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CLIMATE CHANGE IMPACT STUDY ON 100-YEAR FLOODS OF SELECTED SLOVAK CATCHMENTS

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During the ongoing climate change, this work provides an analysis of the modelled expected change in floods (100-year) for 11 Slovak river basins. It also analyses the possibilities of using data from the latest climate projections of global and regional models from the EURO-CORDEX initiative, as well as outputs from two hydrological models from the SWICCA database (Service for Water Indicators in Climate Change Adaptation) within the Copernicus service, for regional conditions in Slovakia. To estimate the 100-year flood, a frequency analysis was applied to each member of the climate and hydrological model output ensemble. The statistical distribution of generalized extreme values (GEV) was used. In case the data showed a significant trend, the non-stationarity of the environment was also taken into account. The bias of hydrological models outputs were corrected by the variance scaling method. The results indicate an increase in Q_{100} for seven gauges, a decrease for three gauges and for one station no change in Q_{100} (change more than ± 5%). Based on the results, we recommend applying hydrological data from the SWICCA database, preferably for large to medium-sized river basins.

KEY WORDS: Copernicus, climate change, hydrological models, 100-year flood

Introduction

In-depth studies of historical climate change confirm that the climate is changing over the last decades to centuries, mainly due to the growing anthropogenic impact. Several studies show that we are already feeling the impact of this change in various areas of life (Huntington, 2006; IPCC, 2014; Duethmann et al., 2020). Impact of climate change is already partially measurable and identifiable on: average annual flows (Nijssen et al., 2001; Krajewski et al., 2019), increase of peak flows and shift of their occurrence (Hirabayashi et al., 2013; Blöschl et al. 2017; Blöschl et al., 2019), changes in long-term flow duration curves (Arora and Boer, 2001), changes in the length of the period with low flows (Stahl et al., 2010; Fendeková et al., 2017) and changes in the elements of the hydrological balance (Pekárová et al., 2018).

It is not easy to estimate the impact of climate change in water management as well as in other fields of study. Climate change is manifested differently in different geographical areas. The great variability of natural processes, not to mention anthropogenic influences, are a natural part of the climate.

The expected climate change brings with it a number of scientific issues and uncertainties that are the subject of studies and discussions. Analysed are mainly: the increase in the extremity of hydrological phenomena (increase in extreme values, but also the frequency of their occurrence) in form of droughts or floods, but also a change in the hydrological regime of watercourses themselves and the impact of these phenomena on society as a whole. The modification of the period with the highest or the lowest expected water bearing of streams in a year, their frequency, but also the values of absolute maximum and minimum discharges, the time shift of snow accumulation and snow melting and the total water balance in river basins are not entirely clear.

Floods occur regularly in Europe. Their incidence is well documented in a recent study by Blöschl et al. (2020) focusing on several flood-rich periods over the last 500 years. Reliable information on the potential change of future hydrological conditions in the field of water management is the basis for long-term strategies and adaptation plans. Solving these tasks is even more urgent given the fact that most Slovak streams originate in Slovakia.

A hundred year flood is an important design variable needed for the planning and operation of water management structures. Generaly, it is determined from a series of measured peak annual flows (or flows exceeding a selected threshold value) by the method of frequency analysis, applying the most suitable theoretical exceedance curve (in Slovakia according to the norm OTN ŽP 3112-1: 03). The measured data can also be supplemented by historical data, which complements and extends the sample of observations with rare data having a long return period (as extreme floods in the past) (Pekárová et al., 2018). The second way one could determine the direction of change in flows is to analyse the trend from measured time series, especially in recent decades, as shown in Bertola et al. (2020). Although such analyses are necessary and important, their disadvantage may be the absence of sufficiently long series of observed data needed for analyses of flood flows with long return periods. Also, from these analyses it is not possible to predict the development of the climate in the future, which seems to be greatly influenced by the development of anthropogenic activity.

An interesting way to quantify the expected impact of climate change on flood flows, but also on the changing hydrological regime of river basins is a method based on analysis of climate change predictions in form of the latest outputs from climate models, climate projections (so-called impact studies) (Hakala et al., 2019). This approach, in contrast to the analysis of long-term historical data and assumption that conditions remain unchanged, makes it possible to obtain the latest forecasted time series of climate characteristics from the future for a sufficiently long period of approximately 90–100 years and apply the frequency analysis on a relatively large and thus more reliable sample of data.

