Changes in river runoff in Latvia at the end of the 21st century

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Apsīte, Elga, Anda Bakute, Līga Kurpniece & Inese Pallo (2010). Changes in river runoff in Latvia at the end of the 21st century. *Fennia* 188: 1, pp. 50–60. Helsinki. ISSN 0015-0010.

This study deals with future climate change impacts on the runoff of five Latvian river basins at the end of this century. Climate data series have been provided by the Faculty of Physics and Mathematics of the University of Latvia where the regional climate model Rossby Centre Atmosphere Ocean was selected for further statistical downscaling. Changes in hydrometeorological data have been analysed based upon one control run (period 1961–1990) and two future scenario A2 and B2 runs (2071–2100). The conceptual rainfall-runoff model, the latest version of METQ2007BDOPT, was used for simulation of hydrological processes in particular river basins. Simulation results revealed that in comparison to the control period, major differences in hydrometeorological parameters in future were observed according to A2 scenario, where long-term mean air temperature will grow by 4 degrees and precipitation by 12%, while mean annual river flow will decrease by 19%. Both scenarios demonstrate changes in seasonal runoff patterns where the major part of river runoff will be generated in winter, followed by spring, autumn and summer. The river hydrograph is going to take a different shape, where the maximum river discharges will occur in winter instead of spring.

Keywords: river runoff, climate change, scenario, rainfall-runoff model, Latvia

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Introduction

Over the last decades, numerous studies about climate change and its impact on freshwater resources have been published (e.g. Vörösmarty et al. 2000; Oki & Kanael 2006; Bates at al. 2008). It can be explained by the increased knowledge of modern society about the hydrosphere, its interaction with other geospheres and natural processes, improved research methods and data basis. At the same time, the growth of population, rapid development of global economy and increased water consumption, as well as the world's changing climate have drawn more attention to the global, regional and local studies about the existing water resources, their sustainable conservation and prediction in the future. Most often such studies deal with river hydrology, including those in Europe. There are many publications describing studies about trends in river discharge, covering the study periods dating back to the nineteenth century and up to today, for instance, in the Nordic countries by Hisdal et al. (2003), and in the Baltic countries by Reihan et al. (2007).

Recently the emphasis has shifted to studies about prediction of climate change impact on water resources, its quantifying and extreme events in the 21st century, using combinations of various global and regional climate models, emission scenarios and hydrological models, for instance, Bergström et al. (2001), Hisdal et al. (2006), Stein et al. (2007), Dankers et al. (2007), Bolle et al. (2008), Kjellström & Lind (2009), ect. Many studies predict that the future climate in Europe will be warmer, the Southern areas will get drier and the Northern parts will become wetter. Precipitation variability is predicted to increase in most parts of Europe, with extreme precipitation events becom-

URN:NBN:fi:tsv-oa2844

ing more frequent and more intense. These climatic changes will determine river runoff patterns: decrease in annual river runoff in the South and increase in the North, and more extreme events like floods or draughts are expected in the stream flow in Europe.

Latvia is located in the Eastern Europe, South-East of the Baltic Sea. The uneven relief, humid climate and geological development have formed a dense network of rivers where the mean value is 0.59 km/km^2 in Latvia. Total number of rivers is about 12 500. In average, the mean annual runoff is 35 km^3, from which only 16 km^3 are formed within the territory of Latvia. Rivers have mixed water feeding: rain, snowmelt water and groundwater. It is typical that the major part of the total annual river runoff is generated in spring season and is followed by winter, autumn and summer. Mean annual precipitation varies from 550 to 850 mm. The mean annual air temperature varies from –3 ^{o}C to –7 ^{o}C in January and from +17 ^{o}C to +18 ^{o}C in July. The resent studies, for instance by Klavins et al. (2006), Reihan et al. (2007) and Apsīte et al. (2009) show that at the turn of the century the climate has changed and modified the Latvian rivers hydrological regime similar to other regions of Europe. The major change in river runoff was observed between winter and spring seasons due to warmer winters in last twenty years. Some early simulation results of climate change impacts on river runoff in this century was done by Butina et al. (1998) and Rogozova (2006), whose results are briefly presented in section Results and discussions. Unfortunately, the latest studies dealing with test results on climate change impacts on Latvian river runoff in the future are missing. Therefore, the aim of our study is to asses the climate change impact on the Latvian river runoff at the end of the 21st century under different climate scenarios.

