Analysis of low flow indices under varying climatic conditions in Poland

Marzena Osuch, Renata Romanowicz and Wai K. Wong

ABSTRACT

Changes in low flow indices under future climates are estimated for eight catchments in Poland. A simulation approach is used to derive daily flows under changing climatic conditions, following RCP 4.5 and RCP 8.5 emission scenarios. The HBV rainfall–runoff model is used to simulate low flows. The model is calibrated and validated using streamflow observations from periods 1971–2000 and 2001–2010. Two objective functions are used for calibration: Nash–Sutcliffe and log transformed Nash–Sutcliffe. Finally, the models are run using the bias-corrected precipitation and temperature data simulated by GCM/RCM models for the periods 2021–2050 and 2071–2100. We estimate low flow indices for the simulated time series, including annual minima of 7-day mean river flows and number, severity and duration of low flow events. We quantify the biases of low flow indices by N-way analysis of variance (ANOVA) analysis and Tukey test. Results indicate a large effect of climate models, as well as objective functions, on the low flow indices obtained. A comparison of indices from the two future periods with the reference period 1971–2000 confirms the trends obtained in previous studies, in the form of a projected decrease in the frequency and intensity of low flow events.

Key words | ANOVA, climate change, low flows, Poland

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INTRODUCTION

Poland belongs to the group of countries with relatively small water resources (Kaczmarek *et al.* 1996). Due to the seasonality of flow regimes, the availability of water in the late summer and autumn is limited and this lack of water is a source of problems to society in a wide range of sectors. Severe problems, including scarcity of drinking water and water for power production during the summer of 2015, were reported by Van Lanen *et al.* (2016). Similar problems related to hydrological drought were observed in the dry summers of 1976, 1985 and 2003. These problems may become more severe as a result of climate change.

Projections of low flow conditions are extremely important for the planning and development of adaptation strategies for water resources and other sectors. The number of studies dealing with analysis of the impact of climate change on droughts in Poland is limited. An assessment of trends of the Standardized Precipitation Index (SPI) in a future climate in Poland was presented by Osuch *et al.* (2016b). As shown in that study, the spatial pattern of trends depends on the climate model applied, the time scale (month, season) and on the bias correction of climate simulations. The influence of bias corrections on the change of projected trend is small in comparison to the variability between climate models. The results of different regional climate models (RCMs) driven by the same global climate model (GCM) outputs are characterized by a similar pattern of changes.

An analysis of the impact of climate change on hydrometeorological drought at catchment scale has been presented by Meresa *et al.* (2016). Three drought indices were evaluated: SPI, Standardized Evapotranspiration Index (SPEI) and Standardized Runoff Index (SRI) using observed

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and projected hydroclimatic data. The estimated changes in these three indicators showed large differences related to the applied index, catchment and climate model. The SPI and SRI projections indicated wetter climates in future while the opposite tendencies (drier conditions) were found for SPEI in the far future.

In both studies a spread in the obtained results (trends or changes) was highlighted. Similar findings were presented by Huang *et al.* (2013), Forzieri *et al.* (2014) and Parajka *et al.* (2016). Future climate predictions are uncertain for a number of reasons. One is the natural variability of the climate, the other is the uncertainty related to human-induced changes and the modelling errors. For this reason, the term projections is used instead of predictions. Projections are based on the results of simulations of GCMs. The GCM model projections are downscaled using RCMs, nested in GCMs. The GCM/RCM models give a very simplified image of the complex processes that govern the Earth's climate. Therefore, any projections based on these simulations are even more uncertain.

Hydrological modelling also contributes to the uncertainty of changes in hydrological indices. Dams *et al.* (2015) indicated that hydrologic model selection introduces an additional source of uncertainty in low flow projections. A study by Najafi *et al.* (2011) showed that, in general, the uncertainties of hydrological modelling are smaller than from climate models, but in the low flow season an influence of hydrological model parametrization is larger than those coming from climate models. Parajka *et al.* (2016) focused on an analysis of the contribution to the uncertainty of low flow projections resulting from hydrological model uncertainty and climate projection uncertainty. The results of the assessment indicated that the impact of the objective function is very important. According to Benninga *et al.* (2016), hydrological model uncertainty plays a bigger role in the uncertainty of flow predictions for low flow events than input uncertainty, and the opposite occurs for high flow events.

In this study, we focus on the influence of climate change on changes in low flow indices at the catchment scale for eight catchments in Poland with different hydro-climatic conditions.

In addition, an analysis of the influence of the choice of objective function that was applied for hydrological model calibration on the estimated changes is performed. For this purpose the HBV model was calibrated using the Nash–Sutcliffe objective function for the original flows (NSE) and log transformed flows (flows transformed using natural logarithm, logNSE). The first objective function is very popular despite its poor performance in low flow studies (Pushpalatha *et al.* 2012). The choice of the logNSE was dictated by its ability to better simulate low flows (Oudin *et al.* 2006; Meresa & Romanowicz 2016; Garcia *et al.* 2017). In addition, the spread of results due to the emission scenarios, climate models, two future periods, catchments and objective functions was quantified using N-way analysis of variance (ANOVA) and Tukey post-hoc test.

In the following section we describe the study area. The methods are presented in the third section, followed by a description of the results of analyses. The discussion and conclusions section gives a summary of our study and suggests ways forward.

STUDY AREA

The analyses were carried out for eight catchments in Poland (Figure 1) with different hydro-climatic conditions. Four of the catchments (Nysa Kłodzka/Kłodzko, Wisła/Skoczów, Dunajec/Nowy Targ and Biała Tarnowska/Koszyce Wielkie) are situated in southern Poland and they are mountainous catchments with steep slopes. The other catchments (Oles nica/Niechmirów, Myśla/Myślibórz, Guber/Prosna and Narewka/Narewka) are located in the lowland area.

The choice of catchments was dictated by their semi-natural conditions with pristine or insignificant changes in land use with urban area less than 10% and without water management works (dams, substantial control structure upstream or water extraction within the basin, or diversion between basins) that could significantly change streamflow dynamics (Tongal *et al.* 2017). The catchment areas range from 297 km^2 to 1,555 km^2. A detailed description of the catchments is presented in Romanowicz *et al.* (2016).

METHODS

Climate change impact analyses on hydrological extremes are carried out following a well-established modelling

