Check for updates

Climate change impacts on water balance in Western Bohemia and options for adaptation

Adam Beran, Martin Hanel, Magdalena Nesládková, Adam Vizina, Petr Vyskoč and Roman Kožín

ABSTRACT

Several basins in Western Bohemia are regularly confronted with water scarcity problems during dry periods that have far-reaching impacts on stream ecology and the availability of drinking water for users. This paper presents a hydrological balance assessment of catchments in Western Bohemia for present and future conditions together with possible directions for climate change adaptation at the local scale. Assessment of climate change impacts on hydrological balance components using an ensemble of regional climate models revealed an increase in air temperature for all months during the year leading to an increase in evaporation. Along with changes in precipitation distribution during the year (increasing winter precipitation and decreasing summer precipitation), groundwater recharge and groundwater storage in general both decrease. Adaptation measures such as water transfers and the construction of water reservoirs are assessed with respect to the goal of increasing water availability in the Western Bohemia region during dry periods.

Key words | adaptation measures, climate change, hydrological balance, water resources, water use

Adam Beran (corresponding author)
Martin Hanel
Magdalena Nesládková
Adam Vizina
Petr Vyskoč
Roman Kožín
T. G. Masaryk Water Research Institute,
p.r.i., Podbabská 2582/30, 160 00 Prague,
Czech Republic
E-mail: *beran@vuv.cz*

Adam Beran
Martin Hanel
Adam Vizina
Roman Kožín
Faculty of Environmental Sciences,
Czech University of Life Sciences,
Kamýcká 129, 165 21 Prague,
Czech Republic

INTRODUCTION

Climate change impacts on hydrological balance have already been observed for a number of years in some regions of the Czech Republic, the most obvious of which is the increase in air temperature which causes an increase in potential evapotranspiration. Studies focusing on climate change impacts on hydrological balance in the Czech Republic (Hanel *et al.* 2011, 2012) report a projected increase in the mean air temperature of around 2 °C and 3 °C for 2055 and 2085, respectively. Results also indicate an increase in the winter runoff and a decrease in the spring, summer and autumn runoff. The projected changes in hydrological balance components lead to faster loss of water from basins and a decrease in water availability, at least during late summer and autumn, over a large part of the Czech Republic.

Simulations of future climate suggest an increase in the frequency and intensity of drought periods (Vlnas *et al.* 2010; Hanel *et al.* 2013a). Periods of drought can have far-reaching consequences for hydrological balance, influencing sectors such as agriculture, industry, tourism and households.

In recent years, the water management sector has had to face a number of new challenges. Increasing emphasis has been placed on topics directly related to climate change such as hydrological modelling of climate change impacts, development of climate change scenarios and adaptation measures, etc.

Generally, there exist two main options for how to deal with the problem of climate change (IPCC 2007). The first option is focused on eliminating the greenhouse gases that cause global environmental change. The goal of these actions is to mitigate the impacts of climate change. The second option is focused on the process of adaptation to moderate the expected harmful impacts of global

doi: 10.2166/ws.2018.080

Downloaded from http://iwaponline.com/ws/article-pdf/19/1/323/507399/ws019010323.pdf
by guest

environmental change and to exploit possible beneficial opportunities. Any intervention which leads to lowering the vulnerability of the man-made or natural system to the predefined acceptable level can be considered as an adaptation measure.

Addressing the issue of adaptation to climate change in the water sector has been relevant for the world over the last few years. A number of recommending documents have been developed at the international level on the implementation of adaptation measures, which set out the appropriate procedures to ensure timely and adequate preparedness for the impacts of climate change, such as the White Paper (White Paper 2009), or Guidance, issued by European Economic Commission (ECE 2009).

One of the most important key messages of ECE (2009) is that the world needs to adapt water management to climate change without delay. The main impacts of climate change are increased frequency and intensity of floods and droughts, water scarcity, intensified erosion and sedimentation, reduction in glacier and snow cover, sea level rise, salinization, soil degradation, and damage to water quality, ecosystems and human health. Many countries are already experiencing climate change impacts and are paying the economic and social price.

According to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2014), the impacts of climate change on natural and anthropogenic systems are observed on all continents and across the oceans. Most climate change impacts are experienced through changes in the hydrological cycle.

A complement to the *Guidance on Water and Adaptation to Climate Change* is served by *Water and Climate Change Adaptation in Transboundary Basins: Lessons Learned and Good Practices* (ECE 2014). The publication intends to compile, analyse and disseminate experiences, and thereby to demonstrate and illustrate important steps and lessons learned as well as good practices to take into account when developing a climate change adaptation strategy for water management in the basin or transboundary context.

In line with the above-mentioned documents, the project described in the paper deals with problems of adaptation to climate change – but on a smaller scale. However, the intention is to upscale the considered measures for the larger area of the territory of the whole Czech Republic.

Some areas in the western tip of the Czech Republic are already experiencing long-term problems with securing water for drinking as well as for industrial use. These problems have drawn public attention and have led to several studies and research projects varying from local (Hanel *et al.* 2007; Kašpárek & Mrkvičková 2009) through subregional (Kašpárek *et al.* 2011; Beran & Hanel 2015) to complex studies evaluating water availability over the whole Western Bohemia region.

An example of such complex studies is presented by Vyskoč *et al.* (2010) who evaluated the security of water resources under present and future conditions in the Karlovy Vary district located in the western tip of the Czech Republic. Their study concluded that there was strong evidence that some areas in Western Bohemia would experience water reliability problems, especially during dry periods. Those problems can be identified in historical records and are predicted to be elevated under future climate conditions. In the context of the whole Czech Republic, the vulnerability of water resources in the Karlovy Vary district as a whole is mild to moderate (Beran & Hanel 2015; Hanel *et al.* 2015).

Recently, a research project entitled, 'Increasing water resources availability in selected regions of Karlovy Vary district' has been financed by the Ministry of Agriculture of the Czech Republic. The objective of the project is the development of methods for proposing adaptation measures leading to increased reliability of water resources during periods of water stress using existing infrastructure as much as possible and considering the pilot basins in the Karlovy Vary district. This paper presents the preliminary project results.

In the paper, we introduce a description of the study area together with a description of the methods used in modelling the hydrological balance and the water management system, as well as a description of the available data. The results of the hydrological balance and water management system modelling as well as the adaptation measures envisioned for the Karlovy Vary district are presented in the two main parts of the paper.

Downloaded from http://iwaponline.com/ws/article-pdf/19/1/323/507399/ws019010323.pdf
by guest

METHODS

Study area

The study focuses on the Karlovy Vary (KV) district in the western tip of the Czech Republic (Figure 1). It has an area of 3,314 km^2, which is ~4% of the area of the whole country. The KV district belongs to the Elbe basin within the drainage area of the North Sea and is divided in the middle from west to east by the Ohře River, with the Teplá, Rolava and Svatava rivers comprising the main tributaries. The northern part of the KV district occupies the Ore Mountains with the highest peak Klínovec reaching 1,244 m above sea level. The southern part consists of the Slavkov Forest upland (Lesný, 983 m above sea level) and Doupov Mountains (Hradiště, 934 m above sea level).

