern is expected to change towards significantly higher runoff during winter, following a decrease in spring and autumn. Maximum river discharge will occur in winter instead of spring. No considerable change in streamflow is predicted for summer. Future climate will change, leading to modifications in the river runoff regime and the shape of the hydrograph, which will be similar to that of the present Western European rivers, i.e. 2 principal periods instead of 4: one with high flow, mostly falling in the cold period of the year; and one with low flow, mostly in the warm period.

KEY WORDS: Climate change · River runoff · Scenario · Hydrological model · Baltic Sea basin

1. INTRODUCTION

The rise of the global temperature has a serious impact on the global hydrological cycle at various spatial and temporal scales. Mean annual temperature over the last century has increased at a higher rate in the Baltic region (0.10 to 0.07°C decade^{-1}) than globally (0.05°C decade^{-1}). Different emission scenarios forecasted an increase of the global temperature by 1 to 6°C (Meehl et al. 2007) during the 21st century, whereas in the Baltic Sea basin the predicted rise of temperature is 3 to 5°C on average (Bolle et al. 2008). Traditionally, climate change impact studies on water resources include identification of natural climate variability, detection of climate signals in historical data, elaboration of possible climate scenarios (Hisdal et al. 2006) and simulation of hydro-meteorological processes for the particular catchment using various hydrological models. The impacts of climate change on river runoff in the Baltic Sea basin over the past millennium have been widely studied (e.g. Graham et al. 2009). Hydro-meteorological trends over the last 100 yr were identified (e.g. Hisdal et al. 2003, Reihan et al. 2007) and changes were predicted in river runoff patterns in the future (e.g. Rummukainen et al. 2003, Graham et al. 2007, Bolle et al. 2008, Jacob & Lorenz 2009, Kjellström & Lind 2009). This includes identification of extreme events, such as floods and droughts (e.g. Dankers et al. 2007, Graham et al. 2007). In recent studies, attention has been paid to the identification and assessment of possible uncertainties (e.g. Bergström et al. 2001, Graham et al. 2007, Bolle et al. 2008).

Concerning the Baltic States in the southeastern Baltic Sea basin, early studies by Jaagus et al. (1998) in Estonia, by Butina et al. (1998) in Latvia and by Kilkus et al. (2006) in Lithuania have predicted an increase in the annual river runoff. At the same time, in Latvia (Rogozova 2006) both increasing and decreasing trends in annual river runoff were identified for 2 river basins. The latest study was done by Kriaučiūnienė et al. (2008) for the Nemuna River in Lithuania. They used the data series for future climate scenarios presented in the Fourth Assessment Report of the IPCC (Carter et al. 2007) in order to evaluate the river runoff changes more precisely and concluded that, in the 21st century, the annual runoff of the Nemuna River in Lithuania will

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decrease. Such new studies are missing as yet for Estonian and Latvian future river runoff patterns.

The present study is a part of the national research program Climate Change Impact on Water Environment in Latvia, KALME, from 2006 to 2009 (http://kalme.daba.lv), which aimed to carry out a simulation of hydrological processes in different river basins and to forecast climate change impacts on river runoff patterns in future according to different emissions scenarios in Latvia. A commonly used strategy is to simulate climate change impacts on water resources off-line, using hydrological models, from differences between a climate model control run, which represents the present climate, and a scenario run (Bergström et al. 2001). Therefore, in this study we used the conceptual rainfall-runoff model METQ2007BDOPT, originally developed using Latvian catchments. The hydrological model was calibrated from 1961 to 1990 and validated from 1991 to 2000 for 8 river basins and sub-basins. Climate changes are predicted by the regional climate model (RCM) Rossby Centre Atmosphere Ocean (RCAO) applied for the 2 IPCC scenarios A2 and B2 and run for the 30 yr time slices 1961 to 1990 (control period) and 2071 to 2100 (scenario period). Scenario A2 is a high emissions scenario in comparison with B2 and was chosen for this study to illustrate the worst-case situation. We used climate data series as a forcing for a hydrological model prepared by Seņņikovs & Bethers (2009) (KALME). The above climate data series originated from the framework of the European Commission research project Prediction of Regional Scenarios and Uncertainties for Defining European Climate Change Risks and Effects (PRUDENCE) (Christensen et al. 2007). The RCM RCAO was selected, with driving boundary conditions from the global general circulation model (GCM) HadAM3H, because it was the most representative model for Latvian conditions. As the spatial resolution of the RCMs was too coarse for direct application of the RCM output in the hydrological model, a method of RCM data correction based on shifting the occurrence distribution of an individual daily output was used. A brief description of prepared climate data for this study is given in the 'Materials and methods'. The aim of the present study is to analyse and discuss the following: model calibration results; changes in mean annual, seasonal, monthly and extreme hydro-climate data; and data and modelling uncertainties.

2. MATERIALS AND METHODS

2.1. Study river basins

This study focuses on 5 river basins (Imula, Bērze, Iecava, Vienziemīte and Salaca) and 3 sub-basins of the Salaca basin (Briede, Seda and Rūja), which differ in size, natural conditions and human impact. Locations and characteristics are presented in Fig. 1 and Table 1. In the framework of KALME, selection of river basins was primarily based on future nutrient flows. The Bērze and Vienziemīte basins are included in the agricultural runoff monitoring scheme. The Bērze River basin is located in the central part of Latvia, where climatic conditions and fertile soils are very suitable for the most intense agricultural production in the country. In total, agricultural lands cover 66% of the

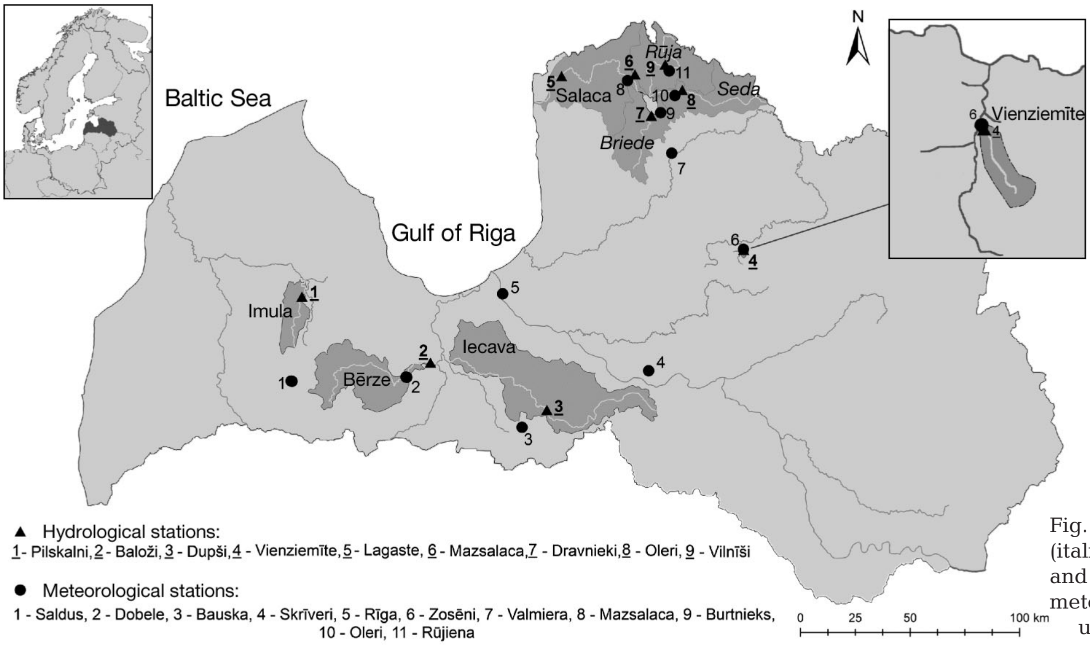

Fig. 1. River basins (italic text: sub-basins) and hydrological and meteorological stations used in the study