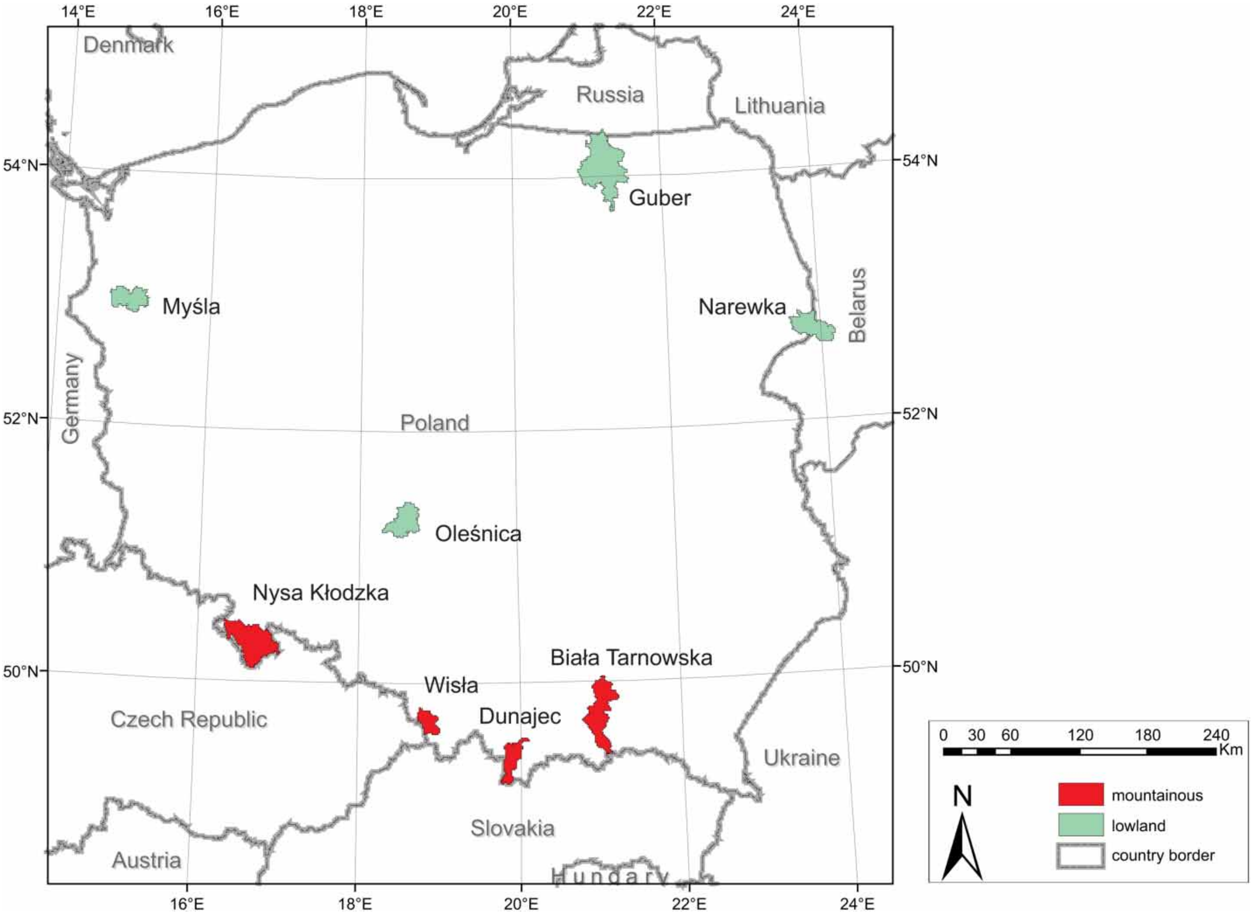

Figure 1 | Study area.

chain (Figure 2) that consists of emission scenarios, climate models, bias correction methods of climate simulations, hydrological models and indicator quantifying processes or variables under study. The outcomes of the modelling chains are used to estimate changes in low flow indices.

Climate simulation

In this paper the analyses were carried out for an ensemble of seven climate model simulations for two emission scenarios RCP 4.5 and RCP 8.5 (Moss *et al.* 2010). These simulations were available from the EURO-CORDEX initiative (Giorgi *et al.* 2009; Jacob *et al.* 2014; Kotlarski *et al.* 2014). The seven selected climate model simulations are based on four RCMs (CCLM4-8-17, HIRHAM5, RACMO22E and RCA4) driven by three different GCMs (CNRM-CM5, EC-EARTH and MPI-ESM-LR) (Table 1). All seven models have the same spatial resolution, i.e., 0.11° on a rotated latitude–longitude grid in rotated coordinates giving a quasi-uniform resolution of approximately 12.5 km.

The analyses were carried out using time-slice approach for three periods: the reference period 1971–2000 (REF) and two future periods 2021–2050 (near future) and 2071–2100 (far future).

Figure 2 | Modelling chain applied in this study.

Table 1 | List of GCM and RCM combinations used from CORDEX

GCM/RCM	CCLM4-8-17	HIRHAM5	RACMO22E	RCA4	Total simulations
CNRM-CM5	+[r1]	–	–	–	1
EC-EARTH	+[r12]	+[r3]	+[r12]	+[r12]	4
MPI-ESM-LR	+[r1]	–	–	+[r1]	2
Total simulations	3	1	1	2	7

Numbers in brackets correspond to the ensemble member.

Bias correction

Preliminary validation of simulated daily air temperature and daily precipitation totals in the reference period (1971–2000) against observations from synoptic stations (point measurements) indicated significant biases, especially for daily precipitation, that should be corrected before an impact study is performed.

We used two quantile mapping methods, one single gamma distribution-based mapping following Piani *et al.* (2010) for correction of the precipitation time series and an empirical quantile method for air temperature correction (Gudmundsson *et al.* 2012; Sunyer *et al.* 2015). The methods were selected for their feasibility in general application to all of the climate projections and their suitability for evaluating extremes (Sunyer *et al.* 2015; Hundecha *et al.* 2016; Osuch *et al.* 2016a).

In the parametric approach, the probability distributions of the observed and simulated time series are modelled using an appropriate theoretical distribution (gamma distribution in our case), and the parameters of the distribution are estimated from the observed or simulated data. As gamma function is not specified at zero values, only wet days have been used for fitting this function. The inverse of the derived gamma distribution for observed time series is then used to correct the quantiles of simulations, as follows:

$$\hat{P}^{RCM}_{corr} = F^{-1}_{Obs}\left(F_{RCM}\left(P^{RCM}\right)\right) \tag{1}$$

where F_{Obs} denotes the cumulative distribution function (cdf) of observations and F_{RCM} is the cdf of simulated values. The quantile–quantile transformation was parametrized by a power function with three parameters:

$$\hat{P}^{RCM}_{corr} = \begin{cases} b(P^{RCM} - x_0)^c & \text{for} \quad P^{RCM} \geq x_0 \\ 0 & \text{for} \quad P^{RCM} < x_0 \end{cases} \tag{2}$$

where coefficients b and c are calibrated for the best fit, x_0 is an estimated threshold value of precipitation below which modelled precipitation is set to zero.

The number of wet days was first corrected on the basis of the empirical probability of non-zero values in the observations prior to the correction of precipitation values. This is a necessary part of the bias correction, as RCMs tend to simulate too many wet days with low values of precipitation. All values for precipitation below this threshold (x_0) are set to zero for the simulated data.

The quantile–quantile transformation and wet day correction derived for the control period were further applied in the correction of precipitation data for two future periods.

In the case of air temperature, the residuals were corrected after removing the difference in air temperature between the reference and the future periods to maintain the climate change signal (Hempel *et al.* 2013).

The bias correction was carried out independently for each climate model and catchment on a monthly basis to correct discrepancies in the seasonal patterns.

Hydrological modelling

Hydrological projections were obtained using semi-distributed HBV model (Bergström 1995; Lindström 1997; Lindström *et al.* 1997; Booij 2005; Booij & Krol 2010). This hydrological model has been used with success in studying the influence of climate change on hydrological processes (e.g., Bergström *et al.* 2001; Andréasson *et al.* 2004; Graham *et al.* 2007; Demirel *et al.* 2013). Details of the applied version of the HBV are presented in Piotrowski *et al.* (2017). At the calibration and validation stage, the model was run using observed daily air temperature and catchment average precipitation calculated by Thiessen polygons based on data available from meteorological stations. Potential evapotranspiration (PET) was estimated by the Hamon method based on daily mean air temperature (Hamon 1961). The HBV model was calibrated using flow observations from the reference period 1971–2000 and validated on observations for 2001–2010. During an analysis of impact of climate change, the model was run using bias-corrected simulated climate data (seven combinations of GCM/RCM) from grid cells closest to the geometrical centre of each of the study catchments.

In this study, two measures, the Nash–Sutcliffe (NSE) efficiency criterion (Nash & Sutcliffe 1970) and log transformed NSE, were used as objective functions. The first objective function (NSE) is very sensitive to extreme high values as it is based on least-square errors and therefore gives good results for average and high flows (Garcia *et al.* 2017). Due to the logarithmic transformation of flow values, the second objective function (logNSE) is better suited to represent low flows (Oudin *et al.* 2006; Romanowicz *et al.* 2013).

The results of model calibration and validation using both objective functions are presented in Table 2. In the calibration stage, the Nash–Sutcliffe criterion is greater than 0.6 for all catchments. The best fit (0.79) was achieved for the Biała Tarnowska catchment. The results of validation are very good for the four mountainous catchments and for Guber, all having NS values higher than 0.7. In the case of the lowland catchments, the comparison of simulations with observations gives somewhat poorer results, with NS values varying from 0.51 for Oleśnica up to 0.74 for the Guber catchment.