The Copernicus Climate Change Service (C3S) is one of the 6 products of the Copernicus Earth Observation Programme. Copernicus is an EU operational program based on the existing European scientific infrastructure and available European scientific knowledge. The C3S project is, besides its own research, also based on the climate research addressed within the World Climate Research Program (WCRP). C3S provides information on the historical, current and projected future climate of Europe and the world (https://climate.copernicus.eu/, available on 18.02.2020) such as climate observation data, climate reanalysis, seasonal forecasts and future climate projections. By offering consistent information on climate change, the service was set up to support the elaboration of adaptation plans and climate change mitigation policies for the EU. C3S provides specific information for different fields. The water management was served by the SWICCA portal (Service for Water Indicators in Climate Change Adaptation) (http://swicca.climate.copernicus.eu/, available on 15.5.2019) operated by the Swedish Meteorological and Hydrological Institute (SMHI).

In this work, data from the SWICCA database were used to estimate the change in Q_{100}, namely climate data from five global circulation models (GCM), four regional climate models (RCM), three climate scenarios (RCP 2.6; 4.5; 8, 5) and two hydrological models E-HYPE and LISFLOOD.

The aim of this work was to answer the following questions: 1/ whether it is possible to expect a change in 100-year floods on selected Slovak streams due to expected climate change and with what degree of uncertainty, 2/ whether it is possible to find some regional similarities in identified changes, 3/ whether significant growth trends of peak flows will be identified and on which rivers? The methodology of estimating Q_{100} based on the outputs of climate models from the SWICCA database was used for the first time in Slovakia in the project C3S_441_ Lot1_SMHI contract (SWICCA project) (http://swicca. eu/about/, available on 18.12.2018). The first results of the local case study "Flood warnings in a changing climate", which was addressed in the period 2015 to 2017 within the SWICCA project in cooperation between MicroStep-MIS and the Slovak Hydrometeorological Institute, were published in Gaál (2018) and Gaál et al. (2017) for the Bratislava (Danube) water gauging station. Therefore, our next goal was to test the database and methodology for several river basins in Slovakia. In no case does this work provide data on the official change of existing design variables. However, it may point to indications of an expected change that need to be further examined.

Material and methods

The SWICCA portal and database

The first version of the SWICCA portal was created under contract C3S_441_Lot1_SMHI of the C3S service, operated by the ECMWF on behalf of the European Commission. In the period 2015–2018, the portal was operated with the help of SMHI together with ten other partners from all over Europe.

The aim of the SWICCA portal is to provide users with the necessary data to assess climate change and its impact in various areas of water management (for case studies) across Europe in order to subsequently quantify the impact of projected climate change in the field of water resources.

The interconnection of information between experts from different fields (climatologists, water managers, hydrologists, numerical mathematicians), but also competent decision-makers should serve this goal. Case studies serve as basis for the design of adaptation plans, which is also one of the main goals of SWICCA. SWICCA data is currently available through the Climate Data Store (https://cds. climate.copernicus.eu/cdsapp#!/dataset/sis-water-quantity-swicca?tab=overview, available 20.02. 2020) within the portal Copernicus Climate Change Service one can find various simulated impact indicators, e.g. data on water quantity and quality, air temperature, precipitation, cloud cover, air humidity and many others, on which it is possible to analyse the impact of climate change in terms of trends and variability of a particular indicator.

For the purpose of this impact study, two types of time series of average daily flows were downloaded from the SWICCA portal (as of 01.02.2019) as outputs of eleven mutual combinations of five global circulation models (GCM), four regional climate models (RCM), three climate scenarios (RCP) and two hydrological models: 1 / hydrological model E-HYPE and 2 / hydrological model LISFLOOD (Table 1). Table 1 lists the names of GCM and RCM, along with the name of the institute that develops these models.

Representative concentration pathway RCP (Emission scenarios)

Different climate datasets are based on different climate

Table 1. Summary of climate model runs used in SWICCA database. RCP–indicates the representative concentration pathway and its development direction, GCM–global circulation model, RCM–regional circulation model. *missing data in years 2095–2100. The period 1.1.1971–31.12.2000 was taken as the reference period and 1.1.2011–31.12.2100 was considered as future

No.	RCP	GCM	RCM	Time period	Institute
1	2.6	EC-EARTH	RCA4	1970–2100	SMHI
2		MPI-ESM-LR	REMO2009	1970–2100	CSC
3	4.5	EC-EARTH	RCA4	1970–2100	SMHI
4		EC-EARTH	RACMO22E	1970–2100	KNMI
5		HadGEM2-ES	RCA4	1970–2098	SMHI
6		MPI-ESM-LR	REMO2009	1970–2100	CSC
7*		CM5A	WRF33	1970–2100*	IPSL
8	8.5	EC-EARTH	RCA4	1970–2100	SMHI
9		EC-EARTH	RACMO22E	1970–2100	KNMI
10		HadGEM2-ES	RCA4	1970–2098	SMHI
11		MPI-ESM-LR	REMO2009	1970–2100	CSC