Materials and methods

In our study the climate change impact on the river runoff under the past and future climate conditions was analyzed for five pilot river basins: the Bērze, the Iecava, the Imula, the Salaca and the Vienziemīte. The location and characteristics of studied river basins are presented in Fig. 1 and Table 1. The river basins differ in size, natural conditions and anthropogenic impact. The Bērze River basin is located in the central part of Latvia, where climatic conditions and fertile soils are very suitable for the most intensive agricultural production in the country. Totally, agricultural lands cover 66% of the Bērze river basin and up to 45% of it is arable land. Upstream of the hydrological station Biksti the numbers are 50% and 20% respectively. The basin lies very close to the driest area, the Zemgale Lowland where precipitation amounts to 550 mm per year. The Imula and Iecava river basins have similar climatic conditions. The upper reach of the Iecava river basin (566 km^3), located on the sandy and wooded area, is included in this study. The Salaca River basin is the largest studied basin and it is a part of the North Vidzeme Biosphere Reserve. Thus, human activities are limited there. Its total drainage area is 3220 km^2, 62% of which are covered by the catchment of the lake Burtnieks. The percentage of forests is quite high 45% and particularly bogs up to 13%. The Vienziemīte is the smallest river basin. It is located in the Vidzeme Upland, 176 m above the sea level. There are periods of lower air temperature and higher amount of precipitation over the year. Although agricultural land forms 66% of this drainage basin, human impact is comparatively low.

The hydrological model METQ was applied to each of the five river basins with a daily time step. It was used to simulate hydrological behaviour of the river runoff particularly under past and changed future climate conditions. It should be mentioned, that in Latvia several versions of mathematical models have been developed: 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 is a conceptual rainfall-runoff model of catchment's hydrology, originally developed using Latvian catchments. The latest version of the METQ2007BDOPT has 23 parameters and most of them can be kept constant for different river catchments. The model consists of different routines, including the runoff and hydraulic (if there is a lake or reservoir in the river basin which considerably influences the hydrological regime of the river). The total runoff consists of three runoff components (Fig. 2): Q_1 is the surface runoff, Q_2 is the subsurface runoff (runoff from the groundwater upper zone) and Q_3 is the base flow (runoff from the groundwater lower zone). A statistical criterion R^2 (Nash & Sutcliffe 1970), a correlation coeffi-