The calibration results obtained for logNSE are slightly lower than for NSE in almost all catchments except Narewka. The obtained values of logNSE range from 0.56 for Nysa Kłodzka to 0.76 for Dunajec. The performance of validation is also worse for the logNSE than for the NSE, except the results for Oleśnica and Narewka where the values of logNSE are higher than the NSE.

The results of calibration and validation depend significantly on the period chosen. In our case, the HBV model was calibrated using streamflow observations from the period 1971–2000 (30 years) and validated on observations from the period 2001–2010 (10 years). Had we used another ten-year period (e.g., 1961–1970) for validation, we might very well have got poorer fit than the calibration period. Rainfall–runoff process is, after all, a stochastic process, which implies randomness. In addition, the length of calibration and validation periods influence the obtained results.

The results of calibration and validation using NSE and logNSE confirm the overall suitability of the HBV model for simulations of hydrological conditions in the eight tested catchments with differences in the model performance between catchments.

Low flow indices

Analyses of low flows were carried out for the following indices: annual minimum 7-day average flows (AM7),

Table 2 | A summary of the calibration and validation of the HBV model

			Calibration results		Validation results	
River	**Gauging station**	**Meteorological stations**	**NSE**	**logNSE**	**NSE**	**logNSE**
Dunajec	Nowy Targ	Kasprowy Wierch, Zakopane, Jabłonka	0.77	0.76	0.80	0.76
Wisła	Skoczów	Bialsko Biała	0.65	0.58	0.75	0.59
Biała Tarnowska	Koszyce Wielkie	Nowy Sącz, Tarnów, Biecz, Krynica, Wysowa	0.79	0.67	0.75	0.72
Nysa Kłodzka	Kłodzko	Kłodzko, Długopole, Ladek Zdrój	0.72	0.56	0.70	0.62
Oleśnica	Niechmirów	Wieluń, Sieradz	0.72	0.63	0.51	0.68
Narewka	Narewka	Białowieża	0.71	0.73	0.54	0.61
Myśla	Myślibórz	Szczecin	0.71	0.64	0.52	0.56
Guber	Prosna	Lidzbark Warmiński	0.65	0.63	0.74	0.67

Note: NSE and logNSE denote the Nash–Sutcliffe efficiency criterion calculated for flows and logarithm of flows, respectively. The HBV model was calibrated using data from 1971 to 2000 and validated using data from 2001 to 2010.

number of low flow incidents per year, average duration of low flow incidents, low flow volume deficit and number of days with flows below threshold. These indices were calculated directly from the HBV model output for three 30-year periods (1971–2000, 2021–2050, 2071–2100) for each catchment and climate model. Low flow indices were calculated using Q80 from observations in the reference period as a threshold. In this study no pooling procedure was applied. Two low flow events were considered as independent without analysing flows and the duration of time between them.

Quantification of spread in the results

The quantification of the spread of biases in the reference period and projected changes was performed using a variance decomposition technique following the ANOVA approach (Von Storch & Zwiers 2001). In the case of biases in the reference period, the following model was applied:

$$IN_{ijk} = \mu + CM_i + OF_j + CA_k + (CM{*}OF)_{ij} + (CM{*}CA)_{ik} + (OF{*}CA)_{jk} + \varepsilon_{ijk} \tag{3}$$

where IN_{ijk} is a value of a low flow indicator (e.g., biases in AM7) for ith climate model, jth objective function and kth catchment. The first element on the right-hand side of Equation (3) denotes the overall mean. The next three elements represent the principal contributions to the variance corresponding to the climate model (*CM*), the objective function (*OF*) and the catchment (CA). The following three elements describe interactions that quantify the effects that do not combine additively (Yip *et al.* 2011). The last element represents errors (i.e., the unexplained variance).

In the case of projected changes in low flow indices the spread in the results was decomposed into the variance explained by: climate models, emission scenarios, objective functions, catchments and two periods. The analyses were carried out using the Type III sums of squares ANOVA.

To compare results between groups and test the equality of the mean response for groups the N-way ANOVA analysis was supplemented by Tukey post-hoc test (Tukey 1949) that was applied later to explore results of the ANOVA analysis. The results of such analyses are presented as a graph of population marginal mean (PMM, Searle *et al.* 1980) estimates and the comparison intervals represented by a continuous line extending from the symbol. Least squares means are the expected population marginal means, given the model being applied. In this context, PMM is a wider concept than least squares mean (Searle *et al.* 1980). Two group means are significantly different if their intervals do not overlap and they are not significantly different if their intervals overlap.

RESULTS

Validation of flows in the reference period

Annual minimum 7-day average flows (AM7)

Following the methods presented in the previous section, daily flow was simulated using the HBV model forced by projected meteorological variables and thereby low flow indices were derived. A comparison of the simulated annual minimum 7-day average flows (AM7) for 1971–2000 is presented in Figure 3. The boxplots represent the spread in the AM7 calculated using the ensemble of seven climate models. The simulated indices were validated against indices estimated for observed flows. In addition to the indices calculated using real observations, the indices calculated for the HBV-simulated flows using both objective functions are presented. Differences between the lines quantify the ability of the HBV model to simulate the AM7. A comparison of the results indicates that in most catchments simulations based on the logNSE are better than simulations based on the NSE. However, the simulations with NSE gave slightly better results than logNSE for the Guber catchment.

Number of low flow events

The average number of low flow events in a year is the second indicator of low flows. A comparison of simulations and observations is shown in Figure 4. The observed number of low flow events varies between catchments, from 2.25 for Flinta catchment to 9.40 for Nysa Kłodzka. Number of low flow events calculated on the basis of the HBV model simulations indicates problems with an accurate estimation of