Table 1. Characteristics of the studied river basins. Long-term mean discharge was calculated using data from 1961 to 1990. Values for agricultural lands include land use values for arable lands, as well as e.g. pastures and fallowed lands

River basin, hydrological station	Total drainage area (km^2)	Studied drainage area (km^2)	Long-term mean discharge (l s^{-1} km^{-2})	Land use (%) Agricultural/ arable lands	Forests	Bogs	Lakes
Imula, Pilskalni	263	232	7.46	57/26	42	1	0.5
Bērze, Balloži	904	904	5.73	66/45	31	1	0.9
Iecava, Dupši	1166	566	6.43	35/15	62	3	0.5
Vienziemīte, Vienziemīte	5.92	5.92	9.63	66/1.2	13	0.05	0
Salaca, Lagaste	3420	3220	9.53	35/21	45	13	6.7
Briede, Dravnieki	449	369	9.21	39/18	50	9	1.1
Seda, Oleri	542	431	8.35	31/16	53	14	0.5
Rūja, Vilnīši	962	729	7.82	45/26	50	5	0.1

area, of which 45% comprises arable lands. In other basins, agricultural production is less developed. The smallest drainage basin, the Vienziemīte Brook, is located in the Vidzeme Upland, 176 m above sea level, and covers approximately 6 km^2. The Salaca River basin is the largest studied basin and it is part of the North Vidzeme Biosphere Reserve, where human activities are limited. Its total drainage area is 3220 km^2, of which 62% is occupied by the catchment of the lake Burtnieks. Forests cover 45% and bogs account for up to 13% of the territory. The streams Vienziemīte, Imula and part of Bērze can be characterised as upland rivers and the others as lowland rivers.

2.2. The hydrological model

During the last 20 yr, several versions of mathematical models of hydrological processes have been developed in Latvia: METUL (Krams & Zīverts 1993), METQ96 (Zīverts & Jauja 1996), METQ98 (Zīverts & Jauja 1999), METQ2005 and METQ2006, and the latest version of the METQ2007BDOPT with semi-automatic calibration performance (Apsīte et al. 2008). The METQ model is successfully applied to both small and relatively large catchments in Latvia, namely Vienziemīte Brook (drainage area 5.92 km^2) and the Daugava River (drainage area 81 000 km^2), respectively (Zīverts & Jauja 1999).

Similarly to previous versions, the METQ2007 BDOPT is a conceptual rainfall–runoff model describing the hydrological system in a catchment by routing water with a daily time step through 3 linear conceptual reservoirs: snow (water content in snow cover), soil moisture (water in root zone) and groundwater (Fig. 2). The total runoff consists of 3 components: Q_1 is the surface runoff, Q_2 is the subsurface runoff from the groundwater upper zone and Q_3 is the base flow, i.e. runoff from the groundwater lower zone. Runoff routing can be simulated by applying simple hydrological methods, e.g. modifications of the unit hydrograph approach (Zīverts & Jauja 1999). If there is a lake or a reservoir in the catchment and it considerably influences the hydrological regime of the river, the hydraulic runoff routing is required (Apsīte et al. 2008). It is assumed by Zīverts & Jauja (1999) that water evaporates only from the upper layer of land, i.e. from the snow and root zone, and evapotranspiration is proportional to vapour pressure deficit, which is empirically estimated as the multiplication of the daily mean air vapour pressure deficit and the bioclimatic coefficient. The latter depends on the development of plants and climate characteristics. The model has 23 parameters, but most of them can be maintained unchanged for different river catchments. In general, the structure and simulation of hydrological processes of the METQ model are similar to that of the HBV model (Bergström

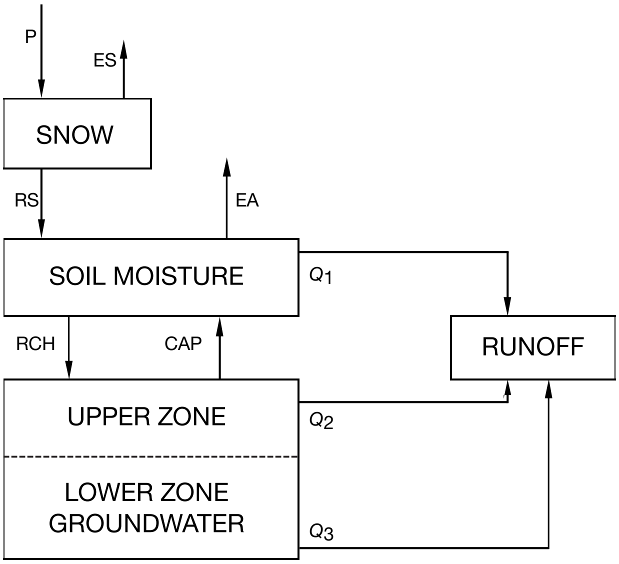

Fig. 2. General structure of the hydrological model METQ (Zīverts & Jauja 1999). CAP: capillary flow; EA: evapotranspiration from root zone; ES: evaporation from snow; P: precipitation; RCH: recharge to groundwater; RS: rain and snow-melt water; Q_1: surface runoff; Q_2: subsurface runoff; Q_3: base flow

1992) developed at the Swedish Meteorological and Hydrological Institute. The main difference between them is that the degree-day (°D) ratio does not have a constant value for snow melting in METQ, and it has a temporal difference depending on the daily potentional insolation of each particular day. The degree-day consists of 2 parts: the constant part and the changing part (radiation), which depends on solar radiation. The influence of the radiation part to the total value of the degree-day ratio is higher in open areas than in the forest. A more detailed description of the model METQ is presented elsewhere (Zīverts & Jauja 1999, Apsīte et al. 2008).

2.3. Calibration and validation data and statistical methods

The observed daily mean air temperature (°C), precipitation (mm) and vapour pressure deficit (hPa) at 11 meteorological stations (MSs) as well as the daily river discharge (m^3 s^{-1}) and water level (m) of Lake Burtnieks at 9 hydrological stations were used as input data for the model. The locations of the utilised stations are shown in Fig. 1. The calibration period of the hydrological model for the particular river basin is from 1961 to 1990 (the same as for the control run period in RCM climate data). The calibration period covers the 5 wettest (1962, 1978, 1980, 1981 and 1990) and 3 driest (1964, 1969 and 1976) years in Latvia over the last 100 yr (see Fig. 4). The validation period from 1991 to 2000 covers one wettest year (1998) and one driest year (1996).

For hydrological model performance assessment, a time series of at least a 5 yr period of daily river discharge should be used for calibration. The Nash–Sutcliffe model efficiency coefficient (E) and the Pearson correlation coefficient (r) were used. The Nash–Sutcliffe model efficiency coefficient was introduced by Nash & Sutcliffe (1970) and is commonly used in hydrological modelling. This efficiency criterion measures the proportion of the total variance of the observed data explained by the predicted data and is defined as:

$$E = \frac{\sum (Q_{\text{obs}} - \overline{Q}_{\text{obs}})^2 - \sum (Q_{\text{sim}} - Q_{\text{obs}})^2}{\sum (Q_{\text{obs}} - \overline{Q}_{\text{obs}})^2} \quad (1)$$

where Q_{obs} is observed discharge, Q_{sim} is simulated discharge and $\overline{Q}_{\text{obs}}$ is mean Q_{obs} over the calibration period. Nash–Sutcliffe efficiencies can range from negative infinity to 1. A perfect model would result in an E equal to 1. However, normally the E ends up somewhere between 0.8 and 0.95. Naturally, this is only the case when there are good quality input data (IHMS 2008). The coefficient r is dimensionless and ranges from –1.0 to 1.0 inclusive, reflecting the extent of a linear relationship between 2 data sets. Essentially, the closer r is to 1, the more accurate the model.