models, as well as three different emission scenarios, which represent the scenarios of climate development. The Intergovernmental Panel on Climate Change (IPCC) lists them in a recent report in the form of representative concentration pathways (RCPs) (van Vuuren et al., 2012). SWICCA works with three basic scenarios, defining them as follows: 1/ RCP2.6 assumes that CO_2 emissions will be constant at the beginning of the century, then start to decrease and reach negative values at the end of the century, 2/ RCP4.5 assumes that CO_2 emissions will increase by the middle of the century and then begin to decline, 3/ RCP8.5 assumes that CO_2 emissions will triple by the end of the century and methane emissions as well as the use of energy and fossil fuels will also increase. The most pessimistic scenario further assumes that understanding the concept of renewables will be very limited and the implementation of the climate strategy will be missing. More information on emission scenarios can be found at: http://swicca.climate.copernicus.eu/wp-content/uploads/2016/02/How-to-use-different-RCPs.pdf (available 5.2.2019).

Estimation of the 100-year flood

The following procedure was chosen for estimating Q_{100}: 1/ download time series of average daily flows from all available climatic outputs and from two hydrological models HYPE and LISFLOOD from the SWICCA portal for selected gauges in Slovakia, 2/ data check and bias-correction for the reference period 1971–2000, 3/ selection of annual maxima, 4/ conversion of annual maxima of average daily flows into annual peak flows according to the methodology of Hlaváčiková et al. (2019), 5/ trend analysis by non-parametric Mann-Kendall test, 6/ frequency analysis (stationary or non-stationary).

Due to the low quality of raw data for the stations Banská Bystrica (Hron), Liptovský Mikuláš (Váh), Janík (Bodva) and Spišské Vlachy (Hornád) found by data check at the reference period, flow outputs from the SWICCA database (from hydrological models Lisflood and HYPE) were not used in this case. Instead the following procedure was adopted: 1/ download of time series of precipitation and temperatures from all available climatic outputs from the SWICCA portal, 2/ calibration of hydrological model HBV for daily step, 3/ model run for different sets of input data from climate models. The next procedure was the same as in the previous one starting at point 2.

Hydrological models used for climate change impact modelling

All hydrological models, the outputs of which were used in this work, are conceptual rainfall-runoff models. The HYPE model (**E-HYPE** v. 3.1.2) is a semi-distributed successfully used model in the short-term and seasonal forecasting, as well as in the hydrological warning operational service at the SMHI. The model was calibrated and validated in a daily step for more than 35,000 sub-basins in Europe with an average river basin size of 215 km^2. For these sub-basins, it has also been assessed for its suitability for application to climate change (Hundecha et al., 2016).

The **LISFLOOD** hydrological model was developed as part of the Natural Hazard Project by the Joint Research Centre (JRC) of the European Commission. LISFLOOD is used for daily forecasts within the EFAS and GLOFAS operational alert systems. More information about the model can be found in the report by Burek et al. (2013).

The application of both models for climate change analyses has also been tested on 46 major European river basins (Greuell et al., 2015). Further details on the hydrological models used in the climate change impact studies and the data obtained from these models are given in Hundecha et al. (2016) (E-HYPE model v.3.1.2) and Greuell et al. (2015), Roudier et al. (2016) and Burek et al. (2013) (LISFLOOD model). The spatial resolution of hydrological models for the SWICCA database is as follows: 0.5 degrees x 0.5 degrees (approx. 50 x 50 km) in the LISFLOOD model, irregular polygons of river basins with a median area of 215 km^2 in the E-HYPE model.

The **HBV** model (IHMS 6.4) is used daily for approximately 60 Slovak river basins in the Department of Hydrological Forecasts and Warnings of the SHMU (Slovak Hydrometeorological Institute). It is also commonly used worldwide in a modified form such as HBV-Light. The model was calibrated in a daily time step for four Slovak river basins, for which it was used to estimate the impact of climate change.

Regional climate models outputs correction

The outputs from the GCM have a coarse resolution. Therefore, a first step of adjusting the climate data is rescaling GCM outputs into a resolution usable by RCM. The next step is to eliminate RCMs structural defects (bias correction) that needs to be applied before using the data in impact studies (Wilcke et al., 2013). The climatic data from the SWICCA database used in this work (outputs from RCM in the spatial resolution of 12 x 12 km obtained within the EURO-CORDEX initiative) were corrected by the "quantile-mapping" method (Wilcke et al., 2013).