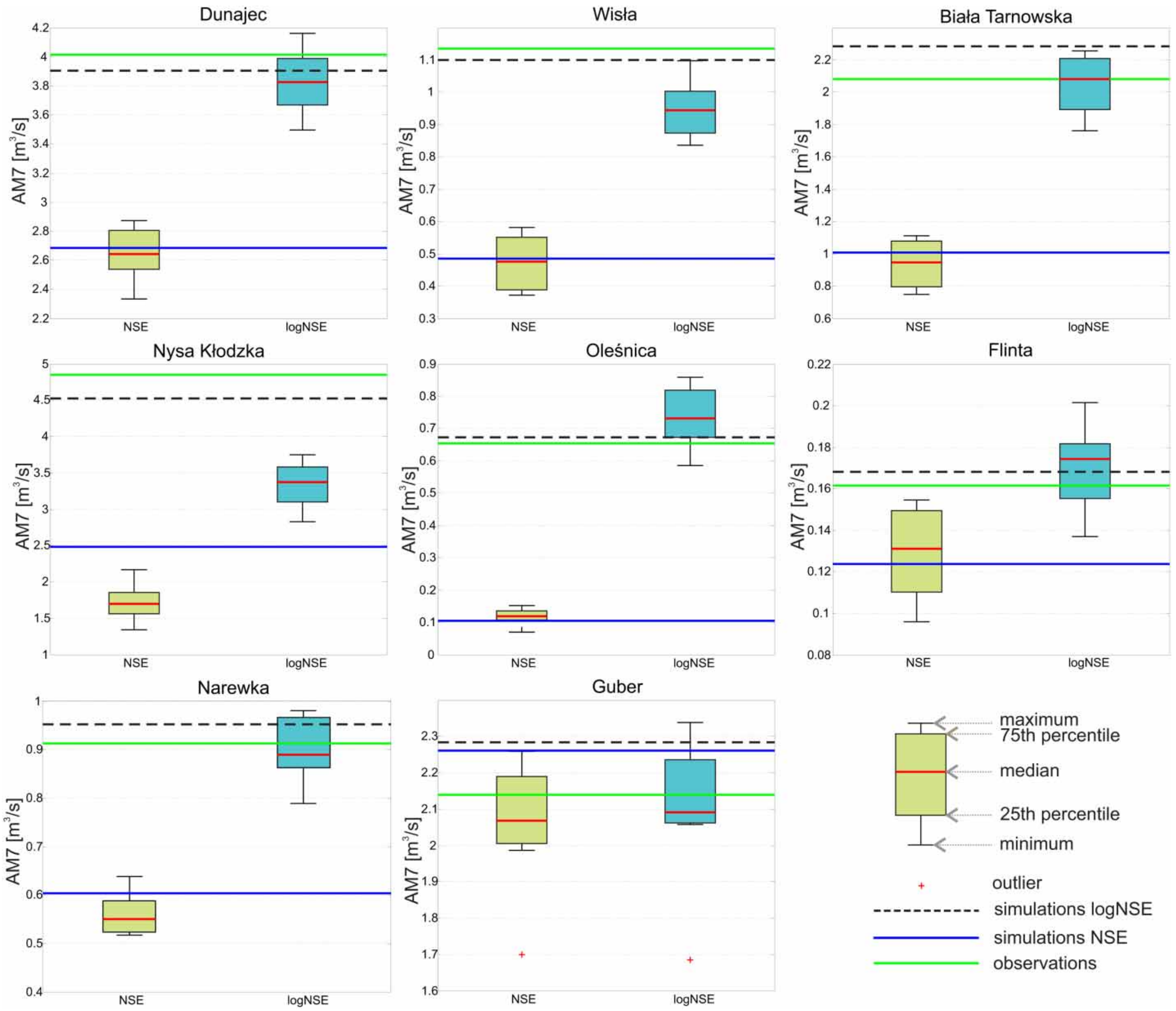

Figure 3 | Comparison of simulated and observed AM7 in the reference period. Boxplots represent the spread of results of seven climate models.

this indicator for most catchments. The simulations using logNSE as an objective function fitted to observations for Flinta only.

The results were then subjected to N-way ANOVA analysis and the Tukey post-hoc test. The outcomes are presented in Figure 5. The spread in the results is mainly due to objective functions and catchment type. No statistically significant differences between estimates of number of low flow events from different climate models are shown (all climate models overlap). Differences between catchments show the opposite effect. Negative biases were estimated for the Guber (−63%) and Nysa Kłodzka (−19%) catchments. The biases for other catchments are positive and vary from 5% for Biała Tarnowska to 53% for Flinta. A comparison of the estimated NSE indicates that better results (lower relative bias −24%) were obtained when logNSE was applied as an objective function. Higher biases are for simulations by the HBV model with NSE (37%). The differences in results for the two objective functions are statistically significant.

Number of days below threshold

The estimation of biases in the number of days below threshold (Q80 from observations in the reference period)

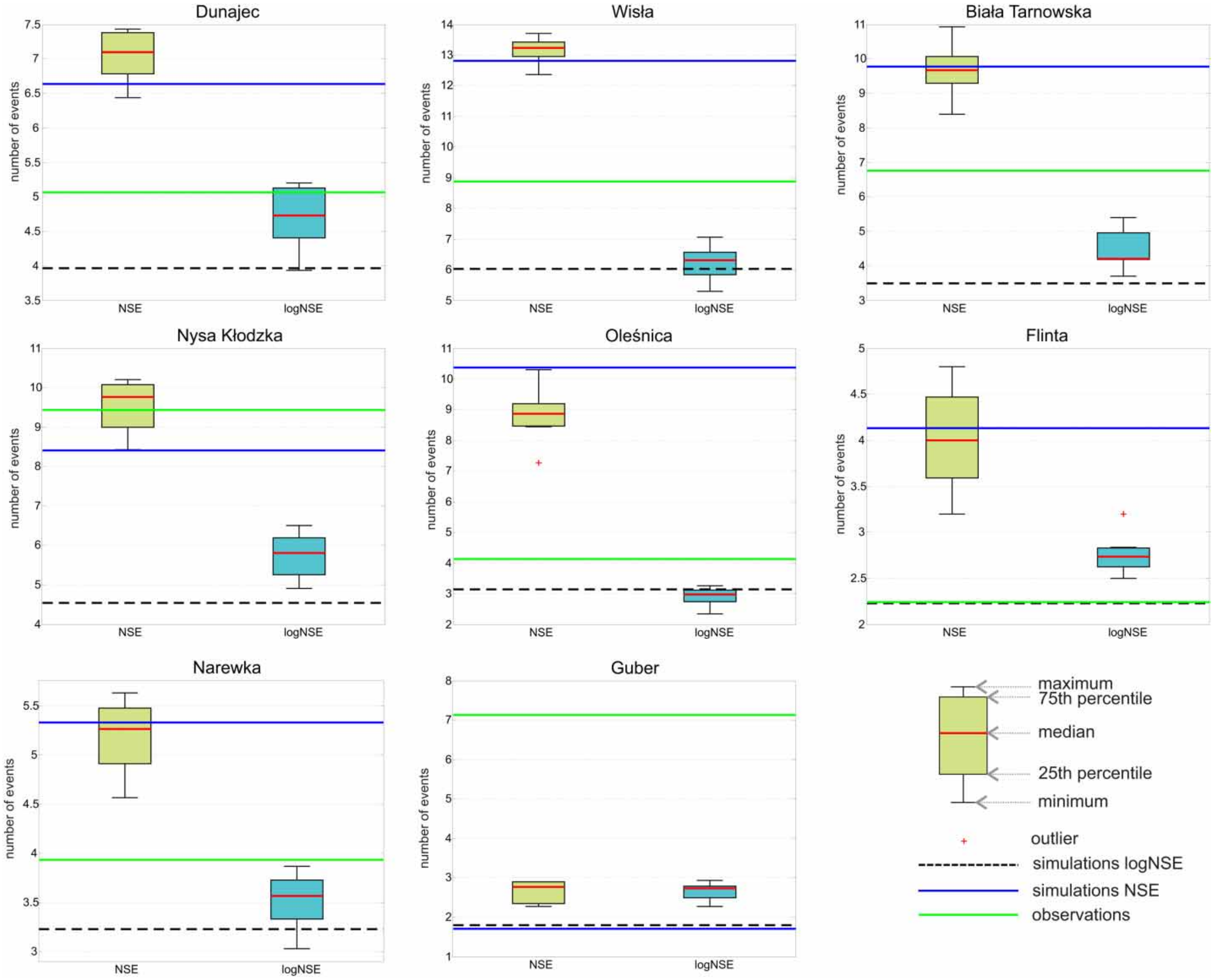

Figure 4 | Comparison of simulated and observed number of low flow events in the reference period.

are presented in Figure 6. For this indicator, biases are positive in all cases. The results of three-way ANOVA and Tukey post-hoc test indicated statistically significant differences between climate models, catchment and objective functions. Taking into account the differences between climate models, the highest biases were obtained for

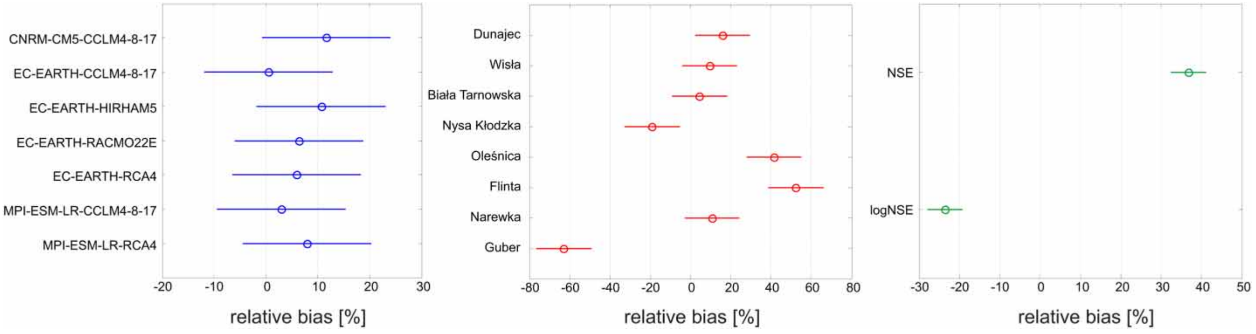

Figure 5 | Quantification of the spread in the results (biases in the number of low flow events) due to differences between climate models, catchments and objective functions. Circles represent the PMM and the bars are the relevant spread.