The average annual air temperature over the period 1961–1990 was 6 to 7 °C, with an average temperature increase of approximately 0.5 °C over the period 1981–2010. Average annual rainfall aggregates ranged between 600 and 800 mm in 1961–1990. Between 1981 and 2010, precipitation increased in the range of 3–10%. The highest rainfall sums are recorded mainly in the north and north-west. On the south-eastern edge of the territory, the precipitation shadow of the Ore Mountains is evident in the precipitation total. Basic characteristics of the individual catchments are summarized in Table 1.

Modelling of hydrological balance components

The Bilan conceptual hydrological model (Tallaksen & van Lanen 2004) was used to model the hydrological balance of 11 catchments covering the whole study area (Figure 1) in monthly time steps. The model consists of a system of relationships describing the basic principles of water balance on the ground, in the aeration zone of the soil, including the effect of vegetation cover, and in the groundwater zone. Time series of basin precipitation, air temperature and observed river discharge are required as inputs for model calibration. Surface water balance depends on the evapotranspiration, which is derived for individual months considering temperature and potential solar radiation (Budyko 1976; Oudin et al. 2010). The model

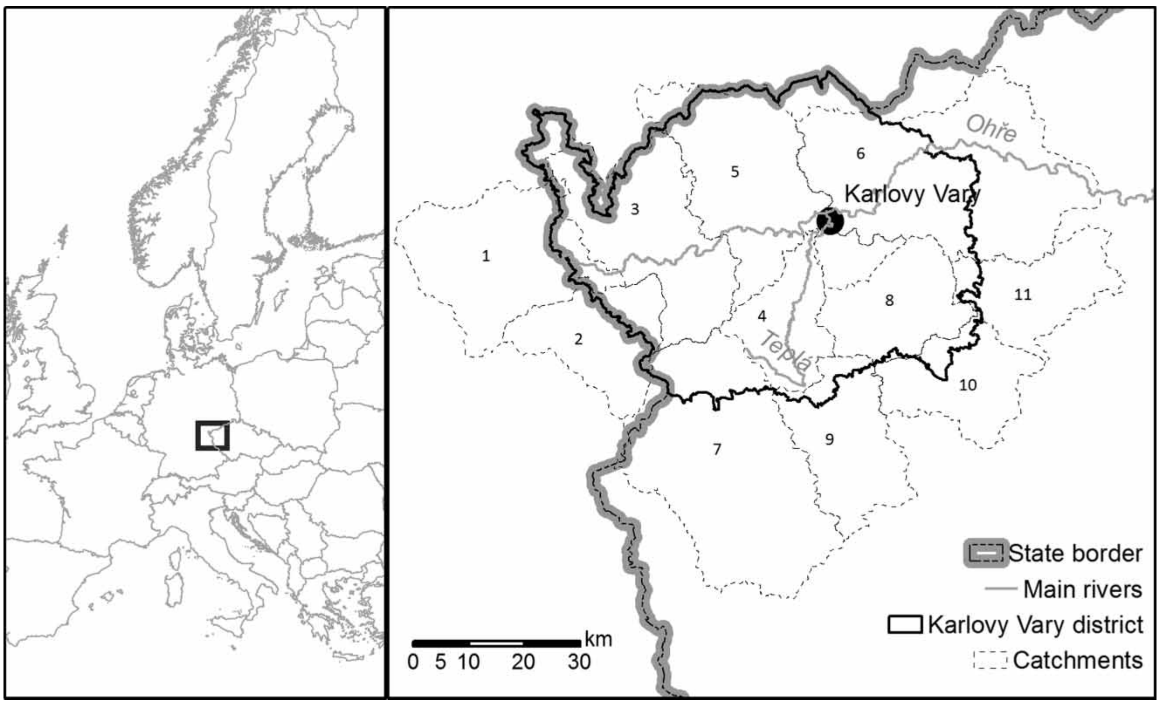

Figure 1 | Study area. The individual river basins are numbered and explained in Table 2.

Downloaded from http://iwaponline.com/ws/article-pdf/19/1/323/507399/ws019010323.pdf
by guest

Table 1 | Basic characteristics of the individual catchments calculated from the available dataset of 1961–2010

Catchment (river location)	Area [km²]	Air temperature [°C]	Precipitation [mm/year]	Pot. evapotranspiration [mm/year]	Evapotranspiration [mm/year]	Total runoff [mm/year]
1 Ohře Cheb	690	6.85	814	540.5	487.5	323.5
2 Odrava Jesenice	412	6.8	723.5	537.5	502.5	219
3 Ohře Citice	678	6.8	710.5	538	456.5	252.5
4 Teplá Březová	309	6	720.5	509.5	483	236
5 Ohře Karlovy Vary	821	6.35	782	520	448	332
6 Ohře Žatec most	1,172	7.2	635	554	484.5	149.5
7 Mže Stříbro	1,144	6.95	662	546	453.5	207
8 Střela Čichořice	393	6.45	610	528	447.5	162.5
9 Mže Hracholusky	465	6.95	575	545	454.5	120
10 Střela Plasy	388	7.2	537	555	467.5	69
11 Blšanka Holedeč	374	7.9	505	581.5	455	50.5

simulates the time series of potential evapotranspiration, actual evapotranspiration, soil infiltration, recharge from the soil to the aquifer and the amount of water stored in snow pack, in the soil and in the aquifer. The total runoff consists of direct runoff, interflow and base flow. The model has eight free parameters: capacity of soil moisture storage (Spa) [mm], temperature/snow melting factor (Dgm), factor for calculating the quantity of liquid water available on the land surface under winter conditions (Dgw), rainfall–runoff equation parameter (Alf) (direct runoff), and parameter controlling distribution of percolation into interflow and groundwater recharge under summer conditions (Soc), under conditions of snow melting (Mec) and under winter conditions (Wic).

The calibration of the parameters is executed in two steps. In the first step, the standard error of the estimate (standard deviation between the observed and simulated runoff series) or mean absolute error (mean calculated from absolute deviations between the observed and simulated runoff series, where 'absolute' means that negative deviations are converted to positive values) is used as the optimization criterion to calibrate Spa, Dgm, Dgw and Alf parameters that significantly affect the mean runoff.

The remaining four parameters (Mec, Wic, Soc, Grd) affecting the runoff distribution in its individual components are then calibrated by using the mean of absolute values of relative deviations (relative means that each deviation is divided by the observed value). It has been demonstrated by experimental calculations that this calibration procedure ensures mostly an acceptable fit in terms of both mean runoff and low flow runoff, which is generated predominantly by base flow. The resulting mean of absolute values of relative deviations is shown (under 'optimization criterion') in the output of the model. The optimization procedures are described in more detail by Horáček *et al.* (2009) and Vizina *et al.* (2015) and in the user's guide of the Bilan model (TGM WRI 2015).

