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Climate change impact on the Nemunas River basin hydrology in the 21st century

Edvinas Stonevičius, Egidijus Rimkus, Andrius Štaras, Justas Kažys and Gintaras Valiuškevičius

Department of Hydrology and climatology, Vilnius University, Čiurlionio 21, LT-03101 Vilnius, Lithuania (corresponding author's e-mail: edvinas.stonevicius@gf.vu.lt)

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Climate change is likely to alter the runoff regime and its origin in the Nemunas River basin. The changes in runoff volume, seasonality and flood regime might affect hydropower production management, the potential of a forthcoming nuclear power plant and the stability of ecosystems. The water balance model WatBal was used to estimate the changes in the Nemunas River basin hydrology during the periods 1981–2000 and 2081–2100. The monthly air temperature and precipitation projections for the 21st century were estimated using the CMIP 5 model outputs. The two most diverse representative concentration pathways, RCP2.6 and RCP8.5, were analysed in this study to evaluate the spectrum of probable changes in the Nemunas River basin hydrology. The results revealed that the hydrological response to climate change in the Nemunas River basin would be most likely related to the change in snow climate. The projected magnitude of runoff changes during winter and spring is comparable for both scenarios, but the most important distinction is the difference in the cold-season hydrological regime, and especially water supply during winter and spring. According to the climate change scenarios both rain-snow and only rain dominant hydrological regimes are probable in the Nemunas River basin at the end of the 21st century.

Introduction

The Nemunas River is the main tributary of the Curonian Lagoon and one of the largest tributaries of the Baltic Sea. In the Nemunas River basin there is a high concentration of industry and also a large part of the basin area is used for agriculture. One of the main issues in the Nemunas River basin is the management of nutrient loadings from point and diffusive sources, which contribute to eutrophication of freshwater bodies, the Curonian Lagoon and the Baltic Sea (HELCOM 2011). Climate change is one of the factors affecting eutrophication, as well as the loadings of nutrients to waterbodies (Inkala *et al*. 1997, Bring *et al*. 2015, Wu and Malström 2015).

There are more than 800 reservoirs in the Nemunas River basin. Most of them are very small and are important only locally. The expansion of hydropower usage is currently ongoing in the Belarusian part of the Nemunas River basin. In Lithuania, the Kaunas hydropower plant (100.8 MW) with a 0.46 km^3 reservoir was established in 1960 on the Nemunas River. Since 1992, the Kruonis pump storage power plant (900 MW) has been operational. It can pump into

Editor in charge of this article: Hannu Marttila its reservoir up to 189 $m^3 s^{-1}$ from the Kaunas hydropower plant reservoir. In the last few years, the construction of a nuclear power plant near the largest Nemunas tributary, the Neris River, has been debated. Water from this river would be used to cool the nuclear-plant reactors. It is estimated that water consumption by the nuclear power plant should not exceed 8.7% of the Neris River low runoff (Anon. 2010). Changes in the river runoff volume, seasonal distribution, frequency and magnitude of extreme hydrological events could affect the working of the existing hydropower plants and affect the expansion of the energetic sector in the 21st century.

During the past few decades, the climate in the Nemunas River basin changed notably. The mean air temperature in Vilnius increased by 1.4 °C during the period 1778–2012. The maximum temperature change was recorded during the winter months (Mickievič and Rimkus 2013). Changes in climate extremes are also evident (Kažys *et al*. 2009, 2011, Rimkus *et al*. 2011, 2012, 2014). Climate projections show that the changes observed in recent decades will persist also in the 21st century (Keršytė *et al*. 2015).

The effects of climate change on runoff in the Baltic region have already been observed (Hisdal *et al*. 2006, Wilson *et al*. 2010, Hall *et al*. 2014, BACC II Author Team 2015), and the long-term river runoff trends analysed (Bergström and Carlsson 1994, Klavins *et al*. 2002, Kriauciuniene *et al*. 2012, Arheimer and Lindström 2015). Shifting of river floods in time (Stewart *et al*. 2005, Sarauskiene *et al*. 2015) and seasonal changes in the runoff regime (Silander *et al*. 2006, Godsey *et al*. 2014) are evident for rivers with externalized winter conditions. Most of the river discharge changes are related to altered patterns of atmospheric circulation (Graham *et al*. 2009, Sepp 2009, Klavins and Rodinov 2010).

The changes in the Nemunas River runoff in the last few decades were the most extreme since the start of observations at the beginning of the 19th century (Stonevičius *et al*. 2014). The annual and winter runoffs have increased. The greatest changes have been recorded at the end of the cold season. In the Nemunas River basin, there is a clear evidence of a spring flood shift towards the beginning of the year (Meilutytė-Barauskienė and Kovalenkovienė 2007). The changes in spring flood magnitude and timing are related to the snow water equivalent before the snowmelt (Rimkus and Stankunavichius 2002, Stankunavicius *et al*. 2007). Changes during summer and autumn were smaller. The minimum discharge during the warm season did not changed much (Kriaučiunienė *et al*. 2007, Rimkus *et al*. 2013).

In the 21st century, climate change will affect water resources and the flooding regime (Arnell and Lloyd-Hughes 2014), and the magnitude of the changes will largely depend on representative concentration pathways (RCPs) (Koirala *et al*. 2014). There are many future runoff projections for the Baltic Sea drainage basin and the Nordic countries (Vehviläinen and Huttunen 1997, Bergström *et al*. 2001, Rummukainen *et al*. 2003 Graham *et al*. 2007, Beldring *et al*. 2008, Kriaučiūniene *et al*. 2008, Kjellström and Lind 2009, Apsite *et al*. 2011, Salmonsson 2013). The assessments were made using multiple climate model projections (Bergström *et al*. 2001, Rummukainen *et al*. 2003, Graham *et al*. 2007, Beldring *et al*. 2008, Zhang *et al*. 2015) and different hydrological models (Dankers and Christensen 2005, Silander *et al*. 2006, Pohl *et al*. 2007, Woo *et al*. 2008, Aspite *et al*. 2011, Salmonsson 2013, Holmberg *et al*. 2014, Arheimer and Lindström 2015). The studies covered various runoff characteristics typical to boreal climates (Dankers and Christensen 2005, Pohl *et al*. 2007, Berghuijs *et al*. 2014, Arheimer and Lindström 2015, Zhang *et al*. 2015) as well as different views on hydrological processes (Silander *et al*. 2006, Woo *et al*. 2008, Kjellström and Lind 2009, Holmberg *et al*. 2014).

In most studies on climate change effects on the Nemunas River basin hydrology only the runoff changes in the future were analysed (Kilkus *et al*. 2006, Kriaučiūniene *et al*. 2008, Rimkus *et al*. 2012). The runoff represents the integrated climate effect on hydrology. Its integrating nature, however, may overshadow the effects of climate change on some hydrological processes, especially when studies are based on monthly data or only certain parameters of the runoff such as annual runoff, maximum and minimum discharge are analysed. As a result, important aspects of possible future changes may remain unknown. For example, a simultaneous increase in precipitation and evaporation may produce no change in the runoff even though both aforementioned parameters change.

A more comprehensive understanding of the effects of climate change on hydrology is important in regions where projected temperature changes may lead to a shift from a snow- to a rain-dominated hydrological regime (Arnell and Lloyd-Hughes 2014, Berghuijs *et al*. 2014, Vormoor *et al*. 2015). In thhe present study we focused on the effect of climate change on the runoff formation in the Nemunas River basin. Particular attention was paid to the effect of climate change on snowfall and snowpack water equivalent changes in the 21st century.

Data and methods

Study area

The Nemunas River is 14th according to its length (937.4 km) and 15th according to its catchment area (97 864 km^2) in Europe. The Nemunas runs through Belarus, Lithuania, the Russian Federation (Kaliningrad Region), Poland and Latvia. Largest parts of the Nemunas River basin are in Lithuania (47.6%) and Belarus (46.4%). In its lower reaches, the Nemunas is a natural border between Lithuania and the Kaliningrad Region. Before draining into the Curonian Lagoon the Nemunas forms a large delta.

The soil in the Nemunas River basin is mostly sand or sandy clay. Sandy clay and sandy soils are common in the northwest and southeastern parts of the Nemunas basin, respectively. The basin's topography and hydrographical network was formed during the late quaternary period. The uneven and in some places ridged terrain was formed during the retreat of a glacier. Altitudes ranging from 150–200 m are common in the eastern part of the basin. The altitude gradually drops towards the Baltic Sea and in the Nemunas delta region it is only a few meters above sea level. Due to low altitudes, floods are most common and have the largest extent in this part of the basin. Floods with the highest water levels are usually related to ice jams in the Nemunas River basin.

The mean annual air temperature in the Nemunas River basin in 1981–2000 was 6.6 °C. During the same period, the mean temperature in December–February was below 0°, July was the hottest month with the mean temperature of 17.2 °C, and January and February were the coldest months (mean temperature –3.4 °C). In the second part of the 20th century on average 150 days were frost-free. Snow usually appeared in December and melted in mid-March, but in some cases snow cover could last until the end of April.

The mean annual precipitation in 1981–2000 was 670 mm. During wet years the annual precipitation could reach 900 mm, while during dry years it usually did not drop below 550 mm. The highest precipitation was recorded in summer and September, and the lowest in January–April.

The distance from the Baltic Sea is one of most important factors determining the amount of liquid precipitation during winters (Kriauciuniene *et al*. 2006). In the western part of the Nemunas River basin, winters are milder than in the rest of the basin and the percentage of liquid precipitation is higher. Snow cover in the western part is usually thinner and thaws are more frequent. Due to this, spring-flood peak discharge rates are lower in the western part than elsewhere in the basin.

At the end of the 20th century, the annual evapotranspiration in the Nemunas River basin was 450–600 mm (Galvonaitė *et al*. 2007), and the total annual runoff 25 km^3 of which about 40% was from snow melt, 25% from rain and the remaining 35% from groundwater. In the rivers of the Nemunas River basin, about 41%–46% of the annual runoff occurs in spring due to the contribution of snow meltwater. The summer runoff is the lowest: 15%–18%. The autumn and winter runoff volumes are roughly similar: 11%–38% of the annual runoff.

Hydrological model

The WatBal water balance model (Kaczmarek 1993, Yates 1996) was used to represent the hydrological processes in the analysed catchments. WatBal is a lumped conceptual water balance model which uses few model parameters, precipitation and air temperature to calculate the runoff components and relative water storage in the catchment at any given time *t*:

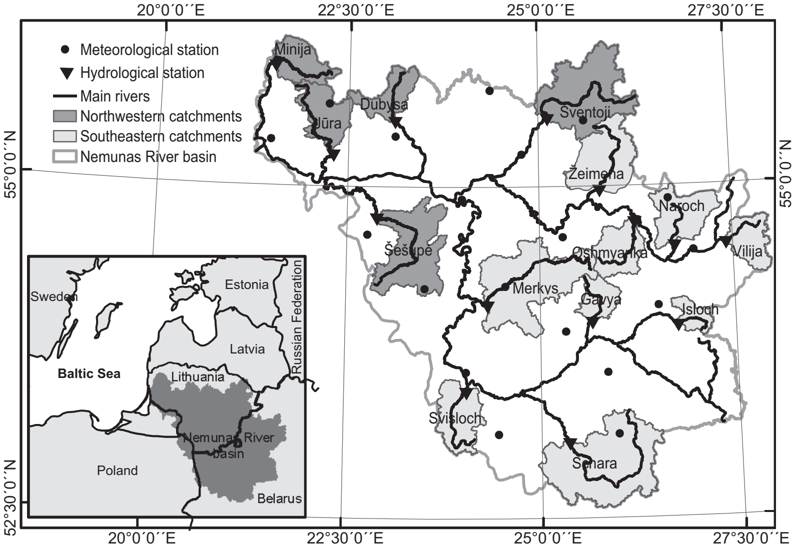

Fig. 1. Locations of the 14 analysed independent catchments in the Nemunas River basin.

$$S_{\max}\frac{dz}{dt}=\left[P_{\text{eff}}\left(P,T_{\text{air}},t\right)\left(1-\beta\right)\right]-R_{\text{s}}\left(z,t\right) \\ -R_{\text{ss}}\left(z,t\right)-E_{\text{v}}\left(T_{\text{air}},z,t\right)-R_{\text{b}}, \quad (1)$$

where $S_{\max}$ is the maximum storage capacity (mm), z is the relative storage, P_{eff} is the effective precipitation (mm), P is the precipitation amount (mm), T_{air} is the air temperature (°C), β is the direct runoff coefficient, R_{s} is surface runoff (mm), R_{ss} is the sub-surface runoff (mm), E_{v} is the evaporation (mm), R_{b} is the baseflow (mm).

The WatBal model was initially designed to study the effect of climate change on the runoff. Identification of the main climate change drivers and most important processes is relatively straightforward with WatBal due to the simplicity of its structure. These conceptual runoff models have more structural uncertainty (Poulin *et al*. 2011), but usually climate change projections are the source of greater uncertainties (Kriauciuniene *et al*. 2013).

Variations in climate, topography, land use and soil in the Nemunas River basin are relatively small, but various combinations of conditions may result in different climate change effects on hydrology in different parts of the basin. An analysis based on the effect of climate change on the large Nemunas River alone could mask effects on hydrology at a smaller scale. To address this issue fourteen small- and medium-sized independent catchments distributed throughout the Nemunas River basin were analysed (Fig. 1). These catchments are located in the upper reaches of the Nemunas River tributaries with hydrological stations in the lower cross section. The area of the analysed catchments varies from 624 km^2 (the Isloch River upstream of the Borovikovshina hydrological station) to 4300 km^2 (Merkys upstream of the Puvočiai hydrological station.

The monthly air temperature and precipitation data were used as input for the WatBal model. The data from 19 meteorological stations (Fig. 1) were used to calculate the meteorological variables for all 14 catchments. The potential evapotranspiration was calculated using the Thornthwaite (1948) equation. Precipitation composition, effective precipitation during the cold season and snow water equivalent were estimated using the temperature index model.

The WatBal model calibration was performed with the hydrological and meteorological data for 1981–2000. Six model parameters were used to fit WatBal to a specific catchment: maximum water storage capacity, surface, subsurface, direct runoff coefficients, and threshold temperature for snow formation and snowmelt. The direct runoff coefficient represents the percentage of impervious areas and waterbodies in the catchment. It was calculated according to land use in the catchments. The values of the other five parameters were obtained during an optimization procedure which is incorporated in the WatBal model. This procedure leads to the loss of the physical meaning of parameters (Yates 1996), but the overall goodness of the model fit might be satisfactory. In our study, the goodness of the model fit was evaluated using Pearson's correlation (r_P) and mean daily bias (ΔR), i.e. the difference between the daily measured and modelled values (*see* Table 1). Both indicators of fit were calculated using monthly data for 20-year periods ($n = 240$). The correlation coefficient allows one to judge the runoff seasonality fit, while the mean daily error estimates the accuracy of the modelled runoff volume. The greatest mean daily bias was in the Jūra River — the modelled runoff was on average 0.0122 mm per day greater than the observed one. The correlation between the modelled and measured runoffs was also very strong ($r > 0.95$, $p < 0.0001$) (Table 1). The 2001–2010 period was chosen for model verification. The correlation between modelled and measured runoffs during the verification period was only marginally weaker in most catchments and the mean daily bias remained negligible (Table 1).

Climate change projections

The impact of climate change on the Nemunas River basin hydrology was estimated using climate projections for the 21st century. The changes were evaluated comparing the averages of the meteorological and hydrological variables between two 20-year periods: 1981–2000 and 2081–2100.

The climate projections for the 21st century were made on the basis of the CMIP5 (Coupled Model Intercomparison Project Phase 5) model outputs. The CIMP5 climate projections are based on four concentration pathways (RCPs), which represents different possible values of radiative forcing (2.6, 4.5, 6.0, 8.5 W m^{-2}) in 2100 to be compared with the pre-industrial level. The two most diverse RCP2.6 and RCP8.5 climate change scenarios were analysed in our study. According to the RCP2.6 scenario, the external forcing and predicted changes in the climate system will be the smallest, while according to RCP8.5 they will be the greatest. In this way, the whole spectrum of possible changes could be evaluated.

A common output data grid of 2.5° lat. × 2.5° long. was used for analysis. The Nemunas river basin area falls into five grid cells. For the purpose of making air temperature and precipitation amount predictions for the end of the 21st century, the projected changes in the analysed indices were derived from the CMIP 5 model output series. These values were added to the

Table 1. Calibration and validation values for the analysed river catchments (r_P = Pearson's correlation coefficient and ΔR = mean daily bias). All correlation coefficients are statistically significant at $p < 0.0001$); $n = 240$.

River	Hydrological station	Catchment area (km^2)	Calibration		Verification	
			r_P	ΔR (mm d^{-1})	r_P	ΔR (mm d^{-1})
Isloch	Borovikovshina	624	0.98	0.0011	0.99	0.0013
Gavya	Lubiniata	920	0.96	0.0008	0.89	0.0006
Schara	Slonim	4860	0.96	0.0003	0.94	0.0007
Svisloch	Sukhaya Dolina	1720	0.98	0.0005	0.91	0.0004
Vilija	Steshytsy	1200	0.98	0.001	0.97	0.0007
Naroch	Naroch	1480	0.98	0.0008	0.97	0.0020
Oshmyanka	Bolshiye Yatsiny	1480	0.95	0.0006	0.97	0.0002
Merkys	Puvočiai	4300	0.97	0.0005	0.91	0.0000
Žeimena	Pabradė	2580	0.99	0.0008	0.92	0.0005
Šventoji	Anykščiai	3600	0.99	0.0019	0.92	0.0012
Dubysa	Lyduvėnai	1134	0.98	0.004	0.95	0.0039
Šešupė	K. Naumiestis	3179	0.99	0.0012	0.96	0.0008
Jūra	Tauragė	1664	0.98	0.0122	0.96	0.0009
Minija	Kartena	1230	0.96	0.0097	0.97	0.0005

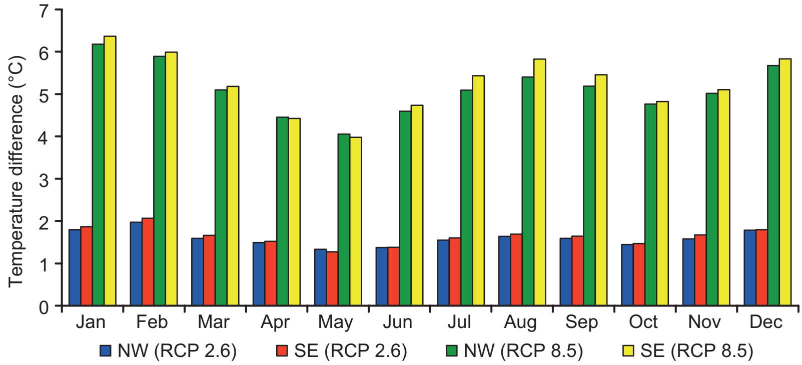

Fig. 2. Projected average monthly temperature changes for 2081–2100 compared with 1981–2000 according to the RCP2.6 and RCP8.5 climate-change scenarios in north-western (NW) and south-eastern (SW) parts of the Nemunas River basin.

mean values of the reference period 1981–2000 from 19 meteorological stations. The projected changes were calculated as the air temperature difference (°C) or precipitation amount ratio (%) between 2081–2100 and 1981–2000 in a particular grid cell where a meteorological station is located. Later, the projected temperature and precipitation values were used to calculate the averages for the analysed catchments. The WatBal model was employed to calculate the runoff, real and potential evapotranspiration for the 2081–2100 period using the precipitation and temperature projections.

Results

Climate projections

It is expected that at the end of the 21st century the air temperature will be higher than during the reference period 1981–2000 (Fig. 2). According to the RCP2.6 scenario, the mean annual temperature in the Nemunas River basin will increase by 1.6–1.7 °C. The seasonal differences of the projected changes will be very negligible: the greatest increase will be observed in winter (up to 1.9–2.2 °C in February), while the smallest in spring (up to 1.3–1.4 °C in May). Slightly greater changes are projected for the eastern part of the investigated area, which is more distant from the Baltic Sea.

According to the RCP8.5 scenario, the mean annual temperature will increase by 4.9–5.4 °C and the seasonal differences of the projected changes will be slightly greater than those indicated by RCP2.6. The winter temperatures will increase the most, by 5.5–6.5 °C, while the spring air temperature changes will be the smallest: 4.4–4.8 °C. In January, the mean air temperature could even rise to 5.7–6.9 °C. The greatest changes are expected in the northeastern part of the basin and the lowest in the west.

The annual precipitation sum will also increase (Fig. 3). According to RCP2.6, an increase of 6%–7% can be expected. More prominent changes will be observed in the northern part of the basin. Meanwhile, seasonal differences in the projected changes will be very minor. In winter, the amount of precipitation will increase by 8%–10% (by 10%–13% in February), while in summer the changes will be smaller: 4%–6% (1%–2% in July). The winter temperature increase will lead to a shift in the phase composition of the precipitation, e.g. liquid precipitation will become more common during the cold period of the year.

According to RCP8.5, the annual amount of precipitation will increase by 9%–10% and 13%–14% in the southern and northern parts of the basin, respectively. The direction of seasonal changes will differ. In winter the amount of precipitation will increase sharply, by 23%–28% (mostly in January and up to 30% in the northeast of the basin), while in summer it will decrease by 2%–7%. The greatest decrease is expected in July (up to 12% in the southeastern part of the river basin).

Runoff

Changes in the climate variables will affect the runoff. The amount of annual precipitation will

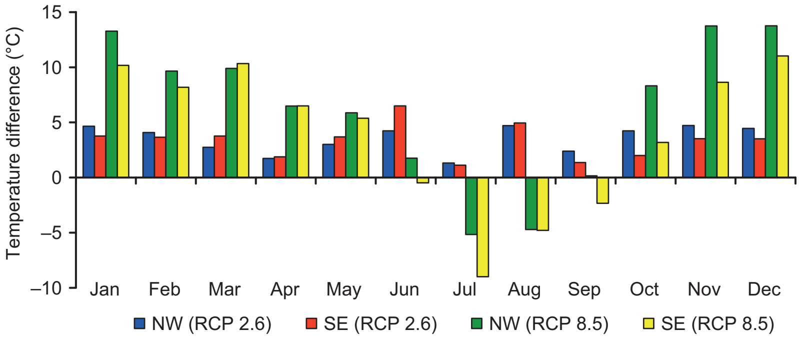

Fig. 3. Projected average monthly precipitation changes for 2081–2100 compared with 1981–2000 according to the RCP2.6 and RCP8.5 climate change scenarios in the northwestern (NW) and southeastern (SW) parts of the Nemunas River basin.

increase under both climate change scenarios, but the projected annual runoff in the analysed catchments will decrease slightly by the end of the 21st century. According to RCP2.6, the decrease in annual runoff will be less than 10% in the majority of the Nemunas River basin catchments. Only in the Jura (western part of the basin) catchment, the projections show a decrease in runoff of 14%. In the more extreme RCP8.5 scenario, the annual runoff changes are likely to be more pronounced in all parts of the Nemunas River basin. The greatest changes are likely to be in the northwestern part of the basin. An annual runoff decrease greater than 15% is projected for the Šventoji, Žeimena, Dubysa and Jūra catchments.

The projected seasonal runoff changes are much greater than the changes in annual runoff (Fig. 4). According to both climate change scenarios, in winter the runoff will increase in all the analysed catchments, while in the other seasons it will decrease.

Considering the seasonal runoff changes, the Nemunas River basin can be divided into two parts: northwestern (NW) and southeastern (SE). Changes in the seasonal runoff distribution in five NW catchments (Minija, Jura, Dubysa, Šventoji and Šešupė) are greater than in the SE ones (Isloch, Gavya, Nemunas, Ščiara, Svisloch, Vilija, Naroch, Oshmyanka, Merkys and Žeimena) (*see* Fig. 4).

Both climate change scenarios predict the greatest increase in winter runoff in the NW part of the Nemunas River basin. At the end of the 21st century, the runoff in January will be 15%–20% higher than in 1981–2000 in both parts of the Nemunas River basin. The February runoff is likely to increase by more than 50% in the NW catchments; whereas in the SE part of the basin, the changes in the February runoff will be smaller by 20% (RPC2.6) and 30% (RPC8.5) (Fig. 4).

According to RPC2.6, the March runoff at the end of the 21st century will increase by 10% in the whole Nemunas River basin. From April to September the runoff will decrease by 5%–10% in the SE part of the basin, while during the same time the runoff in the NW part of the catchment will decrease by 25%–30%. In October and November. the runoff will decrease by 10% in both parts of the Nemunas River basin. In the NW part, the December runoff will increase by 20%, while in the SE part it is likely to remain unchanged as compared with the 1981–2000 runoff.

Contrary to the outcome of RPC2.6, in the RPC8.5 scenario the March runoff in the NW catchments is likely to be smaller than in 1981–2000, while in the SE part of the Nemunas River basin the changes will be minor. According to RPC8.5, the decrease in runoff will last from March to November in the NW part of the basin. In April–September, the runoff might decrease by 20–50%. In this part of the Nemunas River basin, a runoff higher than in 1981–2000 is expected only in December–February. In the SE catchments, the runoff increase is projected only for January and February. During the rest of the year the runoff would be smaller than in 1981–2000, the decrease is likely to be between 10% and 20%, i.e. much smaller than in the NW catchments.

Snow cover and evaporation

In the second half of the 20th century, snow cover and river ice were common in the Nemu-

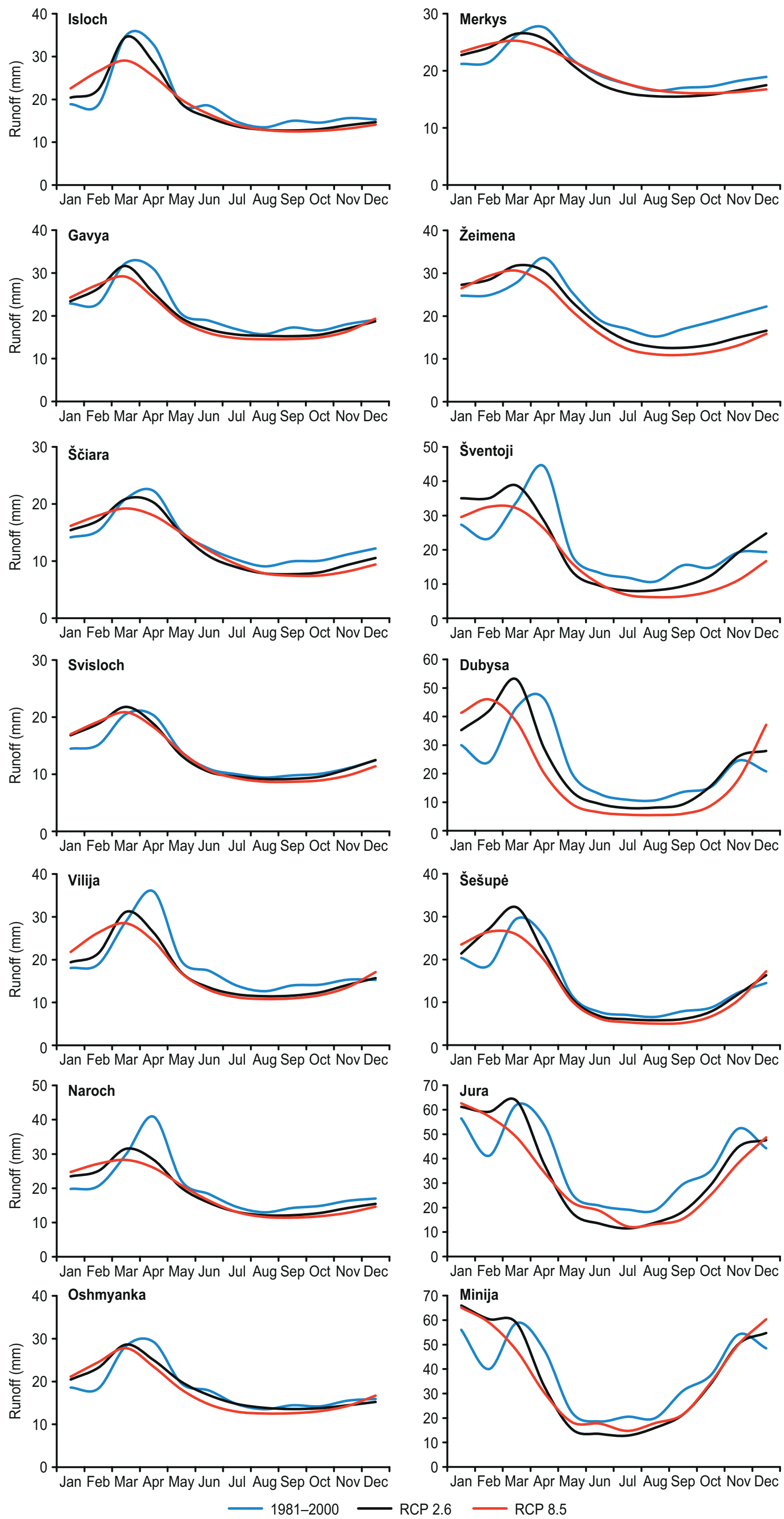

Fig. 4. Average runoff (mm per month) in the analysed catchments in 1981–2000 and the projections for 2081–2100 according to the RCP2.6 and RCP8.5 scenarios.

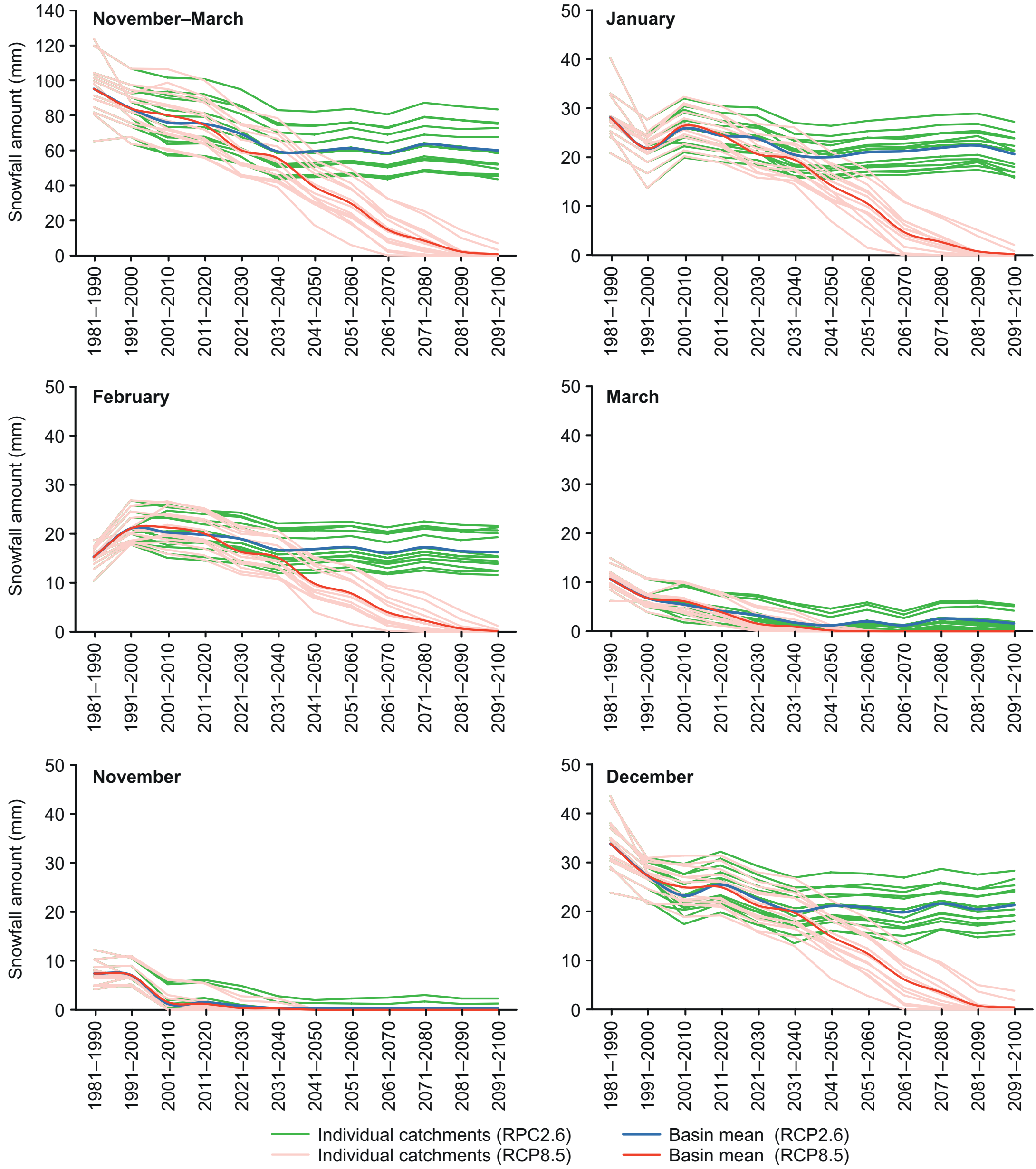

Fig. 5. Monthly snowfall amount in the analysed 14 individual river catchments according to the RCP2.6 and RCP8.5 scenarios and mean snowfall amount in the Nemunas River basin calculated as an average of 14 individual catchment data according to the RCP2.6 and RCP8.5 scenarios.

nas River basin during the cold season lasting from November to April. The runoff changes during the cold season in the 21st century will be mostly driven by the change in the amount and composition of precipitation. With higher temperatures, snowfall is likely to be more frequently replaced by rain. According to both climate change scenarios, from 2030 onwards precipitation in the form of snow in November will be very unlikely in the Nemunas River basin (Fig. 5).

From December to February, the changes in snowfall according to RPC2.6 will be much smaller than according to RPC8.5. In the RPC2.6

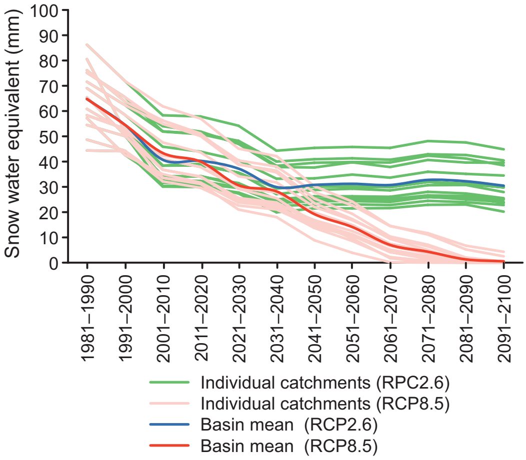

Fig. 6. Maximum monthly snow water equivalent in the catchments according to RCP2.6 and RCP8.5, and the Nemunas River basin mean snow water equivalent based on the 14 catchment data according to the RCP2.6 RCP8.5 scenarios.

scenario, the temperature changes will be smaller and the effect of increased temperature will be moderate because it will still be cold enough for snowfall (Fig. 5). The greatest changes are projected for the beginning of winter. At the end of the 21st century, the December snowfall amount will be ≈30% lower than in 1981–2000. In January and February, the snowfall changes will be even smaller: decrease by 14% and 10%, respectively. According to RPC8.5, the temperature changes will be much greater and consequently their effect on the precipitation composition will be more pronounced. In the second half of the 21st century, the snowfall amount will decrease dramatically (Fig. 5). In the RPC8.5 scenario, from 2060 onwards the snowfall amount in the NW catchments will seldom exceed 5 mm per month, while in the SE catchments the same conditions will occur 2–3 decades later.

According to both scenarios, snowfall in March will became very rare from 2040 onwards. In the second part of the 21st century, the snowfall amount exceeding the 5 mm per month will be still probable in the eastern part of the Nemunas River basin if the climate change follows the milder RPC2.6 pathway.

Higher winter temperatures might be related to more frequent thaws. Together with a smaller amount of snowfall the thaws will result in less water accumulating in the snow cover. During the observation period, the spring flood peak discharge was closely related to the amount water accumulated in the snow cover (Stonevičius *et al*. 2014). With less water in the snow cover the spring flood peaks are likely to be smaller. According to RPC2.6, the maximum monthly snow water equivalent is likely to be about 50% smaller from 2050 onwards (Fig. 6), while RPC8.5 indicates the maximum monthly snow water equivalent to gradually decrease, and in many catchments permanent snow cover will not form during the final decades of the 21st century. In the 21st century, the time of maximum snow water equivalent will shift towards January and February. Projections based on the RPC8.5 scenario suggest that at the end of the 21st century the snow cover is likely to be very temporary and thin; thus its effect on flood formation will be negligible and the time of maximum water equivalent will become irrelevant.

Changes in both liquid precipitation and snow melt will affect the water supply during the cold season. The general changes in water supply will be similar in both the NW and SW parts of the Nemunas River basin (Fig. 7). The main difference between the water supply in the SW and NW parts is a higher water supply in the NW part in November–January (10–15 mm per month). In both scenarios, the water supply in November–February is likely to increase in 2081–2100. In March and April the projected water supply is smaller than in 1981–2000. According to RCP8.5, the water supply will peak in December, whereas according to RCP2.6 the peak is likely to be in November and March in the NW and SE parts of the basin, respectively. According to RCP2.6, the November–February water supply from snow melt in 2081–2100 will remain similar to that in 1981–2000. In March it will be 60% smaller and in April the runoff is likely to be formed only from rain water. According to RCP8.5, the snow melt water contribution to the total water supply will be negligible at the end of the 21st century. The changes in the water supply projected in particular by RCP8.5 are likely to completely change the runoff regime in the cold season. In the 20th century, spring floods caused by snow melt were common in the Nemunas River basin. The river runoff had one

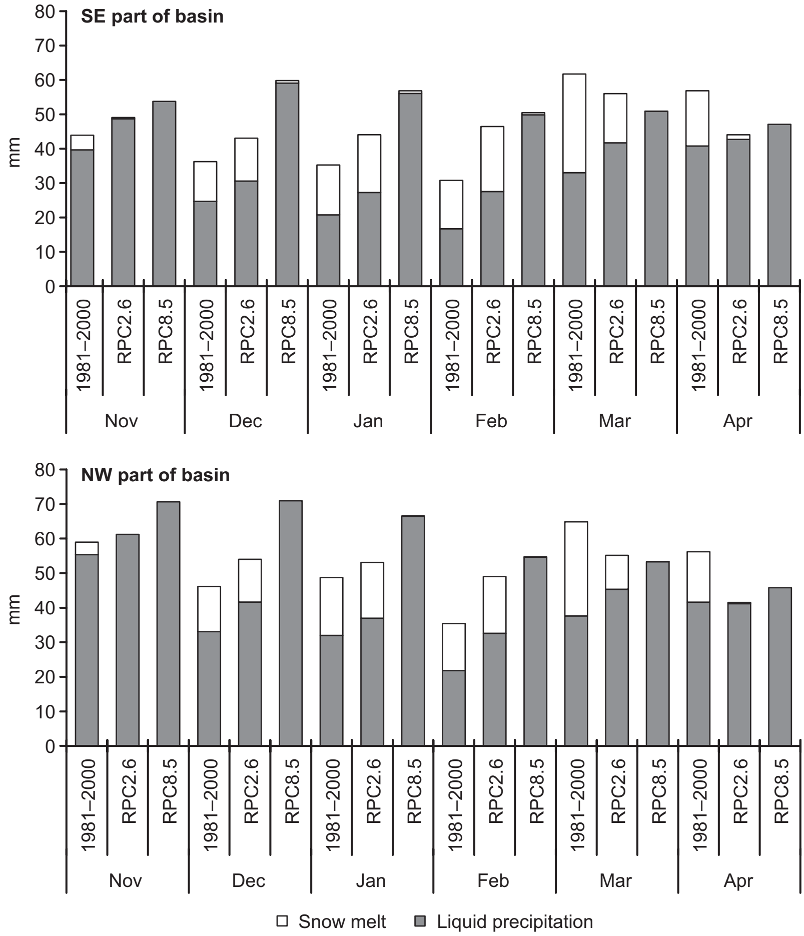

Fig. 7. Snow-season average water supply in the southeast and northwest catchments of the Nemunas River basin in 1981–2000 and projections for 2081–2100 according to the RCP2.6 and RCP8.5 scenarios.

or more well-defined peaks during spring floods and winter thaws. It is likely that rain might become the main source of water for the rivers even in winter and spring. In such a case, runoff peaks will follow rainfall events; they will be more frequent but smaller than the flood peaks caused by snow melt.

After May, evaporation becomes an important factor in runoff formation. The increase in evaporation and the smaller amount of water accumulating in the basin at the end of the cold season are the main drivers for lower runoff from May to October (Rimkus *et al*. 2013). It is likely that in the SE part of the basin the main reason for smaller runoff in the warm season will be increased evaporation (Fig. 8). The rivers located in the NW part of the Nemunas River basin have more pronounced seasonality than the rivers in the rest of the basin. With higher seasonality, the runoff falls back towards the baseflow much quicker after the spring flood and consequently there is less water accumulated in the catchment before summer. This might be the main reason why projected evaporation in the NW catchments only increases slightly according to the RCP8.5 scenario and even decreases according to the RCP2.6 scenario (Fig. 8) despite the increase in potential evapotranspiration. In the SE part, where the runoff seasonality is less evident and evaporation increases in March–August, it becomes much more influential.

Discussion

Climate change will certainly affect the winter and spring runoff regime in the Nemunas River basin, but a lot of uncertainty remains (Kriauciu-

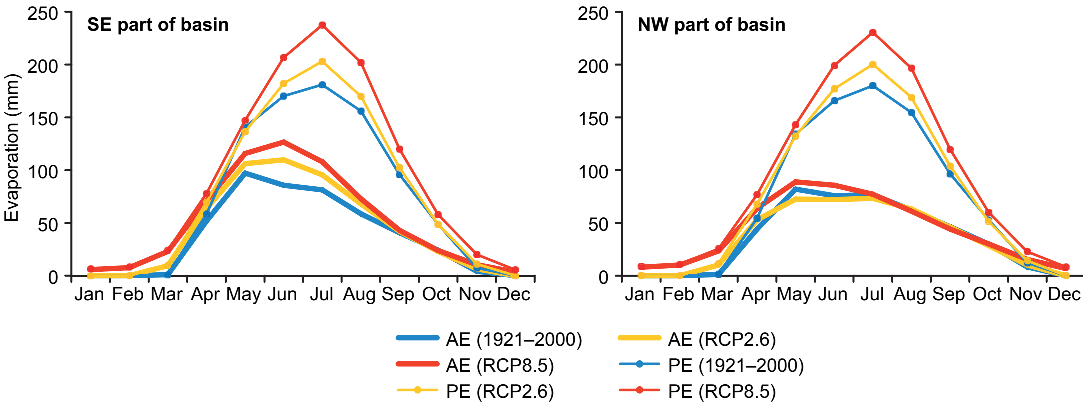

Fig. 8. Actual (AE) and potential (PE) evapotranspiration in the southeast (SE) and northwest (NW) parts of the Nemunas River basin in 1981–2000 and projections for 2081–2100 according to the RCP2.6 and RCP8.5 scenarios.

niene *et al*. 2013). Uncertainty about the impact of climate change is likely to be a challenge for water managers and planners, especially in the case of planning long-term measures (Silander *et al*. 2006).

In the past, winters with thick snow cower and springs with large floods were common in the Nemunas River basin (Stonevičius *et al*. 2014). In the final decades of the 20th century and at beginning of the 21st century, the amount of snow was decreasing, mostly due to higher temperatures. The same tendency is likely to persist throughout the 21st century, as it has been confirmed in other studies carried out in the Baltic Sea drainage basin (Kriaučiūniene *et al*. 2008, Kjellström and Lind 2009, Aspite *et al*. 2011, Arheimer and Lindström 2015). Projections of temperature based on the CMIP5 model outputs follow the trends observed at the end of the 20th century (BACC 2008). As it did during the last 60 years, the annual temperature will increase in the Nemunas River basin in the 21st century. The basin is located in the transitional zone between southern Europe, where precipitation decreased, and northern Europe, where precipitation increased at the end of the 20th century (McCarthy *et al*. 2001). Climate projections foresee an increase in precipitation throughout the whole area of the Nemunas River basin by the end of the 21st century (Keršytė *et al*. 2015).

Projected changes in the Nemunas River basin hydrology will also continue according to the changes observed at the end of the 20th century (Stonevičius *et al*. 2014). Despite the increase in annual precipitation, according to both climate change scenarios annual runoff is likely to decrease. During the second part of the 20th century, an increase in runoff was observed in the northwestern part of the Nemunas River basin, while in the southeastern part a decrease was more common. Projections of annual runoff show its decrease in the 21st century throughout the whole Nemunas River basin. Studies based on the CMIP5 modelling outputs project an increase and a decrease in runoffs in northern and southern Europe, respectively (Alkama *et al*. 2013, Koirala *et al*. 2014). The results of WatBal suggest that the boundary between opposite runoff trends is likely to be located towards the north of the Nemunas River basin.

The main effect on the Nemunas River basin hydrology in the 21st century is likely to be the change in the snow regime. The changes in the winter-precipitation composition were evident in the Nemunas River basin during the final decades of the 20th century (Gečaitė and Rimkus 2010). The amount of liquid precipitation during the cold season increased, while the amount of snowfall decreased. Similar was observed in other parts of the northern hemisphere (Huntington *et al*. 2004). The Nemunas River basin is located in an area with a relatively mild winter climate and an increase in winter temperature will affect the snow climate. Temperature is projected to increase through the 21st century and snowfall along with the snowpack are likely to decrease (Mankin and Diffenbaugh 2015). According to RCP2.6, the winter temperature will increase by up to 2 °C. This increase in temperature will lead to the disappearance of snow in November and March in the majority of the Nemunas River basin, but the effect on the coldest winter months of December to February will be small. During these months the projected snowfall will decrease only by 10%–15% in the late 21st century. More frequent thaws are likely to lead to the snowpack thicker by 50% at the end of the cold season.

The recent greenhouse gas emission trends are above those in the most extreme RCP8.5 scenario (Peters *et al*. 2013). The projections made in this scenario show that the winter temperature in the Nemunas River basin might increase by 5.5–6.5 °C until the end of 21st century. In such a case, the winter temperatures will become too high for snow. Also, the snow might only fall during short periods in colder winters. Other studies based on the Fourth and Fifth Assessment Report of the Intergovernmental Panel on Climate Change scenarios also indicate a future decrease in the water equivalent of the snowpack in the northern hemisphere (Diffenbaugh *et al*. 2012, Krasting *et al*. 2013, Räisänen 2016). The mildest areas in Europe, including parts of the Nemunas River basin, are projected to lose almost all of their snow by the late 21st century (Dankers and Christensen 2005, Räisänen and Eklund 2012).

Projections based on both climate change scenarios agree on general runoff trends in winter and spring, but the main difference between the effects of climate change projected by the two scenarios is in the formation of runoff during the cold season. This is supported by changing winter temperatures and precipitation conditions in the 21st century (Keršytė *et al*. 2015). According to RCP2.6, which represents the smallest climate changes, the amount of snowfall and snowpack will decrease, but the Nemunas River basin climate still will be cold enough to have snow throughout the 21st century, while according to RCP8.5, the increase in winter temperature will be high enough for snow to almost disappear from the Nemunas River basin from the mid-21st century onwards. Such important differences might be overlooked in studies focusing only on projected runoff data analysis (Kilkus *et al*. 2006, Kriaučiūnienė *et al*. 2008, Čerkasova *et al*. 2016).

In the RCP2.6 scenario, the projected decrease in maximum snow water equivalent could lead to a decrease in snow melt floods in the 21st century. But during cold winters with a strong advection of cold air, the amount of water accumulating in the snowpack might be similar to the volume that accumulated during normal winters of the 20th century (Räisänen and Eklund 2012). Rapid snow melt can result in the high flood peak discharge. On the other hand, if greenhouse gas emissions follow the RCP8.5 pathway, the effect of the melting snowpack on runoff will be minimal, and the runoff peaks are likely to be smaller than at the end of the 20th century (Berghuijs *et al*. 2014, Vormoor *et al*. 2015).

Severe floods with the highest water levels and the largest extent of inundated areas in the Nemunas River basin are related to ice jams. It is likely that in the 21st century, river ice formation will be affected by higher winter temperatures (Keršytė *et al*. 2015). In the case of the RCP8.5 scenario, higher temperatures could lead to a decrease in river freeze-up events. According to the milder RCP2.6 scenario, the winter temperatures will be higher, but they might still be low enough for the river ice to form. Due to higher temperatures and more frequent thaws, the ice floes are likely to be thinner, resulting in weaker and fewer ice jams.

Warm-season runoff calculated with WatBal according to both climate changes scenarios is likely to decrease. At the end of the 21st century, the reduction in runoff in the first part of the warm season may be related to a decrease in spring floods, while greater evapotranspiration could be responsible for the runoff decrease in summer and autumn. WatBal is a simple model, and its ability to accurately represent soil moisture and base flow is limited. The simplifications made in the lumped model can result in a loss of the parameters' physical meaning (Yates 1996), and the model calibrated on the past climate may not be accurate in future climate conditions (Merz *et al*. 2011, Brigode *et al*. 2013). Recent studies show that during warmer winters without snow or with less snow, infiltration to the groundwater in the Nemunas River basin is more intensive, and due to climate change the groundwater level is likely to be higher (Arustiene *et al*. 2012). This is likely to continue throughout the 21st century. Changes in spring groundwater storage may affect the sub-surface runoff and baseflow, and consequently increase the warm season runoff. Despite the increase in potential evapotranspiration at the end of the 21st century, the actual evapotranspiration calculated with WatBal for the northwestern part of the Nemunas River basin remains almost unchanged. This might be an indication that in this part of the basin, the catchment storage is low during the warm season and the baseflow is the main component of the total runoff.

It seems that confidence in the effect of climate change on warm season runoff formation should still be improved by studies based on more detailed and physically-based models with potentially less structural uncertainty. Uncertainty in the baseflow estimation is likely to be transformed into even higher uncertainty in the projected runoff. In order to better understand the impact of climate change on warm season runoff the employment of physically-based models might be needed.

Conclusions

According to RCP2.6 and RCP8.5 projections for the 21st century, annual precipitation and air temperature are both going to increase and the annual runoff is likely to decrease. The winter runoff will increase and the spring runoff will decrease. The magnitude of the changes in runoff is comparable for both scenarios. The main distinction between the effect of climate change predicted by both scenarios is the difference in the cold-season hydrological regime, and especially the water supply during winter and spring. If greenhouse gas emissions follow a mostly conservative pathway, the temperature increase will lead to a decrease in snowfall and a reduction in the maximum snow water equivalent in the second half of the 21st century, while the most pessimistic pathway suggests the almost complete disappearance of snow from the Nemunas River basin.

According to RCP2.6, the spring floods associated with snowmelt will remain common and an important feature of the Nemunas River basin runoff. In RCP8.5, the runoff formation from the snowpack melt will be negligible. With the probability of two distinct hydrological regimes the planning of long-term water management measures will be a very challenging task.

Potential evaporation driven by higher temperatures will increase throughout the 21st century, and in some parts of the Nemunas River basin the actual evaporation is also likely to increase from April to September. The WatBal model results show that with a reduction in the water accumulating in the snowpack during winter there will be less water in the catchments at the beginning of the warm season. However, observations of the ground water levels during warmer winters in recent decades suggest that the groundwater levels have tendency to increase during winters with higher temperatures.

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