The *t*-test at the significance level $p < 0.05$ (Sokal & Rohlf 1995) was used to compare mean annual, seasonal and monthly values of the mean and maximum discharge; mean, minimum and maximum temperature; mean vapour pressure deficit; and amount of precipitation between the control and scenario run of the 30 yr period. The 95 % confidence intervals were calculated for the hydro-climate data values using the Student's *t*-test, with the software R (version 2.12; R Development Core Team 2010).

2.4. Climate data and uncertainties

As a forcing for the hydrological model to predict river runoff changes according to present and future climate conditions, we used daily time series of climate data (air temperature, precipitation and vapour pressure deficit) prepared by the Laboratory for Mathematical Modeling of Environmental and Technological Processes, University of Latvia.

The collection of RCM calculations organised in a web-accessible database at the Danish Meteorological Institute under the European Commission Framework Programme 5 research project PRUDENCE EVK2_CT2001-00132 (http://prudence.dmi.dk) were considered and analysed by Seņņikovs & Bethers (2009). The horizontal resolution of the analysed models was approximately 50 km and the temporal resolution was 1 d. The RCMs provide meteorological parameters at each grid point. Each considered model run contained at the least calculations for both the control run and the emission scenarios run. More details on the RCMs and their results can be found in Jacob et al. (2007) and Christensen & Christensen (2007).

In the study by Seņņikovs & Bethers (2009), the size of the considered domain covering the east coast of the Baltic Sea was approximately 600 × 600 km. The performance of 21 model runs for the control run of the period 1961–1990 was analysed by statistically comparing air temperature and precipitation rates with observations at 118 MSs for the same period. Overall, all models reasonably represented the seasonal cycle of temperature, though they overestimated winter precipitation and underestimated summer precipitation in the study area. Therefore, a bias correction method of RCM data was developed, based on shifting the occurrence distribution of individual daily meteorological parameter (temperature or precipitation). Two cumulative distribution functions — one of the observed data, and one of the RCM data — were constructed for each day of the year, for each parameter in each observation station. The correction function was constructed in a way to have equal probabilities of a particular daily parameter for both observed and corrected RCM data. The correction functions were spatially interpolated, allowing the creation of modified RCM data for both the control and scenario runs.

Major uncertainties in climate data series are related to uncertainties caused by combination of RCMs and GCMs (Jacob et al. 2007, Graham et al. 2007). Seņņikovs & Bethers (2009), who are the authors of the developed climate data modification method, consider that it provides a possibility to minimise uncertainties, which can be caused if the data, which are taken directly from the RCM, are used as input data in the hydrological model. Performance analysis (i.e. comparison of monthly statistical parameters of observed data with corrected RCM data at a selected station) of the statistical bias correction method has shown that statistical moments of distribution of temperature and precipitation were corrected. At the same time, the interannual variability — as well as temperature–precipitation cross-correction properties — cannot be significantly improved by such bias correction as the former are inherited from the RCMs. However, the proposed approach of RCM data modification allows the changing of modelled temperature and precipitation time series for the control period in such a way that the characteristics are preserved over a short (30 yr) time scale, at the same time having the statistical properties of the observed data. The time series for the future climate scenarios were obtained assuming that the histogram modification algorithm is the same for present and future climate. For example, in the modified climate data time series, the number of days with precipitation in the future climate scenarios is maintained equal to the number of such days within the control period. Another possible uncertainty is connected with land-use data in studied catchments. It is difficult to forecast the change in land-use in the future; therefore, these data have been maintained equal to the used hydrological model calibration (RCM control run period) and 2 IPCC scenario runs (A2 and B2) for the period 2071–2100.

On the basis of previous results (Seņņikovs & Bethers 2009), we selected the RCM RCAO run by the Swedish Meteorological and Hydrological Institute with driving boundary conditions from the GCM HadAM3H. Assumptions about future greenhouse gas emissions in Latvia are based on the IPCC A2 and B2 scenarios (Nakicenovic et al. 2000).

Evapotranspiration is one of the critical components of the water balance for the rainfall-runoff model, and is represented by vapour pressure deficit. It was not possible to estimate this meteorological parameter directly from the RMC data set. Therefore, vapour pressure deficit was calculated based on the simplified equation by Murray (1967). In order to calculate daily vapour pressure deficit based on temperature values for a separate climate scenario, the equation was tested using daily observations of relative humidity, temperature and vapour pressure deficit for the control period. Further, the bias correction method for each day of the year was used for data from each observation station.

In all cases, the climate data series used in our study are denoted as follows: control represents the control run for the period 1961–1990 and characterises present climate conditions; A2 and B2 represent scenario runs for the period 2071–2100 and the forecast future climate conditions. All climate data series were prepared for the MSs involved in our study.

3. RESULTS

3.1. Calibration and validation of the rainfall–runoff model METQ

The conceptual rainfall-runoff model METQ2007 BDOPT was calibrated and validated for 8 river basins and sub-basins (Fig. 1). The calibration results present quite a good fit between the observed and simulated daily discharges for river basins of different size, where *E* values vary from 0.52 to 0.86 and r values vary from 0.75 to 0.93 (Table 2). The best coincidence was obtained for the smallest river basin Vienziemīte and also the largest river basin Salaca (Fig. 3). The lowest values were found for the River Rūja. However, in the case of the Salaca River basin and sub-basins better coincidence between the simulated and observed daily discharges for the model validation period was

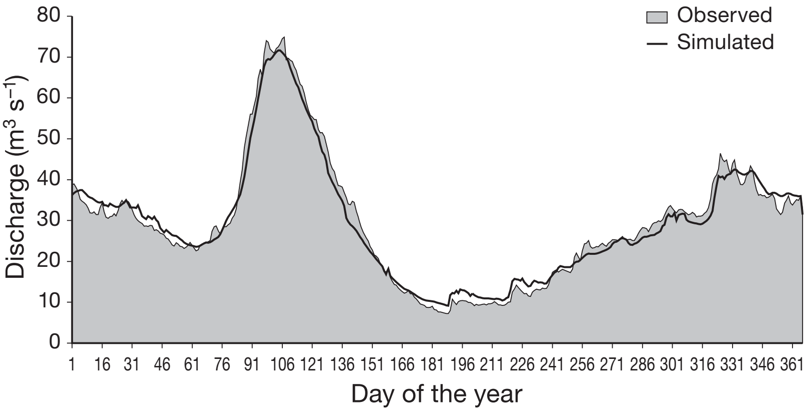

Fig. 3. Observed and simulated long-term mean daily discharge at the hydrological station Salaca-Lagaste for the entire calibration period (1961–1990)

Table 2. Results from Nash–Sutcliffe model efficiency (*E*) and correlation (r) analyses for the studied river basins

Hydrological station	Calibration period (1961–1990)		Validation period (1991–2000)	
	E	r	*E*	r
Imula-Pilskalni[a]	0.66	0.77	0.63	0.75
Bērze-Baloži	0.72	0.85	0.69	0.80
Iecava-Dupši[a]	0.66	0.82	0.64	0.79
Vienziemīte	0.86	0.91	0.83	0.90
Salaca-Lagaste	0.80	0.93	0.87	0.95
Briede-Dravnieki	0.69	0.85	0.72	0.87
Seda-Oleri[b]	0.60	0.81	0.62	0.87
Rūja, Vilnīši[c]	0.52	0.75	0.57	0.77

[a]Closed since 1995; [b]Operating since 1979; [c]Operating since 1978

obtained ($E = 0.57$ to 0.87, $r = 0.77$ to 0.95). One of the drawbacks of calibrating a daily model against observations is that the resulting hydrographs tend to be somewhat smoothed, as runoff peaks are dampened in the model, while low flows tend to be overestimated.