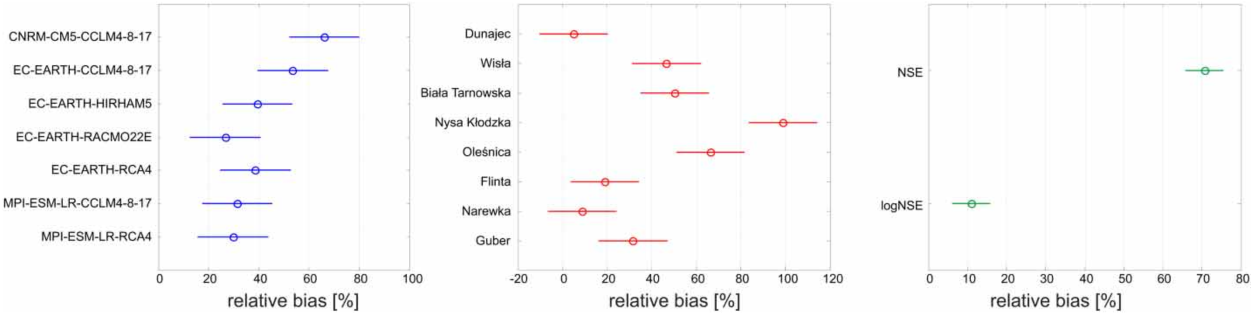

Figure 6 | Quantification of the spread in the results (biases in the number of days below threshold) due to differences between climate models, catchments and objective functions. Circles represent the PMM and the bars are the relevant spread.

CNRM-CM5-CCLM4-8-17 model (66%). The PMMs vary from 5% for the Dunajec to 99% for the Nysa Kłodzka. The values of relative biases strongly depend on the objective function. Smaller biases were obtained for simulations with logNSE (11%) than with NSE (71%).

Mean low flow duration

A comparison of the biases in mean low flow duration in the reference period is shown in Figure 7. For this index there are statistically significant differences in the estimates from different climate models. The highest biases were found for CNRM-CM5-CCLM4-8-17 model (115%). Large differences in estimated relative biases between catchments were found. In two cases, Flinta (−34%) and Dunajec (−13%), biases have negative values that indicate underestimation of observations. The biases for other catchments are positive and range from 10% for Oleśnica to 268% for Guber catchment. The outcomes of the analysis for two objective functions indicated that smaller biases are for NSE (62%) than logNSE (81%). This difference is statistically significant.

Volume deficit

An analysis of biases in volume deficit in the reference period was performed in a similar way to the other low flow indicators. The results of three-way ANOVA for climate models, catchments and objective functions are presented in Figure 8. There are no statistically significant differences between the climate models but differences can be seen for catchments and objective functions. A comparison of the outcomes between eight catchments (middle panel of Figure 8) indicates a large variability in the results that range from 3% for Flinta to 257% for Nysa Kłodzka. A large spread in the results of two objective functions was found. Smaller biases were estimated for logNSE (15%) than NSE (195%).

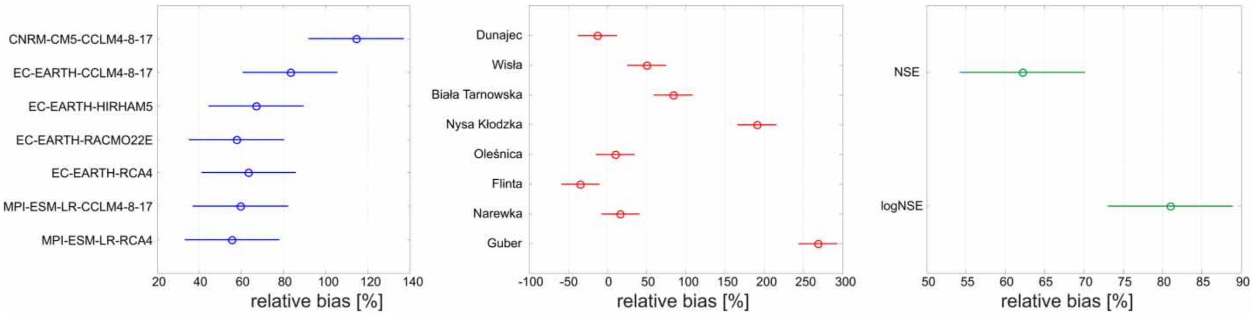

Figure 7 | Quantification of the spread in the results (biases in low flow duration) due to differences between climate models, catchments and objective functions. Circles represent the PMM and the bars are the relevant spread.

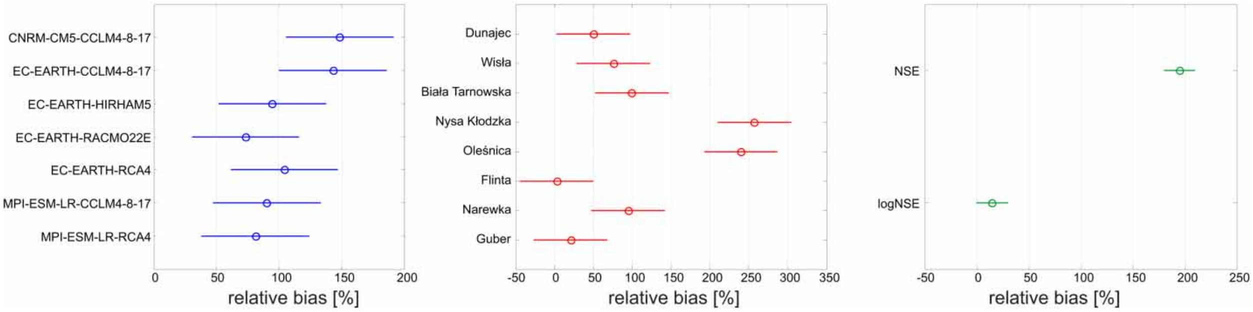

Figure 8 | Quantification of the spread in the results (biases in volume deficit) due to differences between climate models, catchments and objective functions. Circles represent the PMM and the bars are the relevant spread.

Future changes

Following the methods presented in the previous sections, five low flow indices were calculated using simulated flow time series for two future periods, near future 2021–2050 and far future 2071–2100. These analyses were carried out for seven climate models, two emission scenarios and two objective functions. As a result of the calculations low flow indices were estimated. For the quantification of the results a five-way ANOVA analysis was performed on the relative changes between the future periods against the reference period.

Changes in AM7

The results of the five-way ANOVA for relative changes in AM7 are shown in Figure 9. In all cases increases in relative changes of AM7 are projected, with statistically significant differences in magnitude. These changes are related to the variability between catchments, periods, emission scenarios and objective functions. A contribution from the differences in results between different climate models is small and can be ignored. A comparison of the outcomes between catchments indicated that the highest increases in AM7 are projected for Oleśnica (48%) and Flinta (58%). The estimated