Bias correction of hydrological data

Hydrological simulations of future will mostly improve if their inputs are bias corrected (Hakala et al., 2019). The parameters of the hydrological models, which were calibrated on the current climate conditions, are then used for simulations of the period of the assumed changed climate with the bias corrected forecasted meteorological data. Despite great efforts to adjust the outputs of RCM models by bias correction and downscaling, several meteorological variables from RCM models are still not suitable for their use in hydrological impact studies (Teutschbein and Seibert, 2012; Dakhlaoui et al., 2019; Gao et al., 2020). This can be resolved using e.g. a multi-ensemble approach, which uses an ensemble of climatic outputs from RCM models (precipitation and temperatures), downscaled so that when used in the hydrological model they correspond to the measured hydrological data as much as possible (usually comparing average monthly flows or peak flow exceedance curves according to the type of analysis) (Teutschbein and Seibert, 2010; Hakala et al., 2019; Gao et al., 2020). Another solution is to use an ensemble of climate and hydrological models (Donnelly et al., 2017; Hakala et al., 2019) without further correction of previously corrected climate data (IMPACT2C, 2015). Some authors also performed the bias correction directly on hydrological data (González-Zeas et al., 2012; Gaál et al., 2017). The reason may be that homogeneous data of historical meteorological characteristics (precipitation and temperature) and measured flows necessary for the calibration of the own hydrological model are not available, or a suitable hydrological model is missing.

The bias correction was performed in this work directly on hydrological data, because the statistical characteristics of hydrological simulations from the SWICCA database sometimes showed a greater or lesser deviation compared to the characteristics of the measured average daily flows.

Because of a high number of analysed data (in the first phase, 572 time series for 26 stations were processed, all listed in Hlaváčiková et al., 2019) it was decided to apply a uniform method of bias correction on hydrological data called the variance scaling method (according to Teutschbein, 2013). The analysis was performed on a control period 1971–2000 for which both outputs from the SWICCA database and observations were available. Four basic criteria were applied to compare the characteristics of hydrological model outputs with measured data: 1/ coefficients Nash-Sutcliffe (NSE) (Nash-Sutcliffe, 1970) and Kling-Gupta (KGE) (Gupta et al., 2009), 2/ visual assessment of box plots with emphasis on capturing extremes, 3/ Mann-Whitney test to assess whether data from models come from the same population as observations, and 4/ visual comparison of time series in the daily time step, monthly averages, and annual maxima. Based on the above criteria, better results (fits) were obtained by data corrected by the above-mentioned variance scaling method than by the linear scaling or raw data.

In this way, the selection of stations for further analysis was also considerably narrowed down. Seven stations were selected for further analysis: Bratislava, Moravský Svätý Ján, Ipeľský Sokolec, Chmeľnica, Vlkyňa, Streda nad Bodrogom and Veľké Kapušany.

However, the intention was to analyse the impact of climate change on the whole territory of the Slovak Republic and the current selection of stations did not cover all large Slovak river basins. Thus, it was decided to supplement the missing river basins with simulations from the HBV model which is used in SHMU operationally in an hourly time step. The model had to be recalibrated to a daily step and then mathematical simulation with inputs from the SWICCA database (daily precipitation and temperature) had to be run. For completion, following stations were tested: Kysucké Nové Mesto, Liptovský Mikuláš, Chalmová, Banská Bystrica, Spišské Vlachy and Janík. All gauges were assessed during the overlapping control period. Four stations met the criteria of good fit: Banská Bystrica, Liptovský Mikuláš, Janík and Spišské Vlachy. Demonstration of raw (unadjusted) data and corrected average daily flows by linear scaling and variance scaling for Moravský Sv. Ján is in Figure 1.

Frequency analysis

The 100-year flood is generally estimated by the method of frequency analysis. It is a statistical method of estimating the frequency of occurrence of rare events