Water management model

The water management system is simulated by a water management model (developed by T.G. Masaryk Water Research Institute) which uses flow series (observed and naturalized or simulated by the Bilan model), water use series (abstractions, waste water discharges and flow regime requirements such as minimum ecological flows and water level limits in reservoirs), technical characteristics (storage capacities of reservoirs, capacities of river channels) and operation rules for flow regulation and water supply for individual users. The simulated data include time series of flows (affected by regulation and water use), water storage and water levels in reservoirs

Downloaded from http://iwaponline.com/ws/article-pdf/19/1/323/507399/ws019010323.pdf
by guest

and simulated water abstractions and waste water discharges.

Data

Input data (time series of basin precipitation and temperature) for the time period 1961–2010 were provided by the Czech Hydrometeorological Institute. The time period was divided into two parts: 1961–1990 (past) and 1981–2010 (present). The data were divided just for description of time changes in the individual elements of the hydrological balance.

For modelling future changes in the hydrological balance, two future time horizons (2021–2050 and 2071–2099) were chosen. Fifteen regional climate model (RCM) simulations from the ENSEMBLES project covering the time period 1961–2099 were used. All simulations were forced by emission scenario SRES A1B and are available in a spatial resolution of 25×25 km^2. The 15 RCM simulations are driven by four global climate models:

- RACMO (Royal Netherlands Meteorological Institute), REMO (Max Planck Institute for Meteorology, Germany), RCA (Swedish Meteorological and Hydrological Institute), REGCM (Abdus Salam International Centre for Theoretical Physics, Italy) and HIRHAM (Danish Meteorological Institute) driven by ECHAM5.
- HadRMQ0, HadRMQ3, HadRMQ16 (Met Office Hadley Centre, UK), CLM (Swiss Federal Institute of Technology Zurich), RCA (Swedish Meteorological and Hydrological Institute) and RCA (Community Climate Change Consortium for Ireland) driven by HadCM3.
- HIRHAM (Danish Meteorological Institute), CNRM5 (National Centre of Meteorological Research, France), ALADIN-CLIMATE (Czech Hydrometeorological Institute, Czech Republic) driven by ARPEGE4.5.
- RCA (Swedish Meteorological and Hydrological Institute) driven by BCM.

An overview of the RCM simulations considered is provided by Beran *et al.* (2016). The scenarios have been developed by the simple delta change method (e.g., Hanel *et al.* 2013b, 2017), i.e., observed data were perturbed in order to result in the same changes estimated by the RCM simulations. Prior to the estimation of the delta change factors, the simulations were corrected by quantile mapping (see, e.g., Gudmundsson *et al.* 2012). Changes in the hydrological balance components were related to the present time period (1981–2010).

The flow series simulated by the hydrological model were subsequently used in a model of the water management system which integrates the hydrological inputs and water management issues on a river basin scale. The water management system model was applied for water management simulation to examine the sufficiency of water resources under hydrological conditions affected by climate change.

RESULTS AND DISCUSSION

Water balance was assessed for four time periods: past (1961–1990), present (1981–2010), near future (2021–2050) and far future (2071–2100). The results for the first two time horizons are based on observed data and for the second two time horizons on climate change scenarios. The water balance components (runoff and baseflow) presented for all time periods are simulated by the hydrological model.

Table 2 lists the time periods of available runoff data, along with the periods for the calibration and validation of the Bilan model. Further, there are evaluation criteria of the model's accuracy.

To evaluate the model's accuracy, three statistical criteria were used. Kling–Gupta efficiency (KGE) was developed by Gupta *et al.* (2009) to provide a diagnostically interesting decomposition of the Nash–Sutcliffe efficiency, which facilitates the analysis of the relative importance of its different components (correlations, bias and variability) in the context of hydrological modelling. Kling–Gupta efficiencies range from –Inf to 1. Essentially, the closer to 1, the more accurate the model is. Root Mean Square Error (RMSE) gives the standard deviation of the model's prediction error. A smaller value indicates better model performance. The correlation coefficient (r) is the quotient of the variances of the fitted values. The closer it is to 1, the more accurate the model is.

The resulting statistical criteria do not show significant negative variations. Based on this, it is possible to assess

Downloaded from http://iwaponline.com/ws/article-pdf/19/1/323/507399/ws019010323.pdf
by guest

Table 2 | Available runoff data

Catchment (river location)	Observed runoff	Calibration period	Validation period	KGE_KAL	KGE_VAL	RMSE_KAL	RMSE_VAL	r_KAL	r_VAL
1 Ohře Cheb	1974–2005	1991–2005	1974–1990	0.84	0.69	10.79	15.04	0.87	0.78
2 Odrava Jesenice	1961–2010	1991–2010	1961–1990	0.83	0.66	9.57	14.72	0.76	0.64
3 Ohře Citice	1974–2005	1991–2005	1974–1990	0.84	0.51	6.95	13.92	0.89	0.65
4 Teplá Březová	1974–2005	1991–2005	1974–1990	0.86	0.81	10.61	14.75	0.89	0.82
5 Ohře Karlovy Vary	1974–2005	1991–2005	1974–1990	0.83	0.46	8.91	14.53	0.87	0.74
6 Ohře Žatec most	1979–2007	1991–2007	1979–1990	0.72	0.66	12.4	14.39	0.82	0.76
7 Mže Stříbro	1979–2006	1991–2006	1979–1990	0.75	0.6	9.42	11.53	0.77	0.67
8 Střela Čichořice	1963–2010	1991–2010	1963–1990	0.76	0.61	7.68	9.21	0.76	0.73
9 Mže Hracholusky	1952–1990	1971–1990	1952–1970	0.5	0.46	8.13	15.76	0.85	0.58
10 Střela Plasy	1974–2005	1991–2005	1974–1990	0.63	0.73	7.9	9.02	0.79	0.74
11 Blšanka Holedeč	1968–2008	1991–2008	1968–1990	0.72	0.55	8.2	9.3	0.78	0.68

Evaluation criteria of model accuracy (KGE_KAL – Kling–Gupta efficiency for calibration period, KGE_VAL – Kling–Gupta efficiency for validation period, RMSE_KAL – relative mean square error for calibration period, RMSE_VAL – relative mean square error for validation period, r_KAL – correlation coefficient for calibration period, r_VAL – correlation coefficient for validation period).

the calibration of the hydrological model for the individual catchments successfully. Values of the KGE criteria during calibration periods are in the range between 0.5 to 0.86 and during validation periods between 0.46 and 0.81. Values of the RMSE criterion range from 6.95 to 12.4 for calibration periods and 9.02 to 15.76 for validation periods. The coefficient of determination takes values from 0.76 to 0.89 for calibration periods and from 0.58 to 0.82 for validation periods.

The mean change in observed temperature between the past and present time horizons for all catchments is about 0.5 °C. However, the temperature increases more rapidly during winter conditions. For the near future, the ensemble mean air temperature increases by 1 °C (compared with the mean of the present period 1981–2010). The largest increase in air temperature is projected for the winter months (1.2 °C for December, January and February) and the increase is also considerable during the spring months (0.8 °C for March, April and May). In the far future, the RCM ensemble projects an increase in air temperature of 2.7 °C with the largest increase during winter (3.1 °C) and spring (3 °C).