The simulations of the wettest and driest years also showed quite a good fit with observed mean annual discharges, e.g. of the Salaca River basin (Fig. 4). Although some mean annual discharge values of an extreme year are a little overestimated or underestimated, generally, the METQ2007BDOPT model responds well in simulation of hydrological processes using meteorological observation data. It also largely maintains the same identified extreme years for the calibration and validation periods, even if the obtained statistical criteria values vary among river basins.

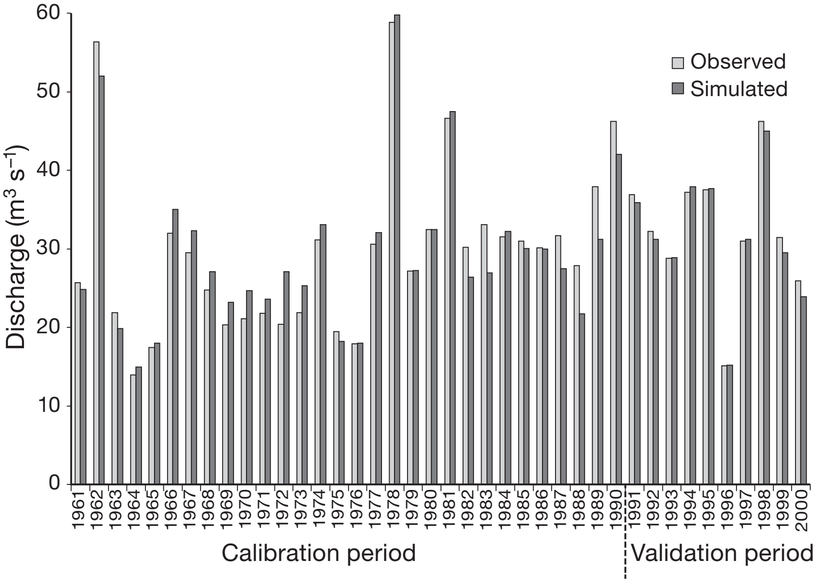

Fig. 4. Observed and simulated mean annual discharge at the hydrological station Salaca-Lagaste for the calibration (1961–1990) and validation (1991–2000) periods

3.2. Changes in climate data

Results of changes in climate data as differences between the scenario and control periods are summarised in Tables 3 and 4. In the studied river basins, the major significant changes in meteorological parameters were forecast according to the A2 scenario, with annual mean air temperature and precipitation predicted to increase by 3.8 to 4.1°C and 10 to 12%, respectively. These trends of increase in temperature and precipitation are shown in Fig. 5, using the Bērze River basin as an example. The annual mean minimum temperature is forecasted to increase at a rate above that of the annual mean maximum temperature, on average by 9.2°C according to A2 and by 6.9°C according to B2, respectively. At the same time, the length of growing season, when the daily mean temperature exceeds 5°C, will increase from 35 to 40 d according to the A2 scenario and from 31 to 35 d according to the B2 scenario. We define heavy rainfall as precipitation >10 mm d^{-1}. The number of days per 30 yr period with heavy rainfall will increase from 33 to 107 according to the A2 scenario and from 44 to 84 according to the B2 scenario. Days with heavy rainfall will occur more frequently, especially during December, January, May and June. Annual evapotranspiration is predicted to increase significantly by 37 to 41% according to A2 and by 20 to 24% according to B2.

The seasonal analysis provided the following results: the mean air temperature will significantly increase in all seasons, but the most considerable increase is forecast for winter and autumn, by 4.1 to 4.9°C according to A2 and 3.0 to 3.4°C according to B2. Similar significant changes in seasonal patterns can be forecasted in relation to the mean maximum and mean minimum temperature according to both scenarios, although the maximum temperature is predicted to increase at a higher rate during autumn and the minimum temperature will increase during winter and autumn. A significant increase in precipitation by 51 to 76% according to A2 and by 29 to 40% according to B2 is observed during the winter season, whereas a decrease is forecasted during the second half of the year, particularly in autumn, but it is not statistically significant. Based on the results of vapour pressure deficit, a significant increase for evapotranspiration is predicted in all seasons, but the most considerable changes are forecast in the second half of a year — in summer and autumn — by 36 to 68% according to A2 and by 11 to 48% according to B2.

Table 3. Changes in temperature (°C) and duration (d) of the growing season (GS; i.e. daily mean temperature exceeding 5°C) between the scenario (A2, B2) and control periods. DJF: winter season; MAM: spring; JJA: summer; SON: autumn. All changes in temperature are statistically significant ($p < 0.05$)

	Temperature (°C)		
	Min	Mean	Max
Imula			
A2 (GS: 36 d)			
Annual	8.6	3.8	3.8
DJF	8.5	4.5	3.4
MAM	4.5	3.7	4.2
JJA	2.3	3.1	3.6
SON	5.3	4.1	4.6
B2 (GS: 34 d)			
Annual	6.2	2.5	1.7
DJF	6.2	3.0	2.6
MAM	4.2	2.3	1.5
JJA	1.1	1.4	1.5
SON	4.8	3.2	3.3
Bērze			
A2 (GS: 36 d)			
Annual	9.7	3.9	4.1
DJF	9.5	4.7	3.7
MAM	4.9	3.8	4.1
JJA	2.3	3.1	4.0
SON	5.7	4.1	4.9
B2 (GS: 35 d)			
Annual	6.9	2.6	1.9
DJF	6.8	3.1	2.7
MAM	4.9	2.4	1.7
JJA	1.1	1.4	1.8
SON	4.8	3.3	3.7
Iecava			
A2 (GS: 35 d)			
Annual	9.3	4.0	4.7
DJF	9.2	4.9	3.7
MAM	6.1	4.0	4.2
JJA	2.9	3.1	4.4
SON	6.5	4.2	4.9
Iecava			
B2 (GS: 31 d)			
Annual	7.0	2.6	2.0
DJF	6.9	3.2	2.5
MAM	6.1	2.8	1.9
JJA	1.5	1.5	1.9
SON	5.0	3.0	3.0
Vienziemīte			
A2 (GS: 40 d)			
Annual	9.6	4.1	4.4
DJF	9.6	4.9	3.6
MAM	7.0	4.1	4.5
JJA	3.3	3.1	4.2
SON	6.3	4.2	4.5
B2 (GS: 32 d)			
Annual	7.3	2.7	2.1
DJF	7.5	3.3	2.5
MAM	6.6	2.9	2.2
JJA	1.7	1.5	1.9
SON	4.5	3.0	2.8
Salaca			
A2 (GS: 39 d)			
Annual	9.0	4.0	4.0
DJF	8.9	4.9	3.5
MAM	6.4	40	4.5
JJA	2.9	3.0	3.8
SON	6.3	4.1	4.1
B2 (GS: 31 d)			
Annual	6.9	2.7	1.7
DJF	7.0	3.4	2.7
MAM	6.1	2.9	2.1
JJA	1.7	1.3	1.5
SON	4.8	3.0	2.6

Table 4. Changes (%) in amount of precipitation (parentheses: heavy rainfall, i.e. in excess of 10 mm d^{-1}; units: no. of days) between the scenario and control periods. $^{*}p < 0.05$

	A2					B2				
River	Annual	DJF	MAM	JJA	SON	Annual	DJF	MAM	JJA	SON
Imula	11* (33)	65*	16	−10	−2	8* (60)	37*	8	−2	−1
Bērze	12* (44)	76*	13	−4	−4	9* (47)	40*	8	−2	−1
Iecava	10* (87)	55*	16	−1	−8	6 (44)	29*	8	2	−5
Vienziemīte	11* (107)	51*	18	−1	−6	6 (84)	29*	8	2	−4
Salaca	12* (62)	53*	11	4	−2	9* (75)	32*	8	9	−2