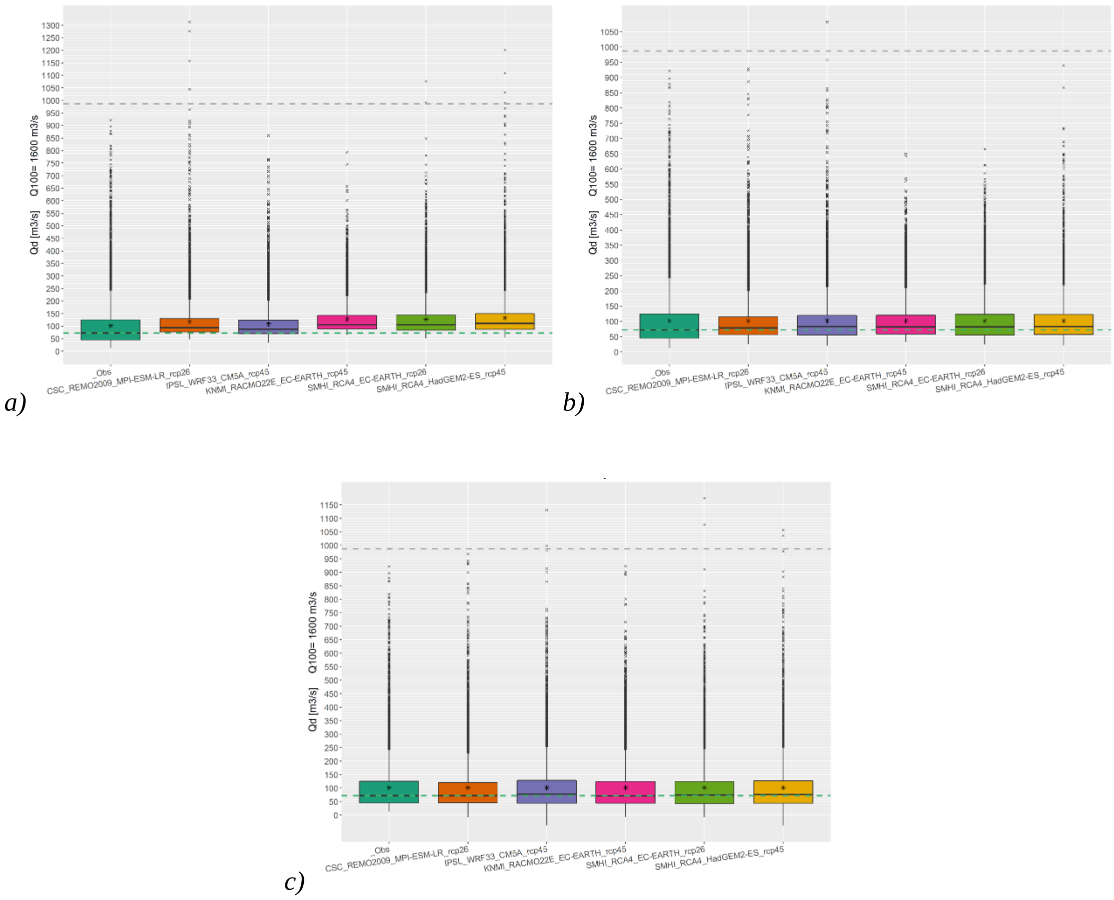

Fig. 1. Boxplots of average daily flows at Moravský Sv. Ján a) uncorrected (raw) data, b) bias correction by linear scaling , c) bias correction by variance scaling. The first box from the left shows the observed flows, other boxes indicate the outputs from climate models for the hydrological model LISFLOOD. The upper dashed line marks the value of the currently valid Q_{100}, the lower one indicates the value of median from observations.

using probability distributions. First of all, for the application of frequency analysis it is necessary to verify whether its assumptions apply: randomness of occurrence, homogeneity and independence of the analysed data. Subsequently, it is necessary to select the distribution function, determine its parameters, and evaluate the goodness of the fit. According to Gilleland and Katz (2016), the distribution of generalized extreme values (GEV) has a theoretical basis for application to the data of block maxima characterizing floods. GEV is a family of continuous 3-parametric probability distributions, which can be divided into three types of distributions according to the shape parameter ξ: Gumbel, Weibull and Fréchet (Pareto). The GEV function is a function that generalizes all three of the above distributions and can therefore be used for the first estimate. Based on its diagnostics, it is also possible to select the most appropriate function, and thus cover the data with a more accurate distribution. Such an approach is recommended especially when estimating long return periods, as this greatly reduces the variance of their confidence interval.

Non-stationarity of future time series

In analyses of the future, it is necessary to take into account the non-stationarity of the environment and to consider the possibility that probabilities of the occurrence of extreme phenomena in hydrology will shift (Milly et al., 2008). The change in extreme events over time can be characterized by expressing one or more parameters of the distribution function as time-dependent. In order to take into account the non-stationarity in the frequency analysis of the maximum annual flows, it is first necessary to determine the trajectory and the significance of the change in the time series. Subsequently, it is decided whether and to which parameter of the distribution function, the non-stationarity will be taken into account. The choice of model should be as simple as possible and at the same time it should be able to take into account variations of the dataset as much as possible. The model of non-stationarity is applied to describe the process of data creation, not the data itself, so if the trend is not particularly significant, a simpler model should be chosen (Coles, 2001).

Trend analysis

For annual maxima series, a linear trend is being used most frequently in the literature. In this analysis, a non-parametric Mann-Kendall test was applied for identification of a significant trend.