In Western Bohemia, the mean annual precipitation for the past time horizon was 600–700 mm. In the present time horizon, the mean annual precipitation increased only slightly (3–10%). The largest rainfall totals were observed in the mountainous areas of the northern KV district. Changes in the mean annual precipitation for the future time horizons are insignificant. Precipitation is almost unchanged in spring and summer for the near future (2021–2050). For the winter and autumn months, the mean precipitation increases by 6% to 11% (compared with the present period 1981–2010). A larger increase (13–25%) in mean precipitation during winter months is typical for the far future (2071–2100). Summer months, however, show a 7–14% decrease. Relative changes in seasonal and annual mean precipitation are illustrated in Figure 2.

Mean annual runoff is almost unchanged during both future time horizons, however, winter runoff increases considerably. The increase between near future and present (~15%) is much larger than between the two future periods. Mean seasonal runoff for the rest of the year decreases up to around 10%. The changes in runoff are illustrated in Figure 3, and seasonal changes of runoff for individual catchments are illustrated in Figure 4. Mean annual baseflow decreases slightly (up to around 7%). The decrease is stronger during the summer (12%) and autumn (19%) months for the far future horizon 2071–2100. These changes are shown in Figure 5. Mean annual potential evapotranspiration increases up to 18%.

Changes in the components of hydrological balance in Western Bohemia are consistent with changes that are observed on the scale of the whole country. Higher air temperature during the whole year together with increasing mean

Downloaded from http://iwaponline.com/ws/article-pdf/19/1/323/507399/ws019010323.pdf
by guest

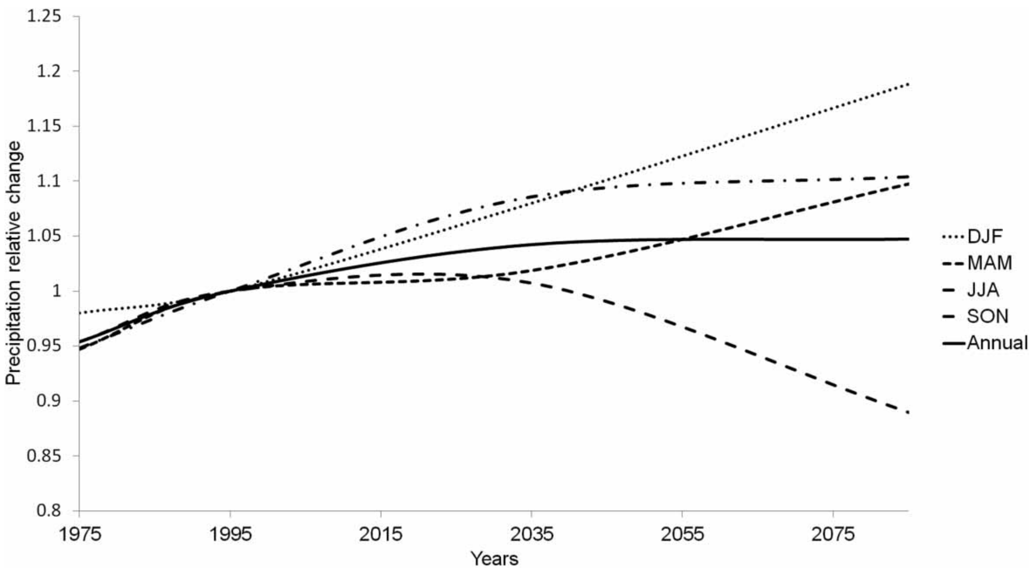

Figure 2 | Ensemble mean relative changes in precipitation for observed time horizons 1975 (1961–1990) and 1995 (1981–2010) and future horizons 2035 (2021–2050) and 2085 (2071–2100). DJF – December, January, February; MAM – March, April, May; JJA – June, July, August; SON – September, October, November.

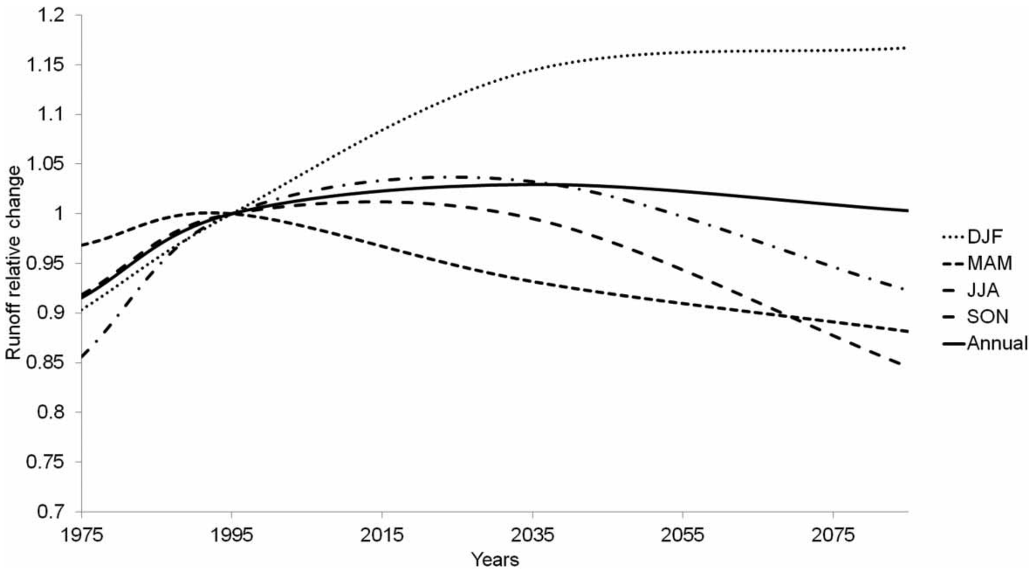

Figure 3 | Ensemble mean relative changes in runoff for observed time horizons 1975 (1961–1990) and 1995 (1981–2010) and future horizons 2035 (2021–2050) and 2085 (2071–2100). DJF – December, January, February; MAM – March, April, May; JJA – June, July, August; SON – September, October, November.

precipitation during winter leads to an increase in runoff and evaporation during this part of the year. This results in insufficient accumulation of water in snow cover, which is crucial for replenishment of groundwater storage and in turn leads to a decrease in the baseflow contribution to the total runoff during late summer. In the case of longer dry periods, water availability is thus limited.

The variability of the hydrological balance components in the ensemble of RCM simulations is shown in Figure 6. For each variable, the first two boxplots correspond to the observed mean within catchments in the study area. The second two boxplots reflect projected changes in the simulated variables of the 15 RCM simulations. The variability due to the climate model (when compared with the climate

Downloaded from http://iwaponline.com/ws/article-pdf/19/1/323/507399/ws019010323.pdf
by guest

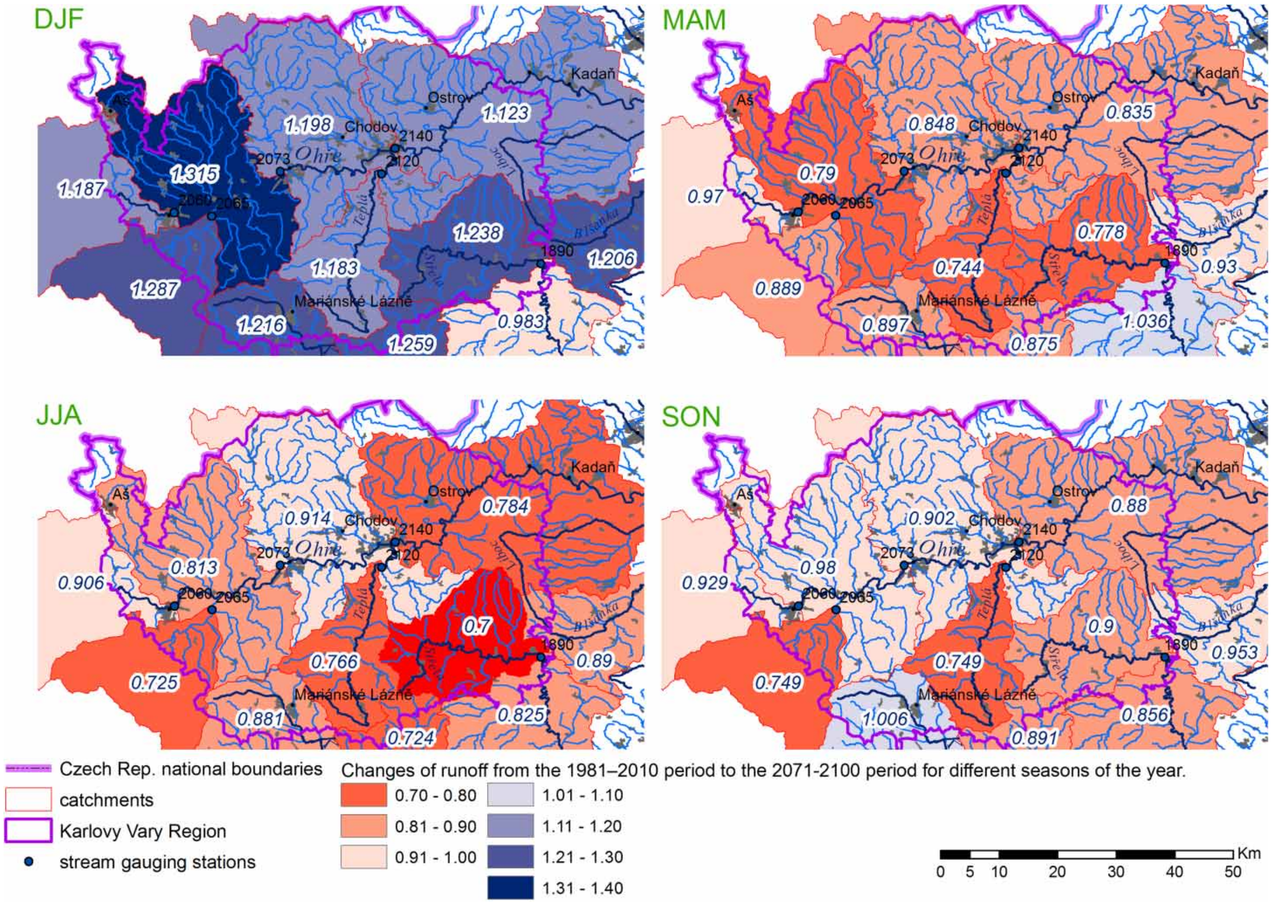

Figure 4 | Changes of runoff from the 1981–2010 period to the 2071–2100 period for different seasons of the year. DJF – December, January, February; MAM – March, April, May; JJA – June, July, August; SON – September, October, November.

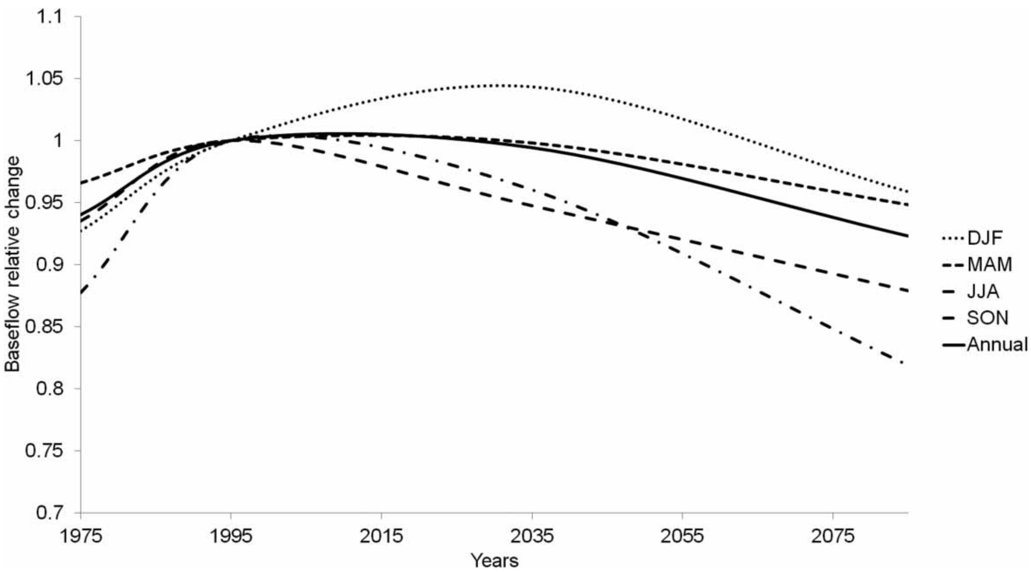

Figure 5 | Ensemble mean relative changes in baseflow for observed time horizons 1975 (1961–1990) and 1995 (1981–2010) and future horizons 2035 (2021–2050) and 2085 (2071–2100). DJF – December, January, February; MAM – March, April, May; JJA – June, July, August; SON – September, October, November.

Downloaded from http://iwaponline.com/ws/article-pdf/19/1/323/507399/ws019010323.pdf
by guest

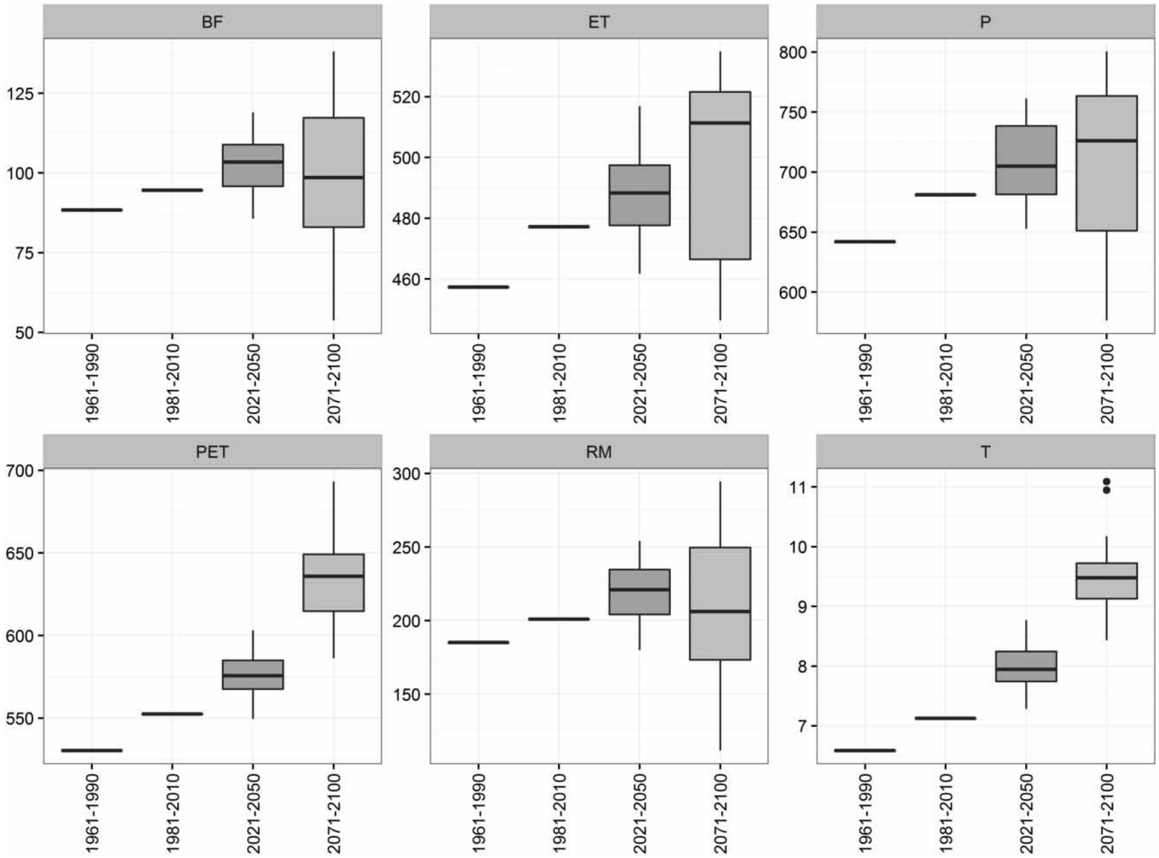

Figure 6 | Average annual sum of baseflow (BF [mm]), precipitation (P [mm]), simulated runoff (RM [mm]), actual (ET [mm]) and potential (PET [mm]) evapotranspiration and annual average temperature (T [°C]) for the periods 1961–1990 and 1981–2010, which are based on observed data, and 2021–2050 and 2071–2100, which are based on the ensemble of 15 RCM simulations. The values are averaged over the region.

change signal) is smallest for temperature and potential evapotranspiration with the difference between RCM simulations being usually less than 2 °C and 100 mm, respectively. The uncertainty is larger for the other variables. The uncertainty in the mean projected future precipitation (runoff) within selected RCM simulations is up to 7% (20% runoff) in 2021–2050 and up to 20% (50% runoff) in 2071–2100. The uncertainty is higher for the far future horizon in all of the modelled hydrological components.

The uncertainty in the projected impacts on the hydrological regime stems from the natural internal variability, incomplete knowledge of the physical processes governing the climate/hydrological system or technical limitations in the implementation of these processes in climate/hydrological models (model uncertainty) and the unpredictability of the socioeconomic factors determining future emissions of greenhouse gases and aerosol particles and other forcing agents such as land use changes (scenario uncertainty). In the present study, only the uncertainties related to the climate model are considered. It is expected that including other sources of uncertainty (more emission scenarios, hydrological models or initial condition ensemble climate model simulations) would further increase the uncertainty in the projected water balance components. Kay *et al.* (2009), however, claim that climate model-related uncertainty greatly exceeds the uncertainty related to other sources.

Possible adaptation measures

The most populated city of Western Bohemia is Karlovy Vary with around 50,000 inhabitants. The city and its surroundings are supplied with drinking water from the Stanovice dam on the Teplá River via the Březová water treatment works. Within present climatic conditions and

Downloaded from http://iwaponline.com/ws/article-pdf/19/1/323/507399/ws019010323.pdf
by guest

taking into account the present rules of water management and preservation of minimal flows, there is already passive water balance below the dam, especially during dry periods. Based on the previous project (Vyskoč *et al.* 2010) and our new results there are two measures proposed to increase the reliability of this water resource. The first possible adaptation measure consists of water transfer from a close profile of the Ohře River. Minimal flows in the river would be secured, and there would be a large water reserve available. By modelling the whole water management system of the district, it was confirmed that the transfer would help to ensure water supply from the Stanovice dam during dry periods.

As another possible measure, the interconnection of water supply systems supplying the areas surrounding the cities of Karlovy Vary and Sokolov was evaluated. The area around the town of Sokolov is supplied by the Horka water reservoir through the Horka water treatment plant (Figure 7). The parameters of the water reservoirs are approximately similar: the Stanovice water reservoir has a storage volume of 18.38 to 20.16 million m^3 (depending on the season) with a long-term average flow of 0.583 m^3/s, and the Horka water reservoir has a storage volume of 16.78 million m^3 with a long-term average flow of 0.624 m^3/s. Currently however, water from the Horka reservoir is significantly less used (4,500,000 m^3 of water) than water from the Stanovice reservoir (approximately 9,500,000 m^3 of water). Using simulations of the storage capacity of the two water reservoirs, the reserves (Horka) and deficits (Stanovice) were quantified for the climate change impact scenarios in the medium term as the difference between the current and future water consumption. The simulation results show that even in the worst-case scenario, the potential deficiency in the Stanovice water reservoir (about 2,000,000 m^3) does not exceed the available reserve in the Horka reservoir (about 5,600,000 m^3). As the Stanovice and Horka water reservoirs supply neighbouring areas (Figure 7), the

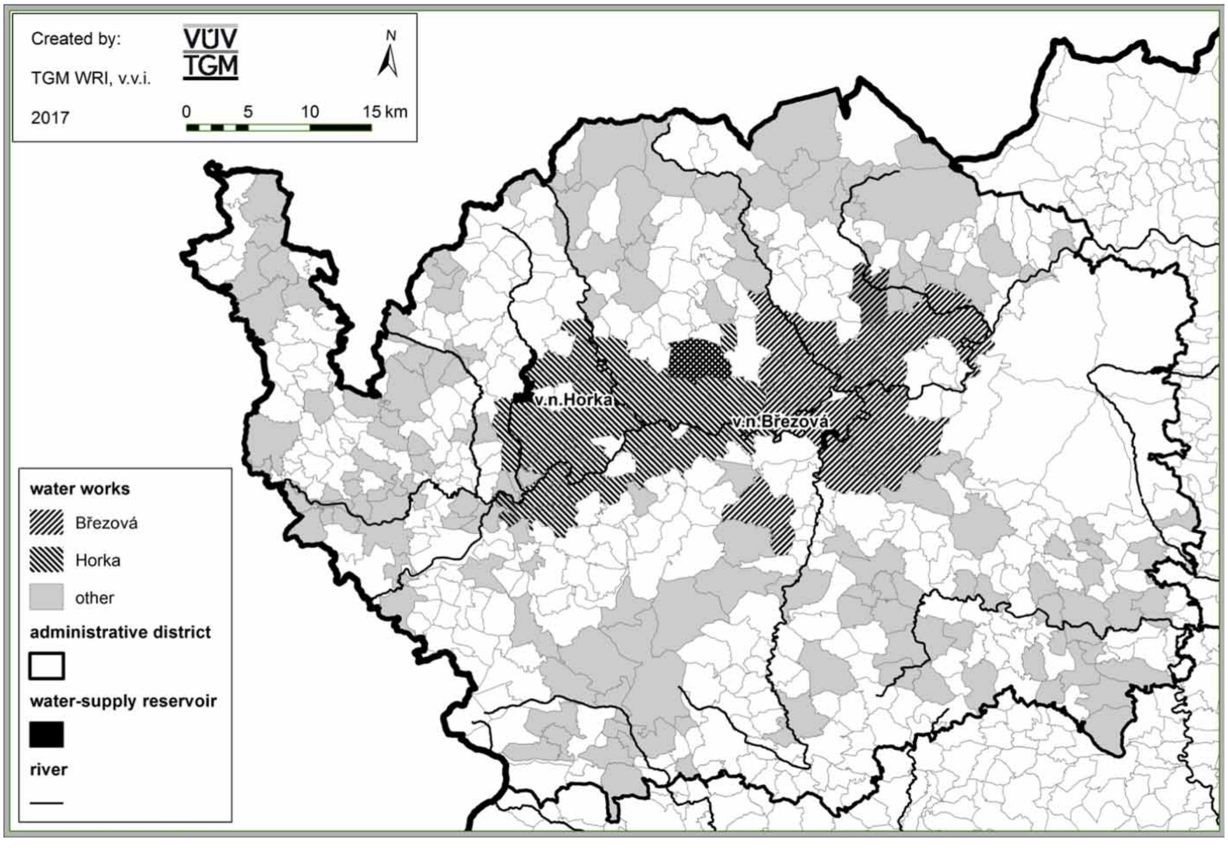

Figure 7 | Březová and Horka water works.

Downloaded from http://iwaponline.com/ws/article-pdf/19/1/323/507399/ws019010323.pdf
by guest

connection of these water supply systems can be considered as a possible future solution in the event of unfavourable scenarios.

Another proposed measure takes advantage of the list of localities that are potentially suitable for the accumulation of surface water (locations for accumulation of surface water, LASW) in the Czech Republic. The list has existed from the beginning of the 20th century and currently mentions 65 localities. The list of LASW is being updated as part of a project described by Kožín *et al.* (2015) that focuses on addressing negative climate change impacts using these potential LASW. Within the near-future period (next 50 years) affected by climate change, the minimal flows in several tributaries of the Ohře River are identified as not being sufficiently secured. A crucial challenge for the present project is to update the water management scheme of the whole Western Bohemia region and model ways to face threats of drought. Table 3 shows a summary of the current and prospective water reservoirs in the study area with their area and volume. The table shows that the usable volume of the prospective water reservoirs (105 billion m^3) almost reaches the volume of existing reservoirs (120 billion m^3). In future years, the need for construction of new water reservoirs should be evaluated using water management system modelling.

Table 3 | Summary of current and prospective water reservoirs in the Karlovy Vary district

Water reservoir	Area [10,000 m^2]	Volume [bil. m^3]	Status
Skalka	340	15.9	current
Jesenice	691	52.8	current
Horka	122	19.2	current
Mariánské lázně	4	0.3	current
Podhora	82	2.2	current
Stanovice	127	24.2	current
Březová	73	4.7	current
Vřesová	24	1.5	current
Chaloupky	193	36	prospective
Dvorečky	152	30.8	prospective
Poutnov	123	11.6	prospective
Mnichov	177	26.8	prospective

CONCLUSIONS

Because observed changes in the hydrological balance are causing problems with water security resources in Western Bohemia, we analysed changes in hydrological balance components (precipitation, runoff, baseflow, evapotranspiration, potential evapotranspiration and temperature) due to climate change. For comparison, two observed periods (1961–1990, 1981–2010) and two future periods (2021–2050, 2071–2100) were chosen. The climate change impact assessment was based on an ensemble of 15 RCM simulations, and possible adaptation measures were outlined. The main results can be summarized as follows:

- In the area of Western Bohemia, there is an observed increase in air temperature and observed changes in the seasonal distribution of precipitation which influence water balance in the catchments and have wider impacts on water availability.
- Assessment of an ensemble of 15 RCM simulations suggests that changes in hydroclimate conditions will continue in the future and will likely lead to further problems with water availability.

Water transfers and new water reservoirs were proposed as possible adaptation measures. These measures will be formally assessed using water management modelling in combination with the water balance model presented here.

ACKNOWLEDGEMENTS

The research was conducted within a project entitled ‘Increasing water resources availability in selected regions of Karlovy Vary district’ (QJ1520318) financed by the Ministry of Agriculture of the Czech Republic. The climate change scenarios were prepared within the project TA02020320 co-financed by the Technology Agency of the Czech Republic. The paper was presented at the 2nd EWaS International Conference: ‘Efficient & Sustainable Water Systems Management toward Worth Living Development’ in Chania, Crete, Greece, in June 2016. The list of localities potentially suitable for accumulation of surface water was prepared within a project entitled ‘Compensation of negative climate change impacts on

Downloaded from http://iwaponline.com/ws/article-pdf/19/1/323/507399/ws019010323.pdf
by guest

water supply and ecosystems using the localities for potential accumulation of surface water', co-funded by the Technology Agency of the Czech Republic (TA04020501).

REFERENCES

Beran, A. & Hanel, M. 2015 Definování zranitelných oblastí z hlediska nedostatku vody na území České republiky (Identification of regions vulnerable to deficits in water resources in the Czech Republic). *Vodohospodářské technicko-ekonomické informace* **57** (4–5), 23–26.

Beran, A., Hanel, M., Nesládková, M. & Vizina, A. 2016 Increasing water resources availability under climate change. *Procedia Engineering* **162**, 448–454.

Budyko, M. I. 1976 *Rekomendacii po rasčotu isparenija s poverchnosti suši (Recommendations for Calculations of Local Evaporation)*. Gidrometeoizdat, Leningrad, Russia.

ECE 2009 *Guidance on Water and Adaptation to Climate Change.* Economic Commission for Europe, Geneva, Switzerland.

ECE 2014 *Water and Climate Change Adaptation in Transboundary Basins: Lessons Learned and Good Practices.* Economic Commission for Europe, Geneva, Switzerland.

Gudmundsson, L., Bremnes, J. E., Haugen, J. B. & Engen-Skaugen, T. 2012 Technical note: downscaling RCM precipitation to the station scale using statistical transformations – a comparison of methods. *Hydrology and Earth System Sciences* **16**, 3383–3390.

Gupta, H. V., Kling, H., Yilmaz, K. K. & Martinez, G. F. 2009 Decomposition of the mean squared error and NSE performance criteria: implications for improving hydrological modelling. *Journal of Hydrology* **377** (1–2), 80–91.

Hanel, M., Kašpárek, L., Horáček, S., Vizina, A. & Fridrichová, R. 2007 *Studie hydrologických poměrů v povodí Srpiny (Study of Hydrology of Srpina Catchment)*. T.G. Masaryk Water Research Institute, p.r.i., Prague, Czech Republic.

Hanel, M., Kašpárek, L., Mrkvičková, M., Horáček, S., Vizina, A., Novický, O. & Fridrichová, R. 2011 *Odhad dopadů klimatické změny na hydrologickou bilanci v ČR a možná adaptační opatření (Estimation of Climate Change Impacts on the Hydrological Balance of the Czech Republic and Possible Adaptation Measures)*. T.G. Masaryk Water Research Institute, p.r.i., Prague, Czech Republic.

Hanel, M., Vizina, A., Máca, P. & Pavlásek, J. 2012 A multi-model assessment of climate change impact on hydrological regime in the Czech Republic. *Journal of Hydrology and Hydromechanics* **60** (3), 152–161.

Hanel, M., Kašpárek, L., Peláková, M., Beran, A. & Vizina, A. 2013a Evaluation of changes in deficit volumes: support for protection of localities suitable for construction of reservoirs. In: *Considering Hydrological Change in Reservoir Planning and Management, Proceedings of H09, IAHS-IAPSO-IASPEI Assembly*, Gothenburg, Sweden, July 2013.

Hanel, M., Mrkvičková, M., Máca, P., Vizina, A. & Pech, P. 2013b Evaluation of simple statistical downscaling methods for monthly regional climate model simulations with respect to the estimated changes in runoff in the Czech Republic. *Water Resources Management* **27** (15), 5261–5279.

Hanel, M., Beran, A. & Kašpárek, L. 2015 *Scénáře změny klimatu (Climate Change Scenarios)*. T.G. Masaryk Water Research Institute, p.r.i., Prague, Czech Republic.

Hanel, M., Kožín, R., Heřmanovský, M. & Roub, R. 2017 An R package for assessment of statistical downscaling methods for hydrological climate change impact studies. *Environmental Modelling and Software* **95**, 22–28.

Horáček, S., Rakovec, O., Kašpárek, L. & Vizina, A. 2009 Vývoj modelu hydrologické bilance – BILAN (The development of Bilan water balance model). *Vodohospodářské technicko-ekonomické informace* **51** (1), 2–5.

Intergovernmental Panel on Climate Change 2007 *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, United Kingdom, and New York. Available from: https://www.ipcc.ch/publications_and_data/ar4/wg2/en/contents.html.

Intergovernmental Panel on Climate Change 2014 *Climate Change 2014: Impacts, Adaptation, and Vulnerability, Part A, Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, United Kingdom, and New York. Available from http://www.ipcc.ch/report/ar5/wg2/.

Kašpárek, L. & Mrkvičková, M. 2009 *Studie potřeb vody pro povodí vodních toků Blšanka a Liboc (Study of water requirements for Blšanka and Liboc catchments)*. T.G. Masaryk Water Research Institute, p.r.i., Prague, Czech Republic.

Kašpárek, L., Horáček, S. & Pavlásek, J. 2011 *Možnosti zmírnění dopadů klimatické změny na hydrologický režim v povodí Rakovnického potoka (Reducing of climate change impacts on hydrological regime in the Rakovnický potok catchment)*. T.G. Masaryk Water Research Institute, p.r.i., Prague, Czech Republic.

Kay, A. L., Davies, H. N., Bell, V. A. & Jones, R. G. 2009 Comparison of uncertainty sources for climate change impacts: flood frequency in England. *Climatic Change* **92**, 41–63.

Kožín, R., Hanel, M., Kašpárek, L., Peláková, M., Vizina, A. & Kašpárek, L. 2015 Možnosti zmírnění dopadů změny klimatu využitím území chráněných pro akumulaci povrchových vod (Possible compensation of negative climate change impacts using the localities for potential accumulation of surface water). *Vodohospodářské technicko-ekonomické informace* **57** (4–5), 11–16.

Oudin, L., Moulin, L., Bendjoudi, H. & Ribstein, P. 2010 Estimating potential evapotranspiration without continuous daily data: possible errors and impact on water balance simulation. *Hydrological Sciences Journal* **55** (2), 209–222.

Downloaded from http://iwaponline.com/ws/article-pdf/19/1/323/507399/ws019010323.pdf
by guest

Tallaksen, L. M. & van Lanen, H. A. J. (eds) 2004 *Hydrological Drought – Processes and Estimation Methods for Streamflow and Groundwater*. Elsevier, Amsterdam, The Netherlands.

TGM WRI 2015 *Bilan Water Balance Model – Manual*. T.G. Masaryk Water Research Institute, p.r.i., Prague, Czech Republic. Available from http://bilan.vuv.cz/bilan/wpcontent/uploads/2015/03/bilan_man_2015-06-23.pdf

Vizina, A., Horáček, S. & Hanel, M. 2015 Nové možnosti modelu BILAN (Recent developments of the Bilan model). *Vodohospodářské technicko-ekonomické informace* 57 (4–5), 7–10.

Vlnas, R., Novický, O., Kašpárek, L., Hanslík, E., Vizina, A., Fiala, T., Šimek, P., Brzáková, J., Ledvinka, O. & Kourková, H. 2010 *Časová a plošná variabilita hydrologického sucha v podmínkách klimatické změny na území České republiky (Temporal and spatial hydrological drought variability in conditions of climate change in the area of the Czech Republic)* T.G. Masaryk Water Research Institute, p.r.i., Prague, Czech Republic.

Vyskoč, P., Vizina, A., Kašpárek, L., Picek, J., Brabec, J., Nováková, H., Filippi, R., Koterová, V., Smrčka, F., Hála, R., Pěkný, L. & Průšová, K. 2010 *Výhledová studie potřeb a zdrojů vody v oblasti povodí Ohře a dolního Labe – východní část (Prospective study of needs and water resources in the area of Ohře basin and lower Elbe basin – eastern part)*. T.G. Masaryk Water Research Institute, p.r.i. and Water Management Development and Construction Joint Stock Company, Prague, Czech Republic.

White Paper 2009 *Adapting to Climate Change: Towards a European Framework for Action*. White paper, Commission of the European Communities, Brussels, Belgium.

First received 20 December 2017; accepted in revised form 9 April 2018. Available online 20 April 2018

Downloaded from http://iwaponline.com/ws/article-pdf/19/1/323/507399/ws019010323.pdf
by guest