Calculated changes in climate data vary among studied river basins, but the differences are relatively small. However, higher changes in temperature values are identified for the Vienziemīte and Salaca Rivers, located in the northern part of Latvia, and a higher change in the amount of precipitation is predicted for the Bērze River, located in the central part. A typical annual cycle of the mean monthly air temperature, evapotranspiration, precipitation values and their changes between the climate scenarios and control periods can be seen from the example of the Vienziemīte River basin (Fig. 6). The pattern of changes in

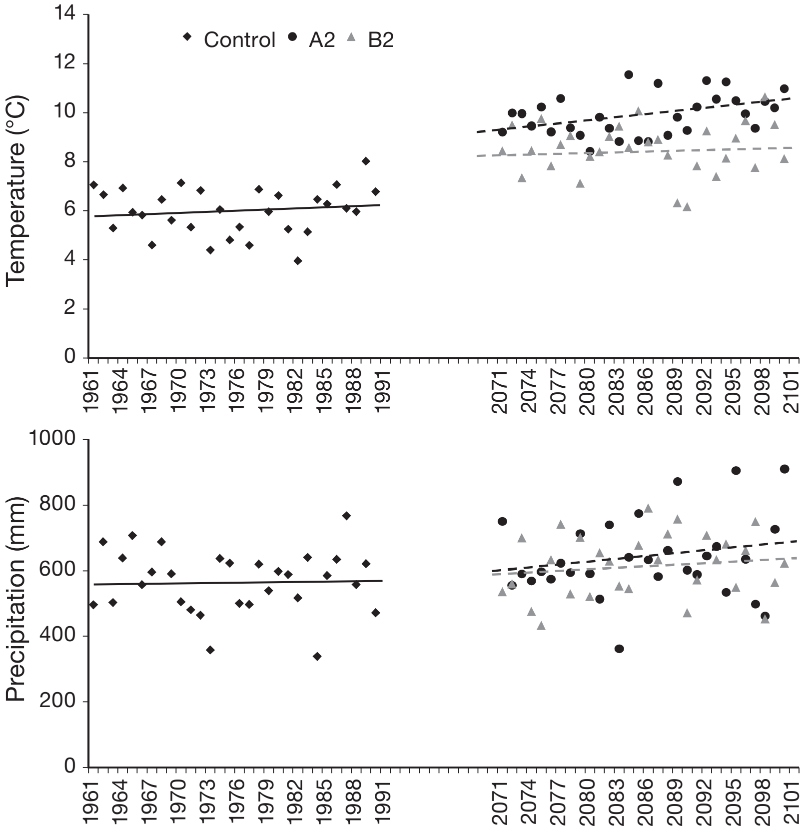

Fig. 5. Trends in air temperature and amount of precipitation for the control period and 2 scenario periods (A2 and B2) in the Bērze River basin

meteorological parameters corresponds to the results of monthly analysis per season and can be seen also in relation to other basins. For both scenarios, no considerable changes in the variation of climate data among the studied Salaca River sub-basins were identified; therefore, climate data are presented for the entire river basin.

3.3. Changes in runoff patterns

Simulation results of the hydrological model showed that the river runoff patterns will change according to both scenarios. Major changes are predicted according to the A2 scenario in both annual and seasonal analyses. For 7 studied river basins, the mean annual runoff is predicted to decrease by 13 to 24% according to the A2 scenario, and by 2 to 11% according to the B2 scenario (Table 5). However, the only statistically significant decrease is maintained for the Vienziemīte and Salaca Rivers, including their sub-basins, according to the A2 scenario. In contrast, for the Bērze River, there was no change in mean annual runoff according to the A2 scenario, and an insignificant increase (10%) according to the B2 scenario. This could be explained by a significant increase in the predicted amount of precipitation (Table 4) and lower evapotranpiration in winter, which results in a significant increase in winter and annual runoff. For other basins, the streamflow is predicted to increase in winter due to warmer and wetter climate, but the increase is statistically significant only for the Vienziemīte River. In other seasons, except summer, runoff is predicted to decrease according to the B2 scenario. In most cases, a significant decrease in runoff is predicted for spring (18 to 24%) and autumn (49 to 58%) according to the A2 scenario.

Fig. 7 shows the predicted changes in the monthly river hydrograph for all studied river basins. In the period from 1961 to 1990, rivers are characterised by a typical hydrograph of Eastern European rivers: 2 main discharge peaks, one during the spring snowmelt and one in late autumn during the intense rainfall, and low river discharge in winter and summer. It is typical that the major portion of the total annual river runoff (32 to 41%) occurs in spring, followed by winter with 25 to 33%, autumn with 16 to 26% and summer with 10 to 15%. According to the A2 and B2 scenarios, at the end of the 21st century the major part of the total annual river runoff will be generated in the winter followed by spring, autumn and summer. These structural or seasonal changes in the total annual river runoff are proven by discharge results in percentage points (Table 6), which are calculated as the difference between the scenario and control periods runoff in percentage points. The river runoff is forecasted to increase significantly by 9 to 18 percentage points according to the A2 scenario and by 5 to 13 percentage points according to the B2 scenario in winter, and to considerably decrease by 4 to 12 percentage points according to the A2 scenario and by 2 to 8 percentage points according to the B2 scenario in autumn. Although, according to both scenarios the river runoff in most cases is predicted to significantly decrease in April and/or May (Fig. 7), total decrease in spring runoff is not statistically significant, except the Bērze River. No considerable change in streamflow is predicted for summer.

A change in shape of the river hydrograph is predicted (Fig. 7). According to the A2 scenario, the spring flood will decrease and the hydrograph peak will shift from April to February. According to the B2 scenario,

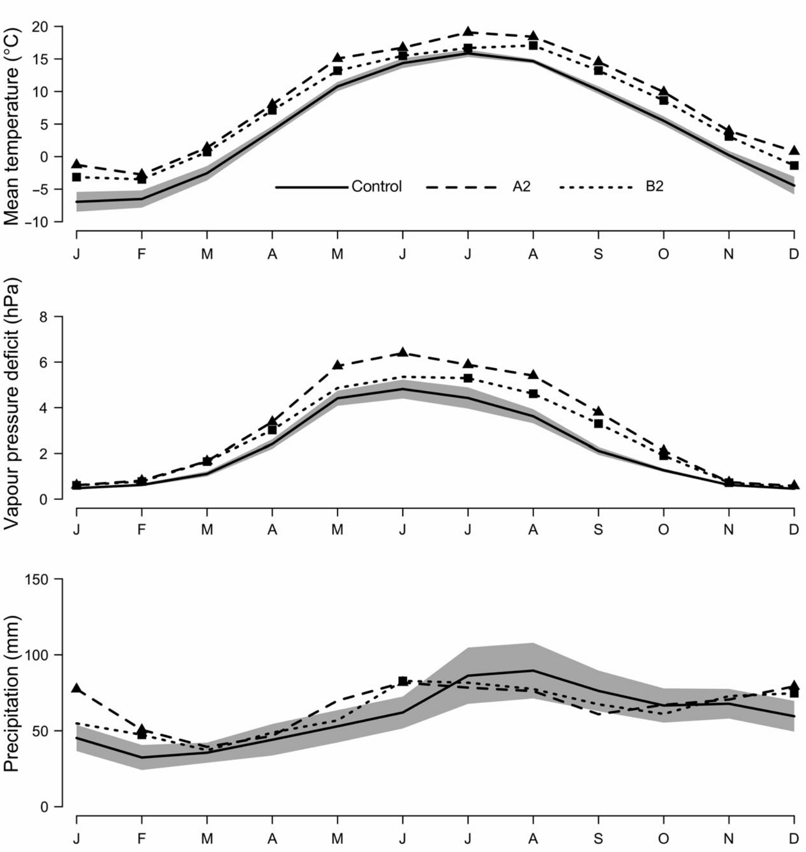

Fig. 6. Annual cycle and changes in mean air temperature, vapour pressure deficit and amount of precipitation for the control period and 2 scenario (A2 and B2) periods in the Vienziemīte River basin. Grey area: 95% confidence intervals for the mean values of the control period. The black triangles and squares for the respective scenarios indicate statistically significant changes in the monthly mean value of the parameter

the river hydrograph is smoother and does not have a typical peak discharge. A decrease in the discharge is observed for spring and autumn months, but it is less pronounced in comparison to the A2 scenario. The significance of predicted changes in annual, seasonal and monthly mean maximum discharge is summarised in Table 7 and presented in Fig. 8. It varies among studied river basins and the emissions scenario used.