Expression of climate change impact for the estimation of Q_{100}

The climate change impact for Q_{100} (CCQ_{100}) was expressed as the percentage change in Q_{100} in the future compared to the present as follows:

$$CCQ_{100}=100*(Q_{100,fut}-Q_{100})/Q_{100} \quad [\%] \qquad (1)$$

where
$Q_{100,fut}$ – is the estimated 100-year flood for the period 2011–2100;
Q_{100} – is the current 100-year flood at the relevant water gauging station.

The final average values of future Q_{100} were obtained from the whole ensemble of climatic and hydrological models available for a given station (i.e. for 11 outputs from climate models and 2 outputs from two hydrological models, i.e. 22 members of the ensemble). Uncertainties in estimating the change in Q_{100} were quantified from the interquartile range of average climatic impact factors of the entire CCQ_{100} ensemble for a particular station. This method expresses uncertainty by giving the range where 50% of the average CCQ_{100} values for a given station were estimated.

Uncertainties in estimation of Q_{100}

Several uncertainties need to be considered in climate change impact studies. These uncertainties cover all aspects of the lack of knowledge of the future climate (IMPACT2C, 2014). The main sources of uncertainty can be divided into several groups, namely the uncertainties associated with:
1 – selection of used climate models (global or regional) and their parameterization and conceptualization (i.e. by way of mathematical description of physical processes in the atmosphere),
2 – selection of climate scenario, but also with the way these scenarios are determined (scenario uncertainty),
3 – by climate model outputs correction using downscaling techniques and bias correction.

In the case of impact studies in the field of water management, it is necessary to take into account the uncertainties arising from the selection of hydrological models and, similarly to climate models, their parameterization and conceptualization.
Models always represent a simplified version of natural processes. All climatic models are based on more or less the same physical principles, but differ in their mathematical expression. Model uncertainties arise from incomplete knowledge of the climate system and from the unlikelihood to include all processes and characteristics of the climate system in models. The same applies to hydrological models, reflecting hydrological processes in river basins. To reduce the degree of uncertainty, climatologists use multi-model ensemble simulations. Different combinations of GCM and RCM are used in regional climate projections resulting in a multi-global/regional-model-ensemble dataset. An example for Europe is the results of the EURO-CORDEX project. Ensemble experiments are a common method of assessing the uncertainties arising from climate change projections (Knutti and Sedlacek, 2013).
We have tried to eliminate uncertainties related to the choice of hydrological models in several ways: First of all, we have tried to use hydrological models that have been and are tested on many river basins in Europe and provide good results. The second method of eliminating the uncertainties was a comparison of statistical characteristics of time series from HYPE and LISFLOOD models for selected Slovak water gauging stations with characteristics from measured time series on an overlapping reference period of 30 years and bias correction of model outputs by variance scaling method. If the results were not satisfactory even after the application of the bias correction, we excluded the models and stations from further analysis, or replaced them with the results from the calibrated HBV model, if these were satisfactory for the reference period.
Other uncertainties may be related to the appropriate choice of the distribution function for the frequency analysis and to the uncertainties of the estimation of the peak flows from the average daily flows (Hlaváčiková et al., 2019).

Results and discussion

The final selection of river basins with the results of the climate change impact on Q_{100}, expressed by the climate change impact CCQ_{100}, which is the percentage change of Q_{100} in the future compared to the present, is shown in Fig. 2 and in Table 2. The results show an increase in Q_{100} for seven stations: Bratislava (Danube), Moravský Sv. Ján (Morava), Liptovský Mikuláš (Váh), Vlkyňa (Slaná), Ipeľský Sokolec (Ipeľ), Streda n. Bodrogom (Bodrog) and Veľké Kapušany (Latorica), in the range of values 5.48–34.12%. A decrease in Q_{100} is indicated for stations Chmeľnica (Poprad), Banská Bystrica (Hron) and Janík (Ida, Bodva river basin) in the range of -17.99 to -47.03%. No significant change in Q_{100} (change of more than ±5%) was found for the Spišské Vlachy (Hornád) station. The most significant increase is indicated for the Liptovský Mikuláš station, where the average impact of climate change CCQ_{100} is +34%, half of the values are in the range of 17–53% (Fig. 3). On the contrary, the most significant decrease is expected in the Bodva river basin (Janík–Ida station), where the impact of climate change CCQ_{100} ranged from -67 to -23% with an average value of -47%.
Uncertainties in estimating the change in Q_{100} can be seen from the interquartile range of average climate change

impact factors of the entire CCQ_{100} ensemble for a particular station (Fig. 3). Fig. 3 shows a relatively wide interquartile range of CCQ_{100} for the stations Veľké Kapušany, Ipeľský Sokolec and Chmeľnica, which indicates a greater uncertainty in the estimation of the future Q_{100}. Based on the CCQ_{100} interquartile range (range of values from the 25th to the 75th percentile), it is possible to divide stations into three categories: stations with the least estimation uncertainty in the range of 18–25% (Bratislava, Moravský Sv. Ján, Banská Bystrica, Vlkyňa, Janík), stations with a medium estimation uncertainty in the range of 34–39% (Streda n. Bodrogom, Liptovský Mikuláš, Spišské Vlachy) and stations with the highest estimation uncertainty in the range of 59–91% (Chmeľnica, Ipeľský Sokolec, Veľké Kapušany).