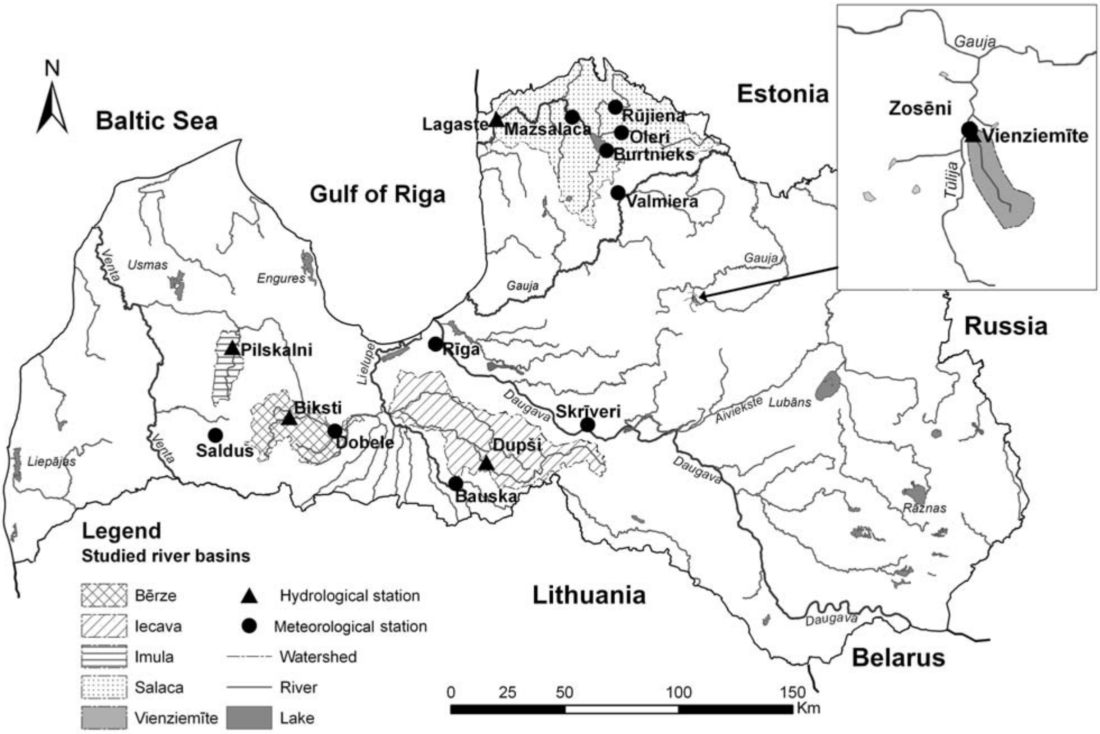


Fig. 1. Location of river basins and hydrological and meteorological stations used in the study.

Table 1. Characteristics of studied river basins.

River basin and hydrological station	Total drainage area, km²	Studied drainage area, km²	Long-term mean discharge, m³/s	Long-term average precipitation, mm	Long-term average air temperature, °C		Land-use, %			
					January	July	Agricultural fields / arable land	Forests	Bogs	Water bodies
Bērze-Biksti	904	275	2.65	650	–4.9	16.4	50 / 20	46	3	1.5
Iecava-Dupši	1166	566	3.64	675	–5.8	16.6	35 / 15	62	3	0.5
Imula-Pilskalni	263	232	1.73	670	–4.8	16.0	57 / 26	42	1	0.5
Salaca-Lagaste	3420	3220	30.5	750	–4.8	16.1	35 / 21	45	13	6.7
Vienziemīte-Vienziemīte	5.92	5.92	0.06	730	–7.1	15.9	66 / 1.2	13	–	–

cient r, mean values and a graphical representation were used in the analysis of the model calibration results.

In general, the structure and simulation of hydrological processes of the METQ model are similar to the HBV (Bergström 1976) model developed in Sweden. The main difference between the METQ and HBV models is that the degree-day ratio does not have a constant value for the snow melting in METQ, but it is rather a temporary difference, depending on the daily potential insolation of each particular day. A more detailed de-

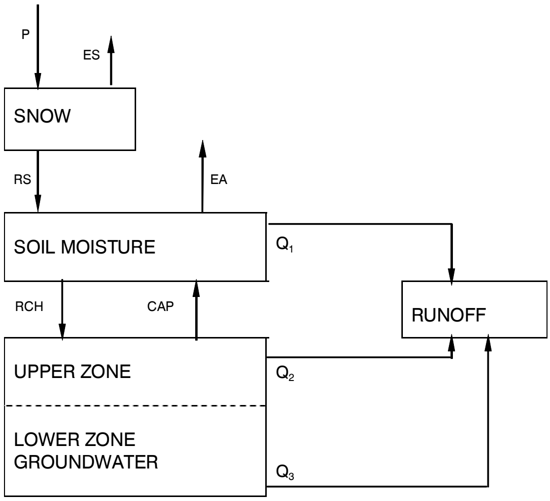


Fig. 2. General structure of the hydrological model METQ (Zīverts & Jauja 1999). P – precipitation; ES – evaporation from snow; EA – evapotranspiration from root zone; RS – rain and snowmelting water; RCH – recharge to groundwater; CAP – capillary flow; Q_1 – the surface runoff; Q_2 – the subsurface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

scription of the model METQ is presented in other sources (Zīverts & Jauja 1999).

The input data for the METQ2007BDOPT model calibration, daily measurements of air temperature (°C), precipitation (mm) and vapour pressure deficit (hPa) at eleven meteorological stations and daily river discharge (m^3/s) of five hydrological stations were used. The location of the utilised meteorological and hydrological stations is shown in Fig. 1. In this study, the selected calibration period was from 1961 to 1990 (30 years as the control period) with the aim to simulate the future climate scenarios from 2071 to 2100, and validation period – next ten years from 1991 to 2000.

For the simulation of river runoff according to past and future climate conditions we have used climate data series (daily mean air temperature, precipitation and vapour pressure deficit) provided by the Laboratory for Mathematical Modelling of Environmental and Technological Processes, Faculty of Physics and Mathematics of University of Latvia. The regional climate model (RCM) Rossby Centre Atmosphere Ocean (RCAO) run by the Swedish Meteorological and Hydrological Institute (driving boundary conditions from the global climate model HadAM3H) was selected as it is most suitable for the area of our interests, i.e. Latvian conditions. The proposed approach of the regional climate model data modification allows to change the modelled temperature and precipitation time series for the control period in such a way that they preserve the characteristics on a small time-scale, and at the same time also possess the statistical properties of the observed data. The climate data series for the future climate scenarios were obtained by assuming that the histogram modification algorithm is the same for both the past and future climate. Full description of the applied downscaling methodology can be found in Seņņikovs & Bethers (2009). The calculated data series denoted the following: CTL represents the control period 1961–1990 and characterises past climate conditions, while A2 and B2 represent the period of future scenarios 2071–2100 and forecast future climate conditions. All data series were extrapolated from the grid cross points to the meteorological stations involved in our study.

Results and discussion

Calibration and validation of the hydrological model

Nowadays hydrological model is a widely used tool for the purposes of water resource assessment, flood forecasting, impact assessment of pollution sources on water quality, and many others, including simulation of hydrological processes under different climate scenarios for predicting water resources in the future. Various kinds of models have been developed, but the conceptual rainfall-runoff model is one, which is used more broadly. These models usually are simple and relatively easy to use for the simulation of different hydrological processes (Bergström 1991; Merz & Blöschl 2004), contrary to more complex, physically-based, distributed models, for example the SHE model (Abbott et al. 1986). The required input data are readily available for most applications.

In this study we have used a model of this type, the METQ, which has been successfully applied to small and relatively large catchments in Latvia, the brook Vienziemīte (drainage area 5.92 km^2) and the Daugava river (drainage area 81.000 km^2) respectively (Zīverts & Jauja 1999) in earlier studies. Furthermore, the METQ model has been used for different hydrological tasks, e.g. to evaluate the model performance before and after drainage con-

Table 2. The obtained statistical criteria for five river basins.

Hydrological station	Calibration period (1961–1990)		Validation period (1991–2000)	
	R^2	r	R^2	r
Bērze – Biksti	0.67	0.83	0.56	0.76
Iecava – Dupši[1)]	0.66	0.82	0.54	0.79
Imula – Pilskalni[1)]	0.66	0.77	0.53	0.70
Salaca – Lagaste	0.80	0.93	0.77	0.87
Vienziemīte – Vienziemīte	0.86	0.91	0.73	0.84

[1)] – closed since 1995

struction and to estimate the eventual maximum flood (Zīverts & Jauja 1999), to study eutrophication and hydrotechnical problems of lakes, including climate change effects (Bilaletdin et al. 2004), to attempt to model parameter sets for ungauged catchments from measurable variables and to simulate nutrient runoffs in agricultural basins (Jansons et al. 2002).

The latest version METQ2007BDOPT model was calibrated and validated for five river basins. The results of calibration showed a good coincidence between the observed and simulated daily discharges from 1961 to 1990: the Nach-Sutcliffe efficiency R^2 varies from 0.86 to 0.66 and correlation coefficient r from 0.93 to 0.77 (Table 2). The best coincidence was obtained for the brook Vienziemīte where R^2 was 0.86 and r was 0.91. On one hand, it could be explained by the fact that the catchment area is small and used meteorological data fit very well to this drainage area for the description of the simulation of hydrological processes. On the other hand, we obtained rather good calibration results also for a large river basin as the River Salaca at Lagaste: R^2 was 0.80 and r was 0.93 (Fig. 3). The lowest statistical criteria were found for the rivers Bērze, Iecava and Imula. The validation of the model was done from 1991 to 2000, except for the river gauging stations Imula-Pilskalni and Iecava-Dupši, which were closed in 1995. In general, we obtained lower statistical criteria compared to calibration period: the statistical efficiency R^2 varies from 0.77 to 0.53 and correlation coefficient r varies from 0.87 to 0.70.

One of the main reasons for the difference between the simulated and observed runoff values is the quality of precipitation and vapour pressure deficit input data, and location of the available meteorological stations characterising the spatial and temporal distribution of precipitation in the studied drainage area. For instance, in the cases of the river basins Imula and Iecava we had to use data series of meteorological stations located outside the river basins (Fig. 1) and obtained lower calibration results (Table 1). As we know, precipitation has typically occasional character of distribution in the area and the conceptual rainfall-runoff models are sensitive to the input data, such as precipitation. Conditions for the calibration models are better, if at least one rainfall gauging station is located within the basin of the studied river. This is proved by the Salaca calibration results, which is the biggest river basin in this study according to its territory, where only one of the five used gauging stations was located outside the river basin.

Changes of river runoff under different future climate scenarios

The results of the long-term annual and seasonal analysis of metrological and hydrological data in the studied river basins are presented in Table 3 and Fig. 4. For the purpose of describing the character of changes in the river runoff, we will first look at the future changes of climatic parameters and determine, based upon which emission scenario most changes can be expected. Compared to the control period, major differences in meteorological and hydrological parameters in the future are forecasted according to A2 scenario, where long-term mean air temperature will grow by 4 degrees and precipitation by 12% and there will be increase of evapotranspiration, while the mean annual river flow will decrease by 19%. For both scenarios the air temperature will increase in all seasons, but the most considerable air temperature increase is forecasted for the winter and autumn seasons: 4.1–4.9 °C according to A2 and 3.0–3.4 °C according to B2. Increase in precipita-

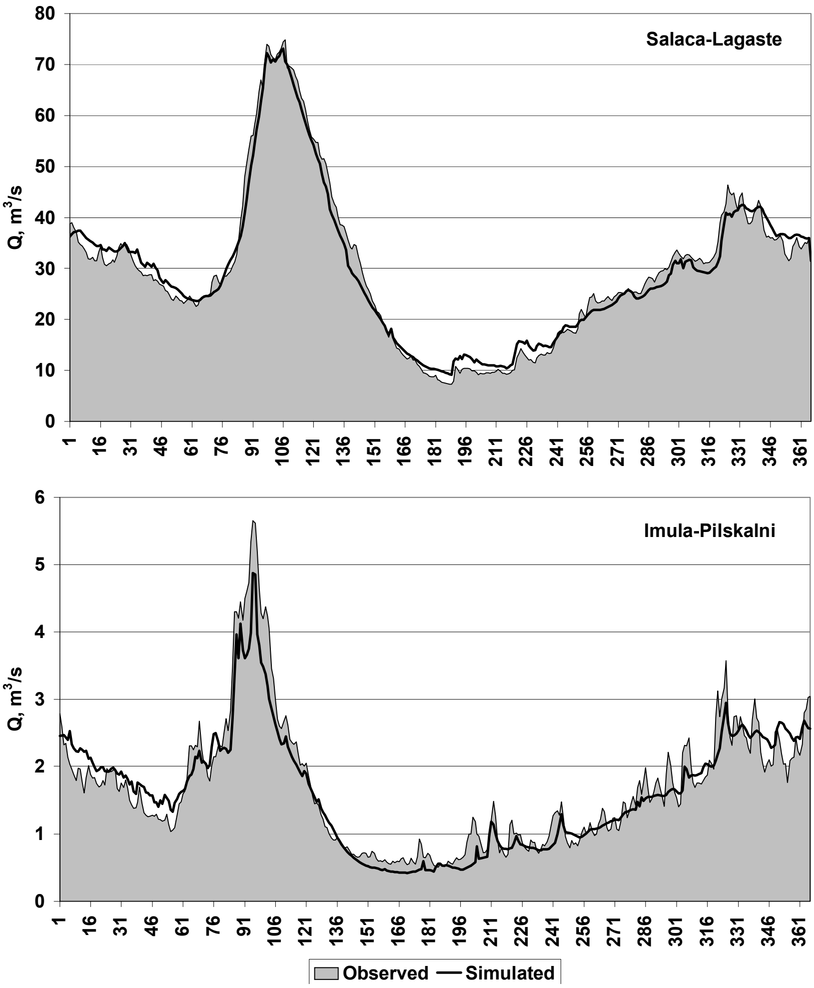


Fig. 3. Observed and simulated long-term mean daily discharge at the hydrological stations Salaca-Lagaste (R^2 – 0.80 and r – 0.93) and Imula-Pilskalni (R^2 – 0.66 and r – 0.77) from 1961 to 1990.

tion is forecasted in winter season by 7–9% according to A2 and 4–5% according to B2, while the decrease is forecasted over the second half of the year, especially in autumn, by 4–5% according to A2 and 2–3.5% according to B2. The simulations results of the studied rivers show the increase of runoff in winter season by 7–18% according to A2 and 4–12% according to B2 and mostly decrease of runoff in spring season by 1–9% according to both scenarios. At the second half-year period, under the conditions of the decreased precipitation and increased air temperature and evapotranspiration, river runoff is forecasted to decrease, particularly in the autumn season, by 3–10% according to A2 and 1–8% according to B2.

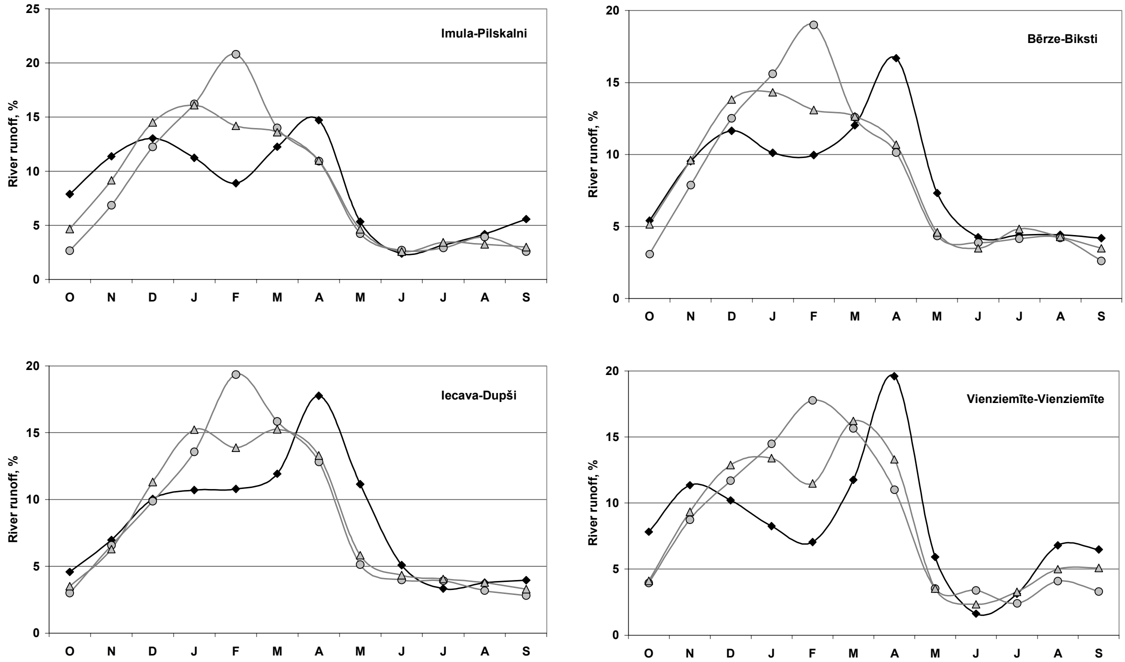
Fig. 4 shows the forecasted changes in seasonality by a monthly step of the total river runoff distribution and a shape of hydrograph for the studied rivers at the end of the 21st century. In the control period from 1961 to 1990 Latvian rivers are characterized by a typical hydrograph of the 20th century: two main discharge peaks during the spring snowmelt and in late autumn during the intense rainfall, and low river discharge in winter and summer. It was typical that the major portion of the total annual river runoff of 32–41% occurs in the spring season, and then followed by 25–33% in winter, 16–25% in autumn and 10–15% in summer. The results of simulation under future climate scenarios A2 and B2 show that the major part of the total annual river runoff will be generated in

Table 3. Changes in long-term mean annual and seasonal air temperature, precipitation and river runoff between A2 or B2 scenario (2071–2100) and CTL control period (1961–1990).

Climate parameter/ scenario	River basin				
	Imula	Bērze	Iecava	Vienziemīte	Salaca
Air temperature, change in ^{0}C					
Annual / A2	3.9	3.9	4.0	4.1	4.0
Annual / B2	2.5	2.5	2.6	2.7	2.6
Winter / A2	4.4	4.5	4.8	4.9	4.9
Winter / B2	3.1	3.1	3.1	3.3	3.4
Spring / A2	3.7	3.8	3.9	4.1	4.1
Spring / B2	2.3	2.4	2.9	2.9	2.9
Summer / A2	3.1	3.1	3.1	3.1	3.0
Summer / B2	1.4	1.4	1.5	1.5	1.3
Autumn / A2	4.1	4.1	4.2	4.2	4.1
Autumn / B2	3.2	3.3	3.0	3.0	3.0
Precipitation, change in %					
Annual / A2	11	11	10	12	12
Annual / B2	8	8	6	9	9
Winter / A2	9	9	8	7	7
Winter / B2	5	5	4	4	4
Spring / A2	0.6	0.6	0.8	1	–0.2
Spring / B2	0	–0.2	0.3	0.2	–0.3
Summer / A2	–6	–6	–4	–3	–2
Summer / B2	–3	–2	–2	–2	0
Autumn / A2	–4	–4	–5	–5	–4
Autumn / B2	–2	–2.5	–3	–3	–3.5
Runoff, change in %					
Annual / A2	–14	–13	–12	–18	–19
Annual / B2	–5	–5	–4	–11	–3
Winter / A2	16	15	11	18	7
Winter / B2	12	10	9	12	4
Spring / A2	–3	–9	–7	–7	3
Spring / B2	–3	–8	–6	–4	–1
Summer / A2	–1	–1	–1	–2	–2
Summer / B2	–2	1	0	–1	2
Autumn / A2	–10	–6	–3	–10	–8
Autumn / B2	–8	–1	–2	–7	–4

winter season (39–49% according to A2, 35–45% according to B2) and then it will be followed by spring (28–37% and 27–33%, respectively), autumn (9–13% and 9–16%) and summer (11–16% and 13–19%).

The river hydrograph is going to take a different shape for the late 21st century compared to the control period. In most cases, according to A2 scenario, the spring flood will decrease and the hydrograph peak will shift to an earlier month, i.e. from April to February. More considerable decrease in runoff is forecasted for autumn, compared to the spring season. According to B2 scenario, the river hydrograph is smoother and does not have a typical peak discharge. However, the river maximum discharges at the end of this century will occur in winter instead of spring. Considerable decrease in runoff is also forecasted for



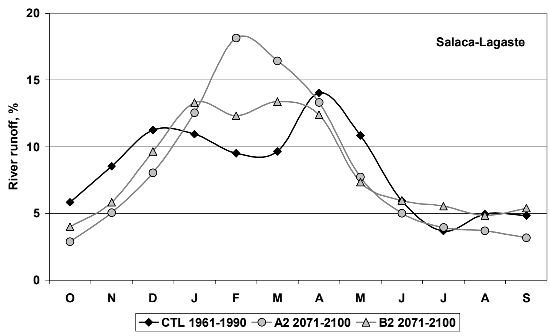


Fig. 4. River hydrograph of a hydrological year from October to September and distribution of the total annual river runoff (in percentages) in five studied river basins by study periods: control period CTL (1961–1990) and future climate scenarios A2 and B2 (2071–2100).

spring and autumn, but it is less pronounced compared to the A2 scenario.

The analysis of simulation results shows that the most considerable annual river runoff decrease is forecasted for the Northern river basins Vienziemīte (18%) and Salaca (19%) according to B2 scenario, and for the Vienziemīte (11%) according to B2 scenario. According to both scenarios in the seasonal analysis higher increase of the river runoff in winter and decrease in autumn can be expected for two upland basins the Vienziemīte and Imula, and higher decrease of runoff in spring can be forecasted for the Bērze, Iecava and Vienziemīte.

Comparison to other studies in forecasting river runoff changes

We have been searching with high interest for similar studies dealing with forecasted river runoff changes within this century to compare the results in the Baltic Sea region, and especially, in the Baltic countries. In earlier studies by Jaagus et al. (1998) in Estonia, Butina et al. (1998) in Latvia and by Kilkus et al. (2006) in Lithuania climate data series from General Circulation Models (GCM) with different emission scenarios were used for simulation of river runoff. In Estonia and Lithuania the forecasted increase of annual river runoff is 20–40% and up to 29% on average. In study by Butina et al. (1998) for the Lielupe river basin it was found out that the river flow was going to increase by 11%–83% on average depending on the scenario. Later Rogozova (2006) studied two Latvian river basins, the Gauja and the Irbe, and identified both increase and decrease trends (ranging from –7% to 17%). However, she came to the conclusion that forecasting of the annual river runoff increase or decrease may depend of the chosen GCM and emission scenario in RCM RCAO.

The latest study in Lithuania was carried out by Kriaučiūnienė et al. (2008) for the Nemuna River. They used new climate scenarios presented in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change which gives an opportunity to evaluate the river runoff changes more precisely. The results of simulation show that the runoff will increase in winter and decrease in spring according to all emission scenarios. Both increasing and decreasing tendencies of runoff were found for summer and autumn. The annual runoff of the Nemuna River was forecasted to decrease in the 21st century.

In the Assessment of Climate Change for the Baltic Sea Basin (Bolle et al. 2008) about 20 scenarios of RCMs were analysed. Regional distinctions in hydro-climate patters in the future forecasts were identified. The annual river runoff is forecasted to increase in the North, and to decrease in the South. Latvia is situated in the middle of both regions; however, the main tendency in the future climate and river runoff change is shifted rather towards the Southern region. In contrary to the South forecast and according to our study results, autumns in Latvia will become much drier followed by streamflow decrease in the autumn season more precisely compared to summer.

In both early and later studies in the Baltic countries it was predicted that the increase of river runoff will be remarkable during winter seasons due to the shortening of the period with snow and ice cover, while the spring runoff maximum will mostly decrease and shift to earlier periods. However, there are different forecasts concerning the total annual river runoff, where the decrease of runoff is forecasted in last studies, and there results comply with the results of our study.

Conclusions

In this study the changes in river runoff prediction in Latvia at the end of the 21st century are based on one control run (1961–1990) and two future climate scenarios A2 and B2 runs (2071–2100) from RCM RCAO. The conceptual rainfall-runoff model, the latest version of METQ2007BDOPT, was used for simulation of hydrological processes in five studied river basins.

Our study demonstrates that climate will change in the end of this century, subsequently modifying the hydrological regime of Latvian rivers. Major differences in hydrometeorological data were observed according to A2 scenario in both annual and seasonal analysis. Simulation results show that compared to the control period both future climate scenarios A2 and B2 forecast that annual river runoff will decrease under climate conditions, when air temperature, precipitation and evapotranspiration increase. Concerning seasonality the major differences in hydrometeorological parameters are predicted for winter and autumn. We can conclude that September and October are going to be among the driest months. The major part of river runoff will be generated in winter due to warmer climate, followed by spring, autumn and summer. In the future the river hydrograph is going to take a different shape, where the river maximum discharges will occur in winter instead of spring. The river hydrograph will have two main periods: a high flow period from November to April, and a low flow period from May to October. Our obtained results of projections of climate change impacts on hydrological processes in Latvian rivers generally correspond to the latest studies in the Baltic region.

ACKNOWLEDGEMENTS

This study was supported by the national research program Climate Change Impact on Water Environment in Latvia and data were provided by the Latvian Environment, Geology and Meteorology Center and SIA Meliorprojekts. Authors would like to thank Professor A. Zīverts for generously provided consultations and knowledge about modeling basics in hydrology.

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