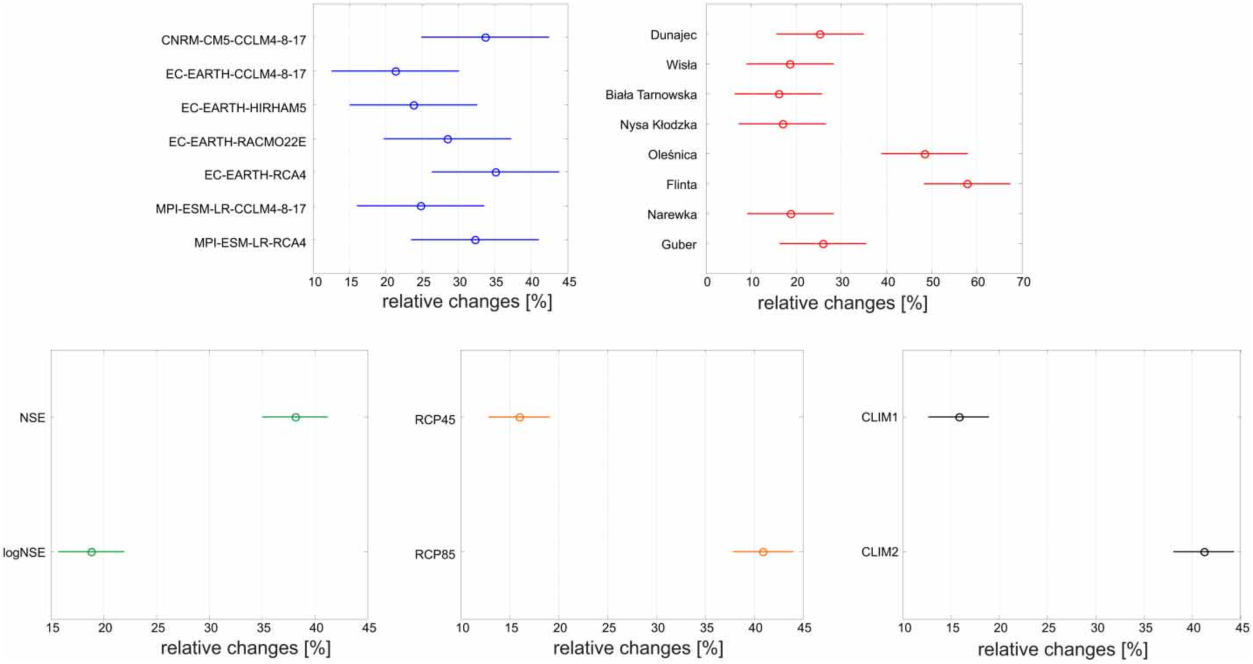

Figure 9 | Distribution of relative changes in the AM7 as a function of climate model, catchment, objective function, emission scenario and future period based on five-way ANOVA and Tukey test. Circles represent the PMM and the bars are the relevant spread.

changes in AM7 for other catchments are statistically different and are smaller than 30%. The choice of objective function influences the results. The changes estimated for logNSE (19%) are smaller than those for NSE (38%). A comparison of the results between emission scenarios and periods indicated that the largest changes were estimated for the RCP 8.5 and the far future (2071–2100).

Changes in number of low flow events

The outcomes of five-way ANOVA analysis and Tukey post-hoc test for relative changes in the number of low flow events are presented in Figure 10. In all cases decreases in the number of low flow events were projected. There are statistically significant differences between climate models, catchments, objective functions and two future periods. The largest spread in the results is due to the differences between catchments. The PMMs vary from 4% for the Wisła catchment to 38% for the Guber catchment. The projected changes for NSE are smaller than for the logNSE. In the case of differences between two future periods changes are larger for far future (2071–2100) than for near future (2021–2050).

Changes in number of days under threshold (Q80)

Analysis of the projected relative changes of the number of days under threshold (Figure 11) showed decreases of this index in all cases. The results of a five-way ANOVA analysis indicated that the spread in the estimated values of ND are mainly due to differences between the catchments and the periods under study. Statistically significant differences between PMM were found for climate models, catchments and periods but for neither objective functions nor emission scenarios. In the case of differences between catchments, larger decreases were estimated for lowland than mountainous catchments. There is a large difference between the two future periods. Larger decreases of ND were found for far future (2071–2100) than near future (2021–2050).

Changes in mean low flow duration

The expected changes in mean low flow duration are presented in Figure 12. In all cases the results indicate decreases in the mean duration of low flow events with differences in magnitude due to catchments, objective

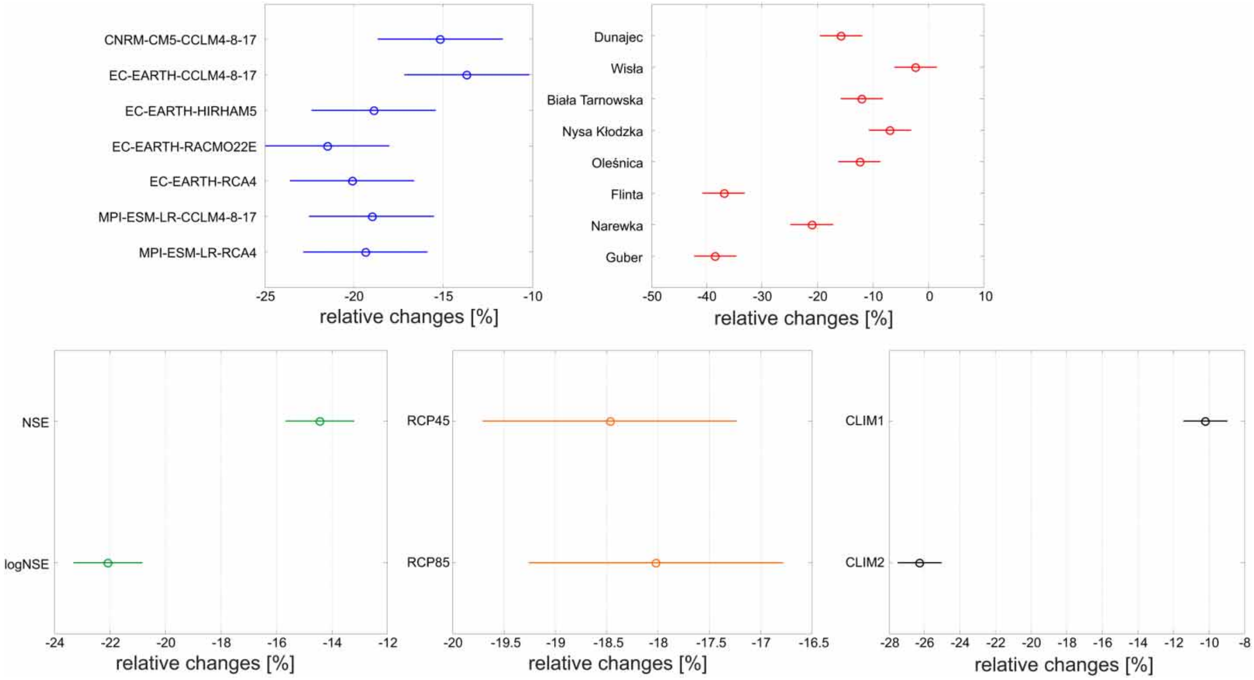

Figure 10 | Distribution of relative changes in the number of low flow events as a function of climate model, catchment, objective function, emission scenario and future period based on five-way ANOVA and Tukey post-hoc test. Circles represent the PMM and the bars are the relevant spread.