Table 3 shows the number of increases or decreases of CCQ_{100} for individual hydrological models as well as for the whole ensemble. Balanced results for Bratislava and Moravský Sv. Ján are indicated by the similar number of increases, decreases or no change for both hydrological models. Conversely, for Ipeľský Sokolec, Chmeľnica and Veľké Kapušany, one model indicates more increases, while the other indicates more decreases in CCQ_{100}.

Peak flows and their development over time represent important information for changes in high flows. Based on trends, possible future changes in Q_{100} can be expected. It was possible to identify several significant trends in future peak flows from model analyses. An upward trend was identified for one model at Bratislava station, and 3 (4) models at Moravský Sv. Ján and Ipeľský Sokolec, whereby the climate model from the IPSL institute indicated an increase for both hydrological models. No significant trends were identified for the Vlkyňa and Liptovský Mikuláš stations. One or two upward trends were identified at other stations. For Janík and Banská Bystrica stations, upward trends were identified despite the fact that the estimate of the future Q_{100} was lower than the current value. These model outputs suggest that although the peak flows at these stations should be lower in the future, it is possible to expect their increasing trend. Only four downward trends were identified among the ensembles (at the stations Moravský Sv. Ján, Ipeľský Sokolec, Streda n. Bodrogom and Spišské Vlachy). Although several significant trends have been identified, their number within the whole ensemble for a particular station is still relatively small.

More detailed results of climate change impact hydrological modeling for the Banská Bystrica station can be found in the literature Kopáčiková et al. (2019).

With increasing global atmospheric temperature, intense precipitation is expected to strengthen due to the greater capacity of the warmer atmosphere to absorb water vapor. This fact is a common argument used for the automatic assumption that the incidence of floods and high flows will globally increase. Recent European studies suggest that the occurrence of floods and changes in their periodicity and magnitude depend primarily on the geo-