4. DISCUSSION

Having analysed the latest results of other studies carried out in the Baltic Sea basin (e.g. Graham et al. 2007, Bolle et al. 2008, Kjellström & Lind 2009) and particularly those in the southeast region to which the Baltic countries belong (e.g. Kriaučiūnienė et al. 2008), we have identified similar changes in hydro-meteorological parameters in the forecast of future climate. Compared with the present climate, both scenarios A2 and B2 indicate an increase in the mean annual air temperature, precipitation and evapotranspiration, whereas the mean annual river runoff is predicted to decrease by 2 to 24% in the studied river basins, except the Bērze River. The magnitude and character of forecasted changes depends upon the emissions scenario and the GCM used to create the input data (Graham et al. 2007). Major changes in the future hydro-meteorological parameters were observed according to the A2 scenario in both annual and seasonal analysis. It can be expected that during this century, there will be gradual increases or decreases in hydrometeorological parameters in the southeast region of the Baltic Sea; this is in agreement with research in the Nemuna basin in Lithuania (Kriaučiūnienė et al. 2008) and in the Baltic Sea basin (Kjellström & Lind 2009). This leads to an intensification of the hydrological cycle, with more precipitation and evapotranspiration under a warmer and wetter climate during the 21st century. Similar to the results of a study in Europe by Dankers et al. (2007), we found that days with heavy rainfall will occur more frequently during the year, which would cause a higher frequency of

Table 5. Changes in volume of runoff (%) between the scenario and control periods. *$p < 0.05$

	A2					B2				
River	Annual	DJF	MAM	JJA	SON	Annual	DJF	MAM	JJA	SON
Imula	−13	22	−14	−23	−58*	−5	21*	−6	−18	−36*
Bērze	0	49*	−25*	−6	−29	10	43*	−15	6	5
Iecava	−13	19	−28	−21	−30	−2	24	−19	13	−19
Vienziemīte	−18*	41*	−34*	−30	−49*	−11	32*	−21*	−18	−36*
Salaca	−18*	15	−18*	34	−51*	−3	15	−14	12	−20
Briede	−21*	10	−26*	−27	−52*	−3	14	−19*	26	−18
Seda	−24*	0	−26*	−28	−54*	−3	11	−19	27	−16
Rūja	−20*	18	−34*	−22	−50*	−2	20	−20*	25	−19

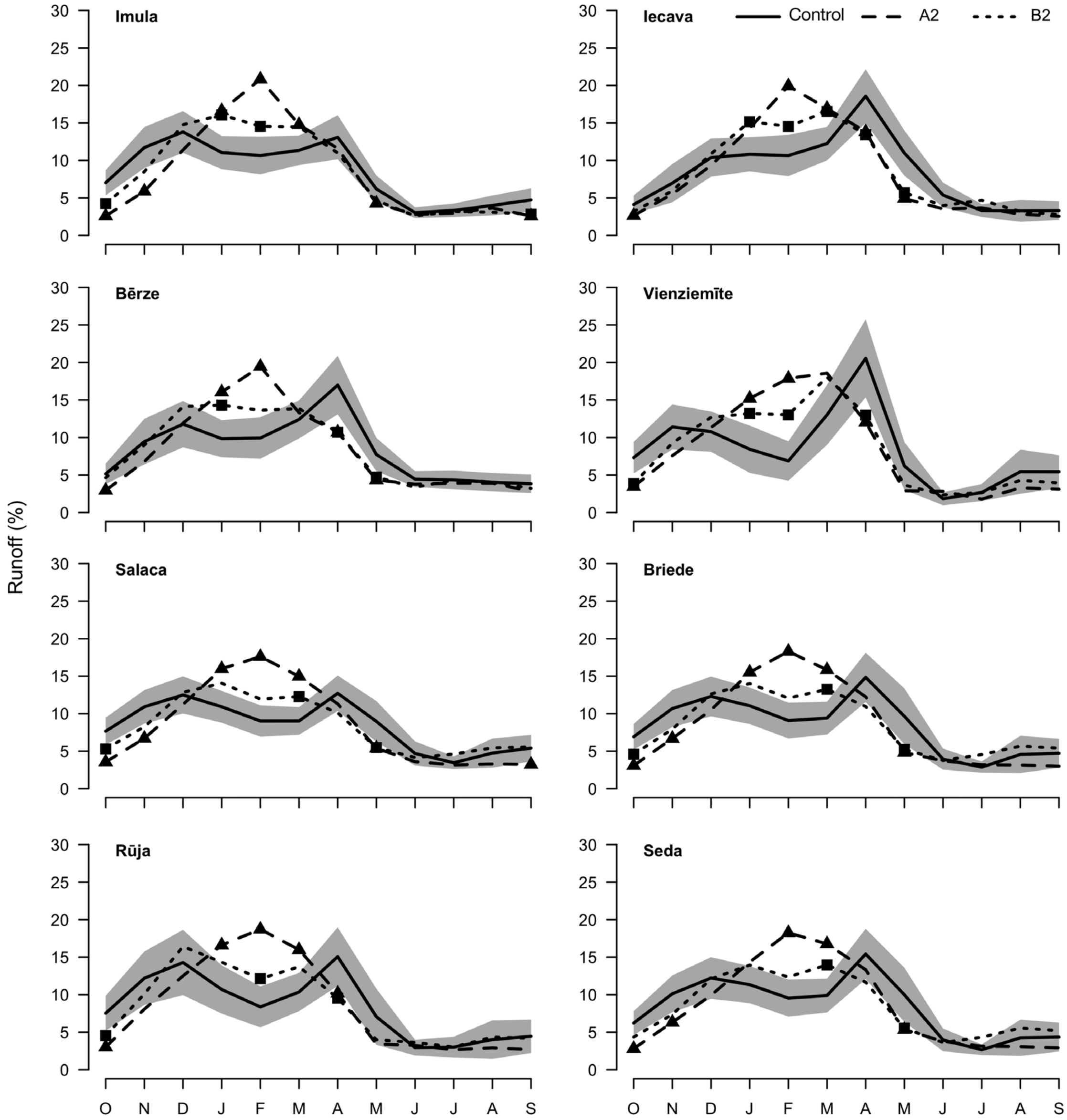

Fig. 7. River hydrograph of a hydrological year from October to September and distribution of total annual river runoff for the control period and 2 scenario (A2 and B2) periods in 8 studied river basins and sub-basins. Grey area: 95% confidence intervals for the mean values of the control period. The black triangles and squares for the respective scenarios indicate statistically significant changes in the monthly mean value of the parameter

Table 6. Structural changes in river runoff (percentage points) between the scenario and control periods. *p < 0.05

	A2				B2			
River	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON
Imula	13*	0	−1	−12*	10*	−1	−1	−8*
Bērze	16*	−9*	−1	−6*	11*	−8	−1	−2
Iecava	12*	−6	−2	−4	9*	−6*	0	−2
Vienziemīte	18*	−6	−2	−10*	13*	−5	−1	−7*
Salaca	12*	1	−3	−10*	6*	−3	1	−5
Briede	12*	−1	−1	−10*	6*	−4	3	−4
Seda	9*	0	−1	−9*	5	−4	3	−4
Rūja	14*	−3	−1	−10*	10*	−5	1	−5

occurrence of high river flow events. It is forecast that minimum temperature values will increase more rapidly than mean and maximum temperature values. In addition, an increase in mean air temperature will result in the prolongation of the growing season in Latvia from 31 to 40 d, depending on the climate scenario; the growing season will occur from late March to early November. These results correspond to previous results for the Baltic Sea basin