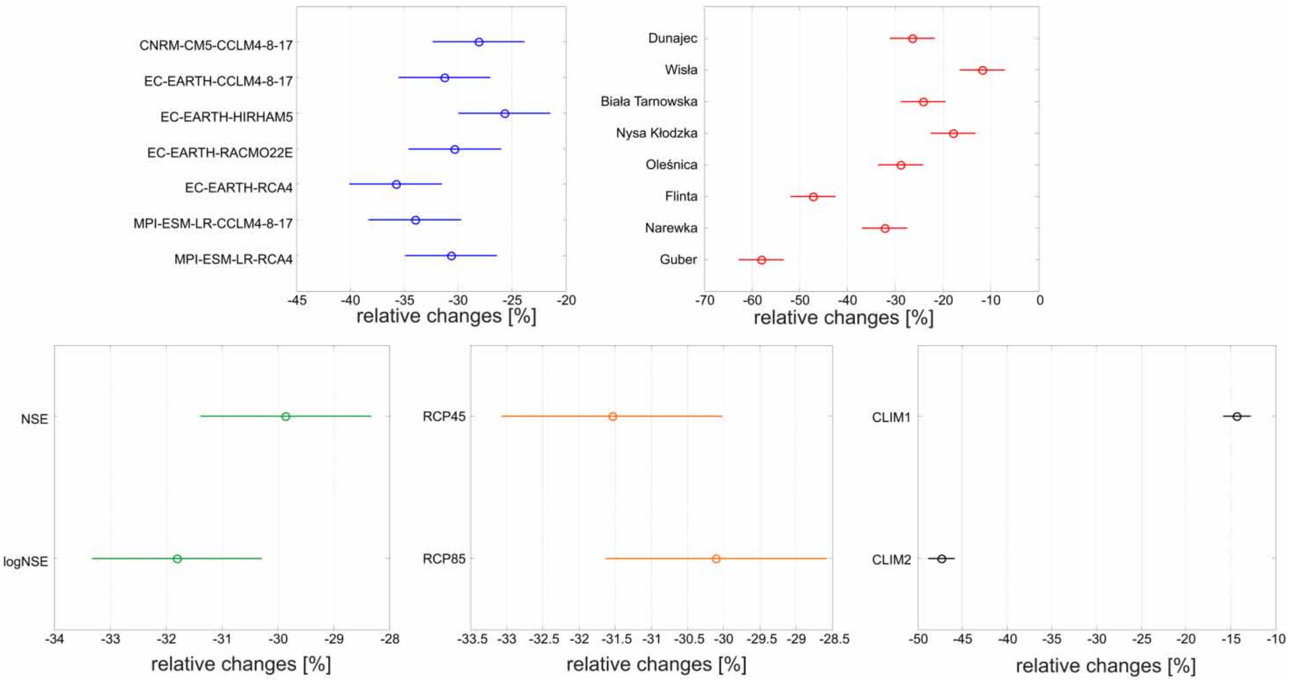

Figure 11 | Distribution of relative changes in the number of days under threshold (Q80) as a function of climate model, catchment, objective function, emission scenario and future period based on five-way ANOVA and Tukey post-hoc test. Circles represent the PMM and the bars are the relevant spread.

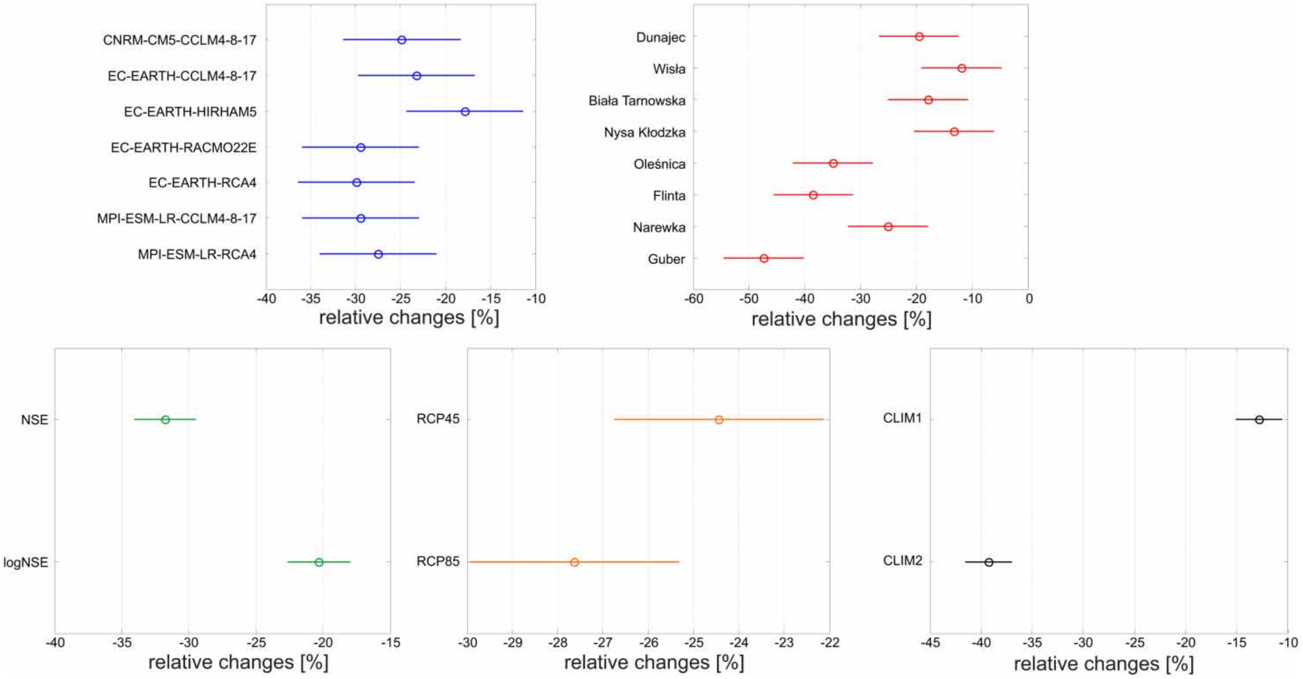

Figure 12 | Distribution of relative changes in the mean duration of low flow events as a function of climate model, catchment, objective function, emission scenario and future period based on five-way ANOVA and Tukey test. Circles represent the PMM and the bars are the relevant spread.

functions and periods. Variability of the results due to climate models and emission scenarios is small and statistically insignificant. Taking into account differences between catchments, larger decreases in mean duration of low flow events are projected for lowland than mountainous catchments. A comparison of the results between objective functions indicated that application of logNSE (−20%) leads to smaller changes than NSE (−32%).

Changes in volume deficit

In a similar way, changes in volume deficit were estimated (Figure 13). The decreases in volume deficit were projected for all cases with differences in the magnitude of changes due to the variability between climate models, catchments and periods. The choice of objective function and emission scenario does not lead to statistically significant differences in the results. A comparison of the outcomes between catchments indicated that the largest changes are projected for the Guber catchment (−63%). The changes for other catchments are smaller and vary from −16% for Wisła to −42% for Flinta. The estimated mean changes for far future (2071–2100, −54%) are larger than for near future (2021–2050, −16%).

DISCUSSION AND CONCLUSIONS

In this paper, analyses of impact of climate change on changes of five low flow indices in eight Polish catchments were carried out. Together with the estimated changes the spread in the obtained results was also quantified using the N-way ANOVA and the Tukey post-hoc test. The contributions of the emission scenarios, climate models, catchments, two future periods and two objective functions were assessed. A summary of the obtained results is presented in Table 3. The results indicate possible future increases in AM7 and decreases in the number of events, number of days under threshold, duration and volume deficit for all tested cases. Despite the same tendency of the changes, differences in magnitude were found. Differences due to catchment geography were found for all tested indices. In general, larger changes were estimated for lowland than for mountainous catchments. These results confirm