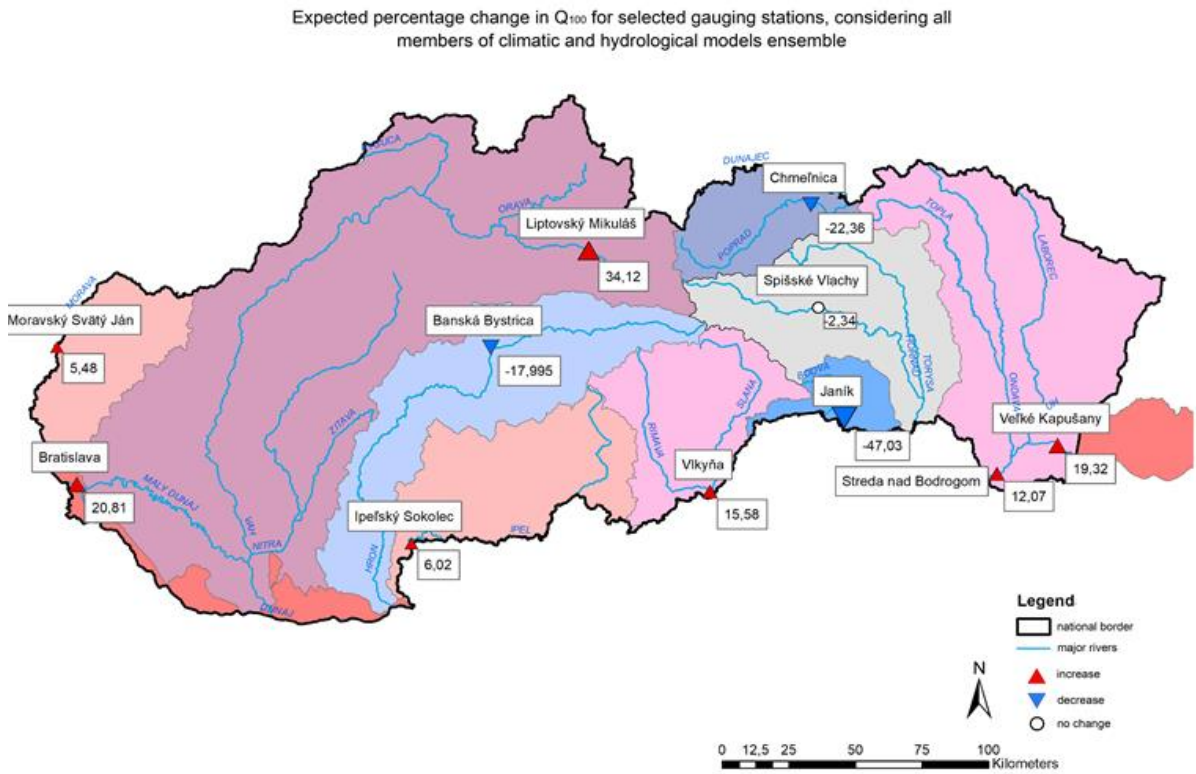

Fig. 2. Location of gauging stations within the territory of Slovakia along with the expected change in Q_{100} expressed by the impact of climate change for Q_{100} (CCQ_{100}) in percent.

Table 2. **Data on gauging stations, current and estimated Q_{100} along with the change in Q_{100} expressed by the average climate change impact for Q_{100} (CCQ_{100}). The applied hydrological model for the respective gauge is given in parentheses; the Hype and Lisflood model were used in the other stations**

Gauging station	River	Catchment	Catchment area [km^2]	Q_{100} current [$m^3 s^{-1}$]	Q_{100} future [$m^3 s^{-1}$]	CCQ_{100} [%]
Bratislava	Dunaj	Dunaj	131331	11000	13290	20,32
Moravský Sv. Ján	Morava	Morava	24129	1600	1690	5,48
Streda n. Bodrogom	Bodrog	Bodrog	11474	1400	1570	12,07
Ipeľský Sokolec	Ipeľ	Ipeľ	4838	670	710	6,02
Veľké Kapušany	Latorica	Bodrog	2915	736	880	19,32
Banská Bystrica (HBV)	Hron	Hron	1766	540	440	-18,00
Vlkyňa (Lisflood)	Rimava	Slaná	1377	190	220	15,58
Chmeľnica	Poprad	Poprad	1262	820	640	-22,36
Liptovský Mikuláš (HBV)	Váh	Váh	1107	500	670	34,12
Spišské Vlachy (HBV)	Hornád	Hornád	775	400	390	-2,34
Janík (HBV)	Ida	Bodva	378	95	50	-47,03

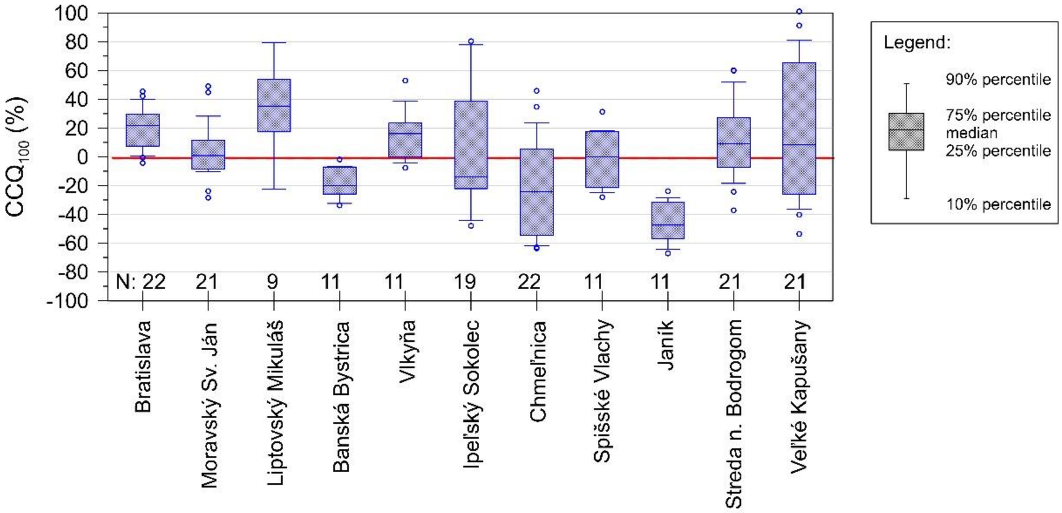

Fig. 3. Box plots showing the variability and extent of the climate change impact for Q_{100} (CCQ_{100}) obtained from ensembles of climate and hydrological models. N is the number of ensemble members used for analysis.

graphical location, the size of the river basin and the conditions under which floods occur (Blöschl et al., 2019). In small river basins, short-term convective precipitation with high intensities is especially important for flood generation. Conversely, in medium-sized and large river basins, longer-lasting synoptic frontal precipitation covering a larger area is crucial. From this point