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Evaluation of changes in deficit volumes: support for protection of localities suitable for construction of reservoirs

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Abstract Climate change scenarios for the Czech Republic indicate an increase in frequency of deficit events and volume of deficit discharges. The Czech water management legislation considers a number of protected areas potentially suitable for construction of reservoirs for flood protection and/or improving the water balance in the drought periods. In the present study we use hydrological modelling to quantify the volume of the deficit discharges as projected by an ensemble of transient regional climate model simulations. The changes in the deficit volumes are assessed using a simple statistical model considering the generalized extreme value distribution for the deficit volumes. Derived deficits are subsequently compared to the potential volume of the considered reservoirs. It is concluded that for many regional climate model simulations the changes in deficits are comparable or larger than the available volume of water in the reservoirs. The uncertainty is, however, large.

Key words deficit volumes; statistical model; regional climate model simulations

INTRODUCTION

In the Czech Republic, the climate change and its impact on water resources has received public and scientific attention since the early 1990s (Kašpárek *et al.*, 2006). Recently, research on adaptation in the water sector has been accelerated due to the problems with water availability in a number of relatively small catchments over the Czech Republic, which might be attributed to the on-going climate change. Practical experiences indicate that the most robust and effective measures are those which increase water supply (in our case specifically, reconstruction of old or design of new reservoirs or water transfers).

In the present paper we therefore primarily focus on the assessment of the effectiveness of technical measures; specifically we consider the construction of new reservoirs at locations potentially suitable for this purpose. The list of such localities (further denoted as LASW, i.e. Localities potentially suitable for Accumulation of Surface Water) in the Czech Republic has existed from the beginning of the 20th century and originally consisted of >400 locations. The main purpose for this list was to protect localities potentially suitable for building infrastructure for drinking water supply and flood protection. Today, this purpose can be extended to climate change adaptation. However, since the LASW are protected by national law, which limits regional development in the area (especially technical and transport infrastructure with international, national or other supra-regional importance, or industrial, energy and mining facilities, etc.), the list has been reduced several times (with respect to both the number and extent of the localities) and its current version, which is recently under discussion, contains <70 locations and further reduction is still proposed by local authorities and ecological initiatives. However, the list of LASW is not intended as the basis for construction of reservoirs, but rather a framework for protection of these locations as some of the pessimistic climate change scenarios could become actual. This is compliant with the recommendation of European Environmental Agency (EEA, 2009) for handling uncertainty related to the climate change projections within the planning of adaptation measures, i.e. preference for measures allowing for later adjustment. The main objective of the research presented in this paper is to stress the need for continuation of LASW protection by presentation of possible future need of some of these localities for the compensation of future discharge deficits. Our study continues the research of Novický *et al.* (2006) and extends it by consideration of different statistical methodology, the actual list of LASW, more climate change scenarios, discharge deficit levels and basins.

The projections of future climate from climate models for the Czech Republic are not consistent, especially with respect to the changes in precipitation and thus the whole hydrological regime. For instance, around half of the climate models considered in the IPCC Fourth assessment report project increase and the second half a decrease in precipitation. Still, the hydrological simulations indicate that due to temperature increase the overall effect on water resources in the area is slightly negative for most of the climate model simulations despite a slight precipitation increase in part of these simulations (Hanel *et al.*, 2012). This emphasizes the need for a multi-model assessment. The present study use the ensemble of regional climate model simulations conducted within the EU funded project Ensembles. The projections are used to quantify the future discharge deficits. These deficits are subsequently compared with the volume of potential reservoirs at the LASW. The LASW and the calculation of the future discharges are described in the Methods section. The resulting deficits and their possible compensation by potential reservoirs at the LASW are given and discussed in the Results and Discussion sections, respectively. The conclusions are presented in the last section.

DATA AND METHODS

The location of the LASW is given in Fig. 1 together with the capacity of the potential reservoirs. The spatial distribution of LASW and their capacity is uneven. Considering the eight river basin districts (RBD) in the Czech Republic the largest capacity is in the northeast of the Czech Republic (MOR and ODR), the lowest in the southwest (HVL, DVL). This is partly due to a relatively large number of already existing reservoirs in those two RBD.

The hydrological model BILAN (van Lanen *et al.*, 2004) has been used for assessing water balance components of a catchment in a monthly time step, since data at finer temporal resolution are not available for the whole area of interest. The structure of the model is formed by a system of relationships describing basic principles of water balance on ground, in the zone of aeration, including the effect of vegetation cover, and in groundwater. Air temperature is used as an indicator of energy conditions, which significantly affect the water balance components. The input data of the model are monthly series of basin precipitation, the air temperature and relative air humidity, which are obtained by interpolation of the station data to the area of the basin considering the distance from the centre of the basin and orography. For calibration of the eight model parameters, a monthly runoff series at the outlet from the basin is used. In total we calibrated the hydrological model for 100 basins that would be affected by reservoirs at LASW. The input data were provided by the Czech Hydrometeorological Institute. For the most of the stations at least 27 years of data were available, only at a few stations was the length of the record shorter, but at least 20 years.

For the modelling of the climate change impacts we used a simple delta change method, in which the observed data are transformed to show the same mean monthly changes between reference and future periods, as derived from the regional climate model. The transformed observed series are then run through the calibrated hydrological model. The resulting time series represent the future conditions. For the derivation of the delta factors we consider periods 1961–1990 and 2071–2099.

In total we considered 15 transient Regional Climate Model (RCM) simulations all covering the period 1961–2099. All simulations were forced by the global climate model simulations under SRES (Special Report on Emissions Scenarios; Nakicenovic & Swart, 2000) A1B emission scenario and have horizontal resolution of 25 km × 25 km. Most of the simulations (14) were conducted within the Ensembles project. The CHMI_ARP simulation was produced by the Czech HydroMeteorological Institute. The overview of the RCM simulations is given in Table 1.

The deficit volumes were derived with the threshold level method (Hisdal *et al.*, 2004): the drought starts when the discharge drops under a predefined threshold and continues until the threshold is exceeded again. In the present study the threshold was set to the 70% quantile from the flow exceedence curve similarly as in Novický *et al.* (2006). For each year the maximum deficit volume was calculated and we further assumed that the annual maximum deficit volume follows the Generalized Extreme Value (GEV) distribution.

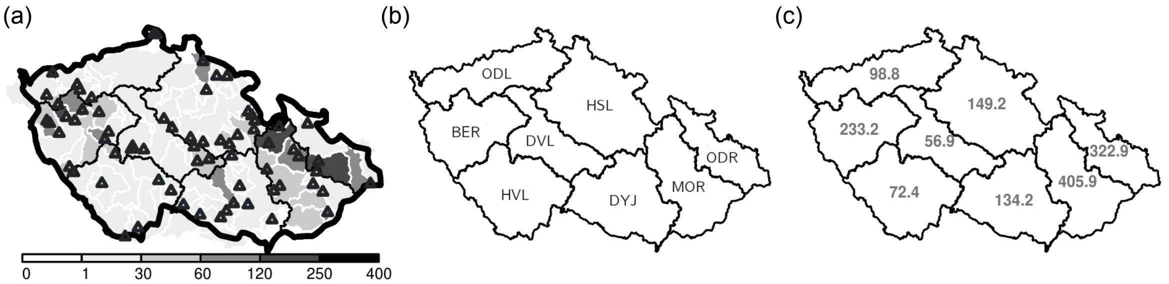

Fig. 1 Localities suitable for accumulation of surface water (LASW): (a) location of the potential reservoirs (red triangles) with colour expressing the amount of available water in the catchments of the reservoirs; (b) the river basin districts (RBD); (c) the capacity of the potential reservoirs aggregated to the area of RBD in mil. m^3.

Table 1 Overview of the RCM simulations.

Acronym	RCM	Period available	Source
ECHAM5 driven			[1] Royal Netherlands Meteorological Institute (KNMI)
RACMO_EH5 [1]	RACMO2.1	1950–2100	[2] Max Planck Institute for Meteorology (MPI), Germany
REMO_EH5 [2]	REMO5.7	1951–2100	[3] Swedish Meteorological and Hydrological Institute (SMHI)
RCA_EH5 [3]	RCA3.0	1951–2100	[4] Abdus Salam International Centre for Theoretical Physics (ICTP), Italy
RegCM_EH5 [4]	RegCM3	1951–2100	[5] Danish Meteorological Institute (DMI)
HIR_EH5 [5]	HIRHAM5	1951–2100	[6] Met Office Hadley Centre, UK
HadCM3Q0, HadCM3Q3, HadCM3Q16 driven			[7] Swiss Federal Institute of Technology Zurich (ETHZ)
HadRM_Q0 [6]	HadRM3.0	1951–2099	[8] Community Climate Change Consortium for Ireland (C4I)
CLM_Q0 [7]	CLM2.4.6	1951–2099	[9] National Centre of Meteorological Research (CNRM), France
HadRM_Q3 [6]	HadRM3.0	1951–2099	[10] Czech Hydrometeorological Institute (CHMI), Czech Republic
RCA_Q3 [3]	RCA3.0	1951–2099	
HadRM_Q16 [6]	HadRM3.0	1951–2099	
RCA_Q16 [8]	RCA3.0	1951–2099	
ARPEGE4.5 driven			
HIR_ARP [5]	HIRHAM5	1951–2100	
CNRM5_ARP [9]	CNRM-RM5.1	1951–2100	
CHMI_ARP [10]	ALADIN-CLIMATE/CZ	1961–2100	
BCM2.0 driven			
RCA_BCM [3]	RCA3.0	1961–2100	

$$H(x)=\begin{cases}\exp\left\{-\left[1+\xi\left(\dfrac{x-\mu}{\sigma}\right)\right]^{-1/\xi}\right\} & if\ \xi\neq 0\\ \exp\left[-\exp\left(-\dfrac{x-\mu}{\sigma}\right)\right] & if\ \xi=0\end{cases}$$

with μ, σ, ξ the location, scale and shape parameter, which have been estimated from data using the method of L-moments. The quantiles x_p are then estimated as:

$$\hat{x}_p=\begin{cases}\hat{\mu}-\dfrac{\hat{\sigma}}{\xi}\left\{1-\left[-\log(1-p)\right]^{-\xi}\right\} & if\ \xi\neq 0\\ \hat{\mu}-\hat{\sigma}\log\left[-\log(1-p)\right] & if\ \xi=0\end{cases}$$

where p is the probability for a quantile to be exceeded during one year.

Since drought does not necessarily occur each year a model:

$$H^*(x)=\begin{cases}p_0 & if\ x=0\\ p_0+(1-p_0)H(x) & if\ x\neq 0\end{cases}$$

(England *et al.*, 2005) is considered, with p_0 the probability of drought, which is estimated as the proportion of zero deficit volume from the total number of years for each basin (30).

The model is fitted to the control and scenario periods and the differences in deficit volumes are calculated. Finally, the differences in deficit volumes are aggregated for river basin districts and compared with the potentially available volume.

RESULTS

To find a suitable probability model for the deficit volumes we examined several distributions (not shown). Among the considered distributions, the GEV distribution was the most appropriate. An example of fitting the GEV distribution to the deficit volumes for the Čistá River for the control and scenario periods in individual RCM simulations is given in Fig. 2. In general, the estimated quantiles compare well with the deficit volumes. However, the differences between the individual RCM simulations are large. For instance, several simulations from Fig. 2 indicate large increases in deficit volumes (CNRM_ARP5, CHMI_ARP, HadRM_Q16) while other simulations show almost no change (RACMO_EH5, REMO_EH5) or even a decrease (HIR_EH5). The large spread between the simulations is typical for all catchments.

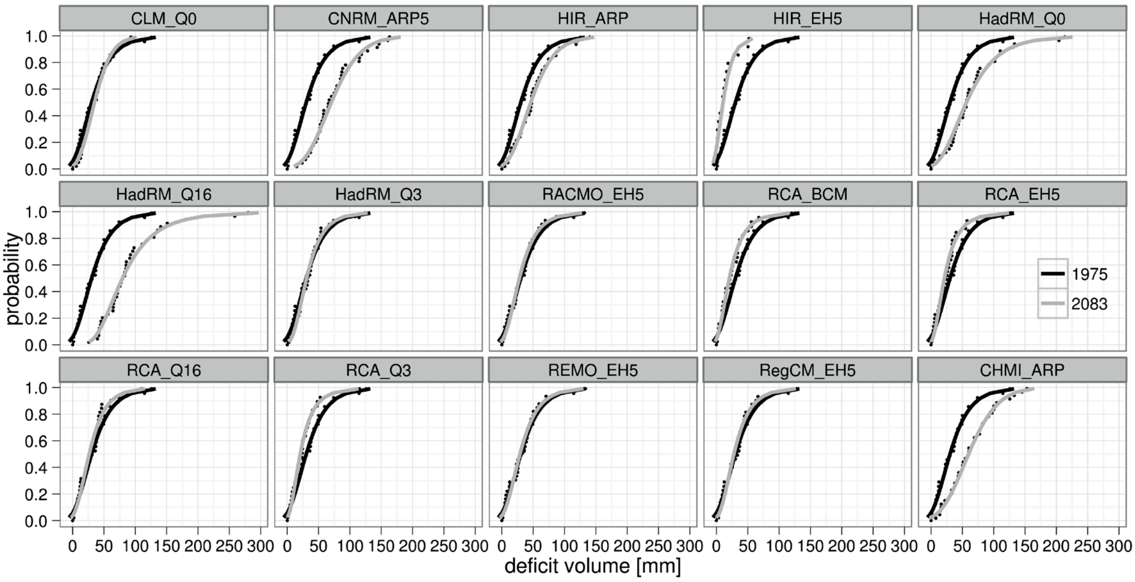

Fig. 2 Annual deficit volumes for the control and scenario periods in the individual RCM simulations for the Čistá River in Hostinné. The GEV fit is given by lines, original deficit volumes by points.

A summary of relative changes in quantiles of deficit volumes is given in Fig. 3. In general, the relative changes are a bit larger for smaller quantiles than for large quantiles. This is accompanied with a large spread among the individual catchments (represented by boxplots). The relative changes for the RCM simulations driven by ECHAM5 global climate model are usually between 0.8–2. Very large increases (1.5–4) are found for the rest of the simulations.

As expected, the average changes in deficit volumes are positive (deficit volumes are larger in the scenario period than in the control period). The summary of the relative changes in deficit volumes is given in Table 2. The relative changes are larger for lower quantiles, however, in absolute values (not shown) the differences in deficit volumes between scenario and control periods are larger for large quantiles. The increase is considerable especially for the Upper Vltava and Upper and middle Elbe (HVL and HSL) river basin districts. The increase in deficit volumes could be compensated in the DVL, ODL, ODR and MOR river basin districts, while the compensation would be difficult in HSL, HVL and BER. The HVL turned out as most problematic, which is partly due to a large increase in deficit volumes and partly due to low potentially available volume. This is because a large number of reservoirs are present in this river basin district and there are not many other localities suitable for construction of reservoirs.

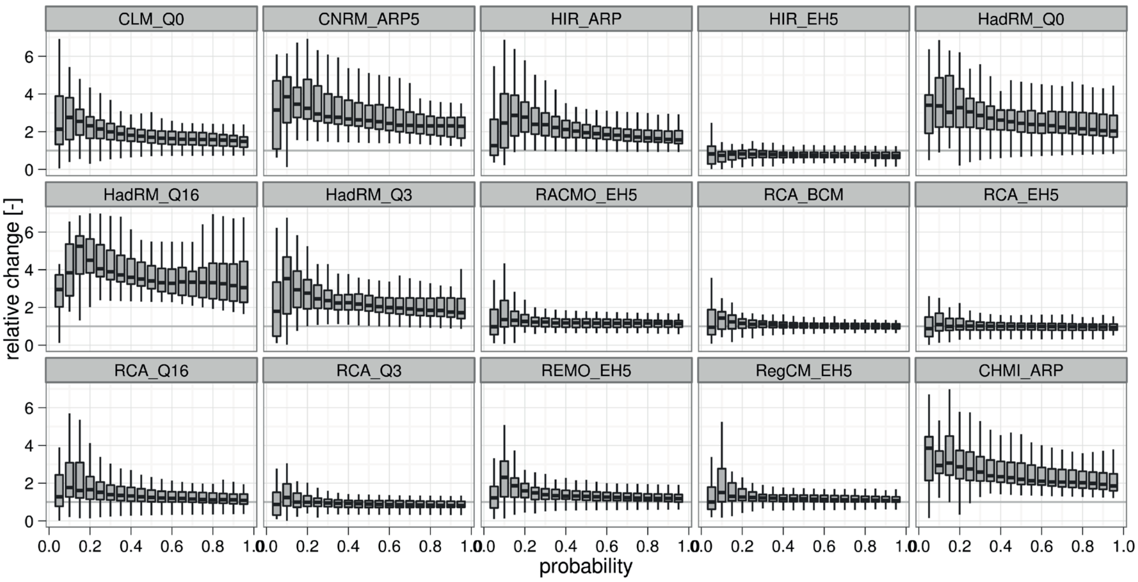

Fig. 3 Relative changes in quantiles of the fitted distribution of deficit volumes for the individual RCM simulations. The boxplots summarize relative changes for all 100 considered basins.

Table 2 Change in various quantiles of deficit volumes for river basin districts and possible compensation by the water potentially available from new reservoirs.

	Change in deficit volume (%)				Change in deficit volume / potential reservoir volume (%)				
Quantile	0.25	0.5	0.75	0.95	0.05	0.25	0.5	0.75	0.95
HSL	40	18	18	14	8	–22	–50	–87	–170
HVL	117	101	86	63	–20	–136	–241	–378	–659
BER	233	145	112	76	50	–27	–96	–184	–357
DVL	139	36	49	53	89	77	67	55	28
ODL	53	35	25	30	82	73	65	53	25
ODR	101	34	9	15	92	89	86	82	69
MOR	51	31	25	15	78	75	72	69	63
DYJ	87	67	50	46	87	59	31	–7	–97

DISCUSSION

The increase in deficit volumes for a number of catchments is very large and suggests that technical measures such as new reservoirs or water transfers have to be considered to provide sufficient water resources. Therefore we advised the preservation of the present protection for all localities. However, additional questions have to be answered. The applied methodology assumes that the reservoirs are full before the deficit events. This assumption would certainly not always be fulfilled and more detailed assessment of individual reservoirs is therefore required. It is also possible that (hydro-) meteorological conditions in some of the protected localities might not allow for the operation of designed volumes in the future. In those cases the protection could be questioned.

The statistical model has to be evaluated further, especially with respect to the goodness-of-fit. Parametric modelling allows for easy comparison of the changes in different basins by looking at the differences in the estimated parameters and their changes. The main limitation of the methodology is that when standard 30 years-time slices are considered, only 30 values are used for fitting the GEV distribution. Alternatives to provide more data include (non-stationary) analysis of transient simulations (which are easily available for a period such as 1950–2100), application of regional frequency analysis or combination of both (as done for precipitation in transient regional climate model simulations by Hanel *et al.*, 2009).

Using the GEV distribution requires the choice of the block size. In the case of drought, the block size of one year might in fact be too short and not always providing independent events. Increasing the block size practically disables statistical modelling since, for instance, using 2 years block size implies only 15 events in a 30 year time slice. A possible solution could be the application of the Generalized Pareto Distribution.

In the present paper, the delta change approach was applied to derive the climate change scenarios. However, it has been shown by Hanel *et al.* (2013) that changes in the characteristics of drought, such as deficit volume or length of deficit period, are strongly dependent on the methodology used for the derivation of the climate changes scenarios. In fact, the changes in deficit volume have been on average about 15% larger when the bias correction method was considered (Hanel *et al.*, 2013). This increases our uncertainty and suggests that changes in deficit volumes could be even larger.

CONCLUSIONS

Parametrical modelling of deficit volumes provides good insight into the deficit volumes and their changes. The application of the statistical model for the assessment of changes in deficit volumes for the protected localities for accumulation of surface water in the Czech Republic revealed that the estimated increase in the deficit volumes is considerable and technical measures such as new reservoirs or water transfers might be necessary. This resulted in the recommendation for further protection of the localities. However, knowing the uncertainties of climate modelling and development of climate change scenarios and limitations of the statistical methodology, further research is needed to allow for competent decision making.

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