Table 7. Changes in the annual and seasonal mean maximum discharge (%) between the scenario and control periods. *p < 0.05

River	A2					B2				
	Annual	DJF	MAM	JJA	SON	Annual	DJF	MAM	JJA	SON
Imula	−7	22	−31	−2	−49*	−15	6	−16	−23	−25
Bērze	3	35*	−27	25	−14	4	16	−12	30	8
Iecava	−12	25	−25	−17	−26	−8	15	−17	24	−8
Vienziemīte	−16	39*	−36*	−6	−21	0	14	−19	29	−10
Salaca	−4	16	−11	−30	−42*	1	15	−9	4	−14
Briede	−24	15	−39*	−26	−38	−13	11	−31	36	−10
Seda	−30*	8	−40*	−27	−39*	−16	8	−32	37	−12
Rūja	−13	6	−35*	−22	−40*	0	−6	−13	51	7

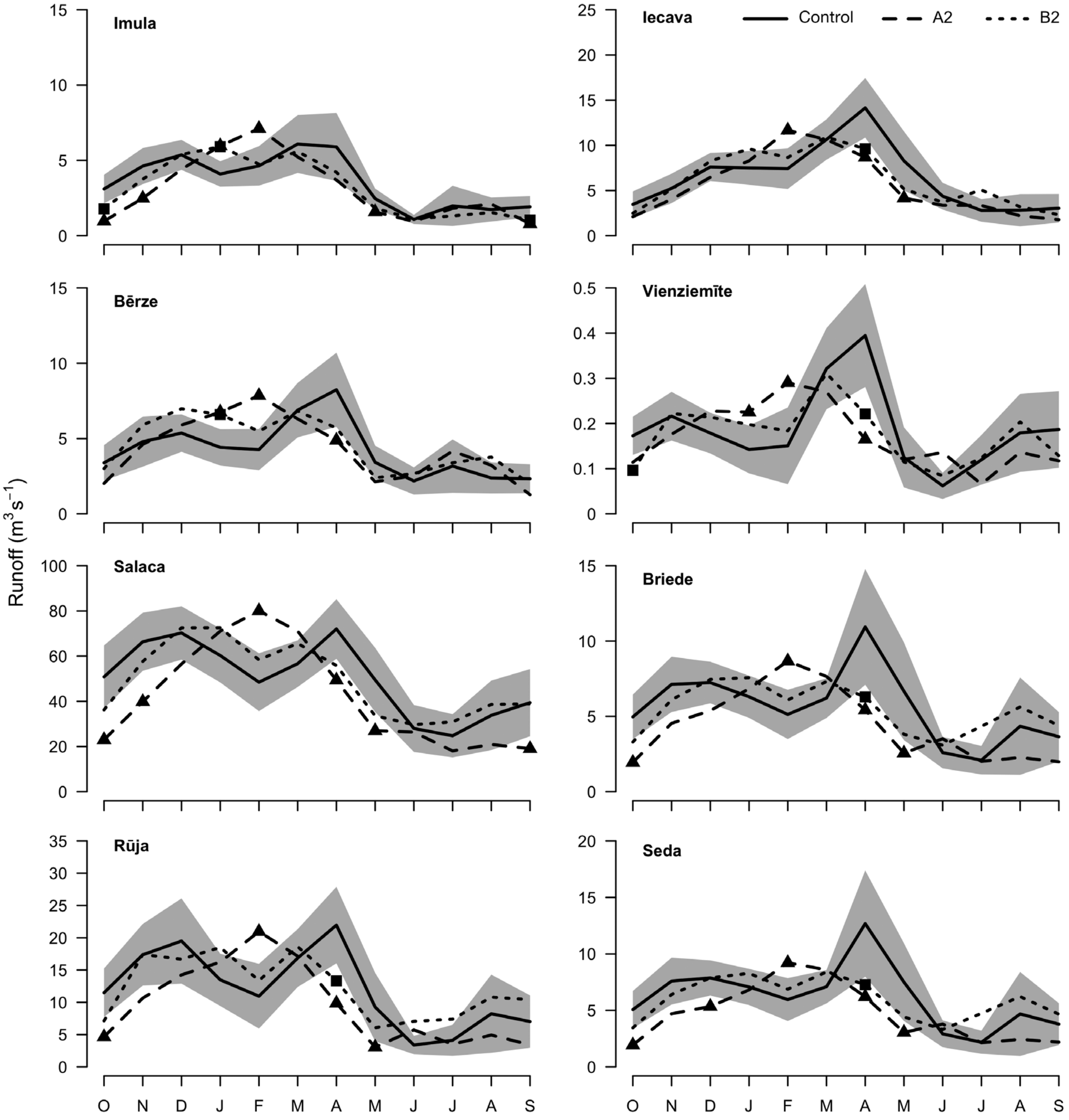

Fig. 8. Changes in the mean maximum discharge of a hydrological year for the control period and 2 scenario (A2 and B2) periods in 8 studied river basins. Grey area: 95 % confidence intervals for the mean values of the control period. The black triangles and squares for the respective scenarios indicate statistically significant changes in the monthly mean value of the parameter

by Bolle et al. (2008), who found that the duration of the growing season will increase by 20 to 50 d in the north and by 30 to 90 d in the south.

Graham et al. (2003) studied the effects of climate change impacts on river runoff for the Baltic Sea basin. They analysed a number of the RCM simulations driven by the GCMs HadAM3H and ECHAM4/OPYC3 (with different emissions scenarios) using the hydrological model HBV-Baltic, and identified a north–south gradient in future hydrological parameters over the Baltic Sea basin; in addition, effects during cold months showed larger relative changes than warm months. This impact of climate change on river runoff is demonstrated by the results of our study in Latvia and those of Kriaučiūnienė et al. (2008) in Lithuania, even though different emissions scenarios, climate and hydrological models were applied. The Nemuna River basin study used climate data series from GCMs ECHAM5 and HadCM3 with different emissions scenarios (A1B, A2 and B1) feeding the hydrological model HBV. However, for the studies in Latvia and Lithuania, warmer winters are forecast, resulting in a considerable increase in river runoff due to an increase in the amount of precipitation when evapotranspiration is low. In addition, a considerable decrease in spring runoff and maximum discharge were identified. Overall, according to the results of Graham et al. (2007), annual river runoff is predicted to increase in the northern region and decrease in the southern region. The Baltic countries are situated in the middle of both regions; however, the main tendency in the future climate and river runoff change is closer to that forecast for the southern region of the Baltic Sea basin. Both increasing and decreasing tendencies of the Nemuna River runoff were predicted for summer and autumn by Kriaučiūnienė et al. (2008). In contrast to the southern forecast by Graham et al. (2007), but in line with our study results, autumns in Latvia will become much drier and warmer followed by a decrease in streamflow. Changes in river runoff will be steeper and more significant in autumn than in summer. This trend in river runoff is already emerging under the present climate conditions. Apsīte et al. (2009) concluded that over the period from 1988 to 2006, in comparison to the period from 1951 to 1987, no considerable changes in Latvian river runoff were observed in summer, whereas autumn runoff decreased by 3% on average, although this is not statistically significant at the moment. At the same time, major runoff differences are observed between winter (11% increase) and spring (8% decrease). Such changes in the present river runoff patterns can be explained by the change in dominating large-scale atmospheric circulation processes over the Baltic region (Kļaviņš et al. 2007).

We searched for similar early studies dealing with predictions of changes in river runoff within this century in order to compare results among Baltic countries. Previous studies by Jaagus et al. (1998) in Estonia, Butina et al. (1998) in Latvia and by Kilkus et al. (2006) in Lithuania used climate data series from GCMs with different emissions scenarios in 2 hydrological models 'Water balance' and HBV for simulation of river runoff. In Estonia and Lithuania, the predicted increase in annual river runoff was 20 to 40% and up to 29% on average, respectively. In the Lielupe River basin, Butina et al. (1998) found that the river flow was predicted to increase by 11 to 83% on average, depending on the emissions scenario used in the model. Rogozova (2006) identified both increasing (from +15 to +17%, GCM ECHAM4/OPYC3) and decreasing (from –7 to –2%, GCM HadAM3H) trends in annual river runoff for 2 Latvian river basins, the Irbe and Gauja; in that study, the climate data series were based on the RCM RCAO using 2 different GCMs and emission scenarios (A2, B2) and the hydrological model HBV. It was concluded that prediction in runoff changes may depend of the chosen GCM and emissions scenario in RCM RCAO. In both early and later studies in the Baltic countries, it was predicted that the increase in river runoff will be marked during winter due to the shortening of the period with snow and ice cover and would be typical for this part of the Baltic Sea basin, whereas the spring runoff maximum will mostly decrease and shift to earlier periods. However, there are contrary predictions concerning the total annual river runoff at the end of this century. An increase in runoff is predicted in early studies to some extent by Rogozova (2006), but a decrease is forecast in the most recent studies, and these results comply with the results of our study.

To our knowledge, there has been no review of uncertainties in research on climate change and water resources. Beven (2001) and Sene (2010) have pointed out that it is necessary to understand uncertainties, which can appear in relation to, for example, applied data of observations, the selected climate model and emissions scenario, hydrological model and calibration performance, as well as assumed conditions for simulating hydrological processes for a particular catchment. In the present study, the conceptual rainfall-runoff model — the latest version of METQ2007BDOPT with semi-automatic calibration performance — was applied to 8 studied river basins and sub-basins. We obtained comparatively good calibration results of the model for small (Vienziemīte) and large (Salaca) river basins. One of the advantages is that models of this type are usually simple and relatively easy to use. The required input data are readily available for most applications (Uhlenbrook et al. 1999). These models predict that impacts of climate change on river runoff can be quite pronounced in areas where snow accumulation and melt presently dominate in the hydrological regime (Bergström et al. 2001), as is the case in Latvia. Further, the semi-automatic or automatic calibration method is aimed at successfully finding the single best-fitting parameter values and reducing parameter uncertainty in the hydrological model, which could arise by manual calibration (Apsīte et al. 2008, Moradkhani & Sorooshian 2009). However, the observations in rainfall-runoff modelling consist of the measurement of the input and output fluxes of the hydrological system and even the storage in the system. The key to potential improvement of rainfall–runoff modelling is associated with true characterisation of precipitation and its uncertainty. Therefore, in our study the location of the available MS, characterising the spatial and temporal distribution of precipitation in the studied basin, presents one of the main reasons for the difference between the simulated and observed discharges. For example, in the case of the Rūja River basin, the model calibration results are not optimal, because of the lower quality of observed precipitation data. Another explanation of the above-mentioned differences might be a broad flood plain and a high percentage of wetlands in the Seda River basin. These characteristics determine the specific hydrological regime, which differs from that of the other studied rivers; therefore, it is difficult to simulate the rainfall–runoff processes without additional riverbed measurements (Apsīte et al. 2008). Usually, a shorter calibration period is selected in studies where the conceptual rainfall-runoff model is applied. In some cases this shorter period results in better calibration results. In most studied river basins, we were able to select a 30 yr period in the model calibration procedure that comprises several high and low water years, characteristic of the 20th century. Inclusion of these extreme values (year, discharge) improves the performance of the hydrological model for the simulation of future climate scenarios, as model parameters already respond to extreme values in the validation phase (e.g. Salaca River, Fig. 4). Although the model calibration period was much shorter for the Seda and Rūja River basins, comparatively lower calibration results have been obtained, which in these cases could be explained by increased uncertainty of the observed precipitation data and the physical peculiarities of the river bed and basin.

Having analysed the METQ2007BDOPT model calibration and river runoff simulation results, we suppose that the uncertainties from the used observations as input data or the model calibration procedure may not be very large as long as the model is run within its range of calibration. We agree to the statement referred to in many studies (Bergström et al. 2001, Graham et al. 2007, Bolle et al. 2008, Minville et al. 2008) that the most crucial aspects in the application of models are the GCM and RCM used in the emissions scenario itself and the uncertainties in the local-scale patterns in applying the downscaling method for air temperatures — and especially that for precipitation — to a specific catchment. Graham (2004) identified that the GCM model used for boundary conditions has as much impact on the total river flow as the emissions scenarios used. Graham et al. (2007) found that the largest range of uncertainty with respect to the relative change in the volume of river flow occurs on the eastern side of the Baltic Sea basin, e.g. in the Gulf of Riga drainage basin, which was explained by the different GCMs used in the RCAO RCM. The same conclusion was made by Rogozova (2006). Coming back to the results of our study, we concluded that the bias correction method applied by Seņņikovs & Bethers (2009) cannot remove the uncertainties that are inherited from the RCAO RCM, i.e. interannual variability and temperature–precipitation cross-correction properties. Thus, the prepared climate data during the control period are still overestimated or underestimated for an individual season (i.e. winter), month (i.e. April, September) and MS. This could explain certain variations in the predicted changes in simulated annual and seasonal river runoff results. We think that the amount of precipitation in winter was overestimated for both scenarios in the case of the Bērze River basin, which resulted in a significant increase of runoff in the cold period of the year, when evaporation was low, and thus determined different annual runoff generation in comparison to other river basins.

5. CONCLUSIONS

In the present study, the assessment of climate change impacts on river runoff prediction in Latvia at the end of the 21st century is based on one control run (1961–1990) and 2 future climate scenarios (A2 and B2 runs; 2071–2100) from RCM RCAO driven by GCM HadAM3H. The conceptual rainfall-runoff model METQ2007BDOPT was used to simulate hydrological processes in 8 studied river basins and sub-basins. We obtained comparatively good calibration results for the small and large river basins for calibration periods from 12 to 30 yr, which suggests that this model will be applicable in future studies.

Our results demonstrate that future climate will change, bringing modifications to the Latvian river runoff regime and shape of the hydrograph, which will be similar to the present Western European rivers. Significant changes in hydro-climate data will be expected according to the A2 scenario from both annual and seasonal analysis. Overall, according to both scenarios, increases in the mean annual air temperature, precipitation and evapotranspiration are forecasted whereas the mean annual river runoff is predicted to decrease. Considerable changes in stream flow are predicted for the winter, spring and autumn. Therefore, the majority of total annual river runoff will be generated in winter because of the warmer and wetter climate, followed by spring, autumn and summer. The spring maximum discharge will mostly decrease and shift to earlier periods. Autumns will become warmer and drier followed by stream flow decrease. No considerable change in runoff is predicted for summer. It is likely that in future the classic breakdown of a calendar year into seasons will be a subject of discussion in hydrology. Two main periods instead of 4, a high flow (mostly falling in the cold period of the year) and low flow (mostly in the warm period), will be distinguished in the river hydrograph. In addition, the days with heavy rainfall will occur more frequently during the year and a prolonging of the growing season will be expected. Therefore, such forecast of hydro-climatic conditions might determine the availability of water resources and facilitate restructuring of the present economy and its development in the long-term perspective, e.g. in the energy, water consumption and agricultural sectors, both in Latvia and in the southeast of the Baltic Sea basin.

In addition, future development initiatives are likely to be implemented against the background of changing climate. There is a need for further work to reduce and evaluate the uncertainty associated with predictions of future climate conditions and land use, and to test the conceptual rainfall–runoff METQ2007BDOPT model for a particular catchment in another part of the Baltic Sea basin.

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