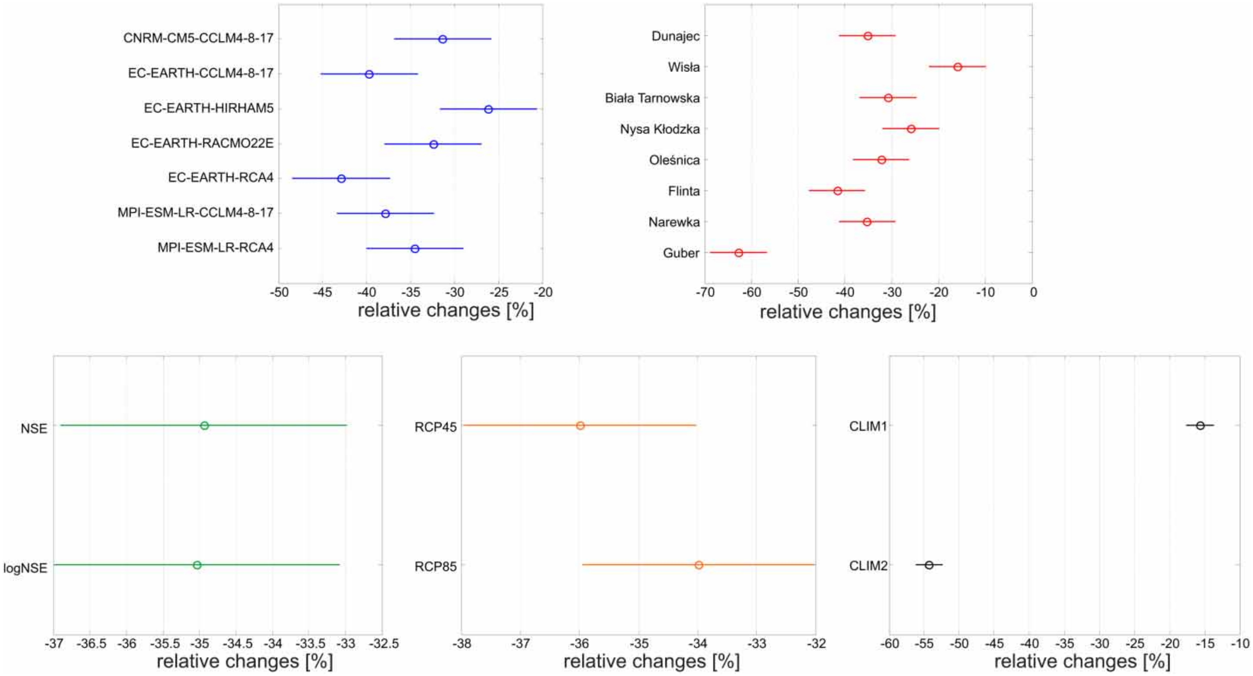

Figure 13 | Distribution of relative changes in the volume deficit of low flow events as a function of climate model, catchment, objective function, emission scenario and future period based on five-way ANOVA and Tukey test. Circles represent the PMM and the bars are the relevant spread.

Table 3 | Summary of projected changes of low flow indices

	Annual minimum 7-day average flows	Number of low flow events	Number of days below threshold Q80	Mean low flow duration	Volume deficit
Tendency of changes	Increase	Decrease	Decrease	Decrease	Decrease
Statistically significant differences in the estimated changes between:					
Climate models	No	Yes	Yes	No	Yes
Catchments	Yes	Yes	Yes	Yes	Yes
Objective function	Yes	Yes	No	Yes	No
Emission scenarios	Yes	No	No	No	No
Two future periods	Yes	Yes	Yes	Yes	Yes

findings presented in Osuch *et al.* (2016b) and Meresa *et al.* (2016). An influence of climate models on the variability in the estimated changes of low flow indices is significant for the number of low flow events, number of days under threshold Q80 and volume deficit while is not important for AM7 and mean duration of low flow events. A comparison of biases estimated in low flow indices between seven combinations of climate models indicated that in almost all cases the worst results (largest biases) were obtained for CNRM-CM5-CCLM4-8-17. These results correspond well with the findings of Kotlarski *et al.* (2014) and Stagge *et al.* (2015). Kotlarski *et al.* (2014) noted that CNRM showed different behaviour than the other GCMs in the CORDEX database regarding precipitation during validation; their simulations were classified as the most dry from the tested model range. Stagge *et al.* (2015) found that the CNRM runs had the greatest increase in wetness and MPI runs had driest future change. Our results confirm these findings; however, differences in changes of low flow indices due to climate models are relatively small as a result of bias correction of climate simulations.

The choice of emission scenario results in statistically different results only for AM7. The outcomes for the other four indices do not have different estimates of changes for RCP 4.5 and RCP 8.5.

The results differ significantly due to the selected period. For all indices the differences between the results for 2021–2050 and 2071–2100 are statistically different. Projections indicate larger changes (increase or decreases) for the far future than for the near future.

An analysis of the influence of choice of the objective function (NSE or logNSE) indicated that the biases in the results calculated for the reference period are smaller for logNSE in almost all indices, except the mean duration of low flow events.

Objective function also influences the estimated changes of low flow indices. The differences in results for both objective functions led to statistically different results for AM7, the number of low flow events and duration of low flow events. Larger changes of low flow indices were estimated for NSE (AM7 and mean duration of low flow events), logNSE (number of days under threshold, number of low flow events and volume deficit).

Even though the indices derived are inter-related each one provides different information on the projected future droughts. In summary, this study suggests that the catchments become wetter, but with a varying speed. The projected changes in the far future are larger than in the near future, but the relative changes of indices between the different emission scenarios are statistically significant only for the AM7.

Our results were compared with other studies at the European scale. It is important to mention that Poland is characterized by a unique climatological location near the fulcrum point between a projected wetter northern Europe and a drier southern Europe (Orlowsky & Seneviratne 2013; Spinoni *et al.* 2015). As a result there are significant differences between our results and the results of the other studies.

Arnell (1999) presented percentage change in drought deficit volumes for Europe. The results for Poland varied a great deal (from −50% to 50%) depending on the location in Poland and the climate model that was used for simulations of future conditions.

Lehner *et al.* (2006) found that changes in recurrence of 100-year droughts based on simulations of global hydrological model (WaterGAP) using two climate models for Poland strongly depended on the climate model and the location in Poland. In the case of southern and central Poland, both models projected strong increases in 100-year droughts. The outcomes of HadCM3 models for northern Poland showed decreases of 100-year droughts while simulations of ECHAM4 indicated strong increases of drought. Our results contradict these findings as decreases of number of drought events, mean drought duration and volume deficit were estimated for all test catchments. Different scenarios of greenhouse emission, different driving climate models, bias correction methods, different types of hydrological models and different calibration criteria make the direct quantitative comparison between different studies virtually impossible.

Feyen & Dankers (2009) analysed low flow characteristics from simulated streamflow series and assessed changes in the magnitude and intensity of streamflow droughts. The outcomes for Poland indicated lack of changes in estimated minimum flows and varying tendency of changes depending on location in Poland.

Projected increases of drought frequency and severity for Central Europe were presented by Prudhomme *et al.* (2014). In that case, results of all climate models and global hydrological models were consistent with directions of changes but with different intensity of increases. In our case, consistency in the results between climate models was also found, but the tendency of changes was different.

Forzieri *et al.* (2014) produced similar results to ours despite large differences in the assessment procedure. The outcomes for the 2080s indicated increases of minimum streamflows and decreases in streamflow deficit. The results from different climate models were rather consistent but estimated changes were statistically insignificant probably due to weaker signal to noise ratio.

These contradictory outcomes for Poland from Arnell (1999), Lehner *et al.* (2006), Feyen & Dankers (2009), Prudhomme *et al.* (2014) were a result of applying different hydrological models, climate models and emission scenarios, low flow indices and the spatial scale. These studies (Arnell 1999; Lehner *et al.* 2006; Feyen & Dankers 2009; Stahl *et al.* 2012; Prudhomme *et al.* 2014) have used large-scale hydrological models and have applied these to the whole of Europe, basing calibration on data from large rivers without taking into account changes in land use or water management. In our approach, the analyses are carried out for eight medium-sized catchments (with areas of up to 2,000 km^2), and these catchments have been specifically selected to avoid problems associated with land use or water management changes and river regulation during the calibration period. In addition, in our case, the hydrological model is catchment-based and it has been calibrated and validated for each individual catchment in order to ensure a good performance in the simulation of streamflows. There are many aspects of the research that should be discussed before robust conclusions from this study are drawn. In particular, the limitation of bias correction methods should be mentioned. Low flow indices such as number of low flow events, mean low flow duration and volume deficit might be influenced by the temporal correlation of precipitation from the RCMs. The bias correction methods applied do not correct the temporal sequence of dry day, wet day (compared to the observations) and the biases inherited from the RCMs can be 'passed on' to the hydrological model projections. It is possible that ANOVA analyses attributed those temporal biases to the climate models.

Another issue is the influence of hydrological model uncertainty, which was not taken into account. To some extent, the hydrological model reliability was illustrated by differences between the simulated and observed indices in the reference period. One has to be cautious when interpreting the results for near and far future periods when the reference period does not 'reflect' the present day climate well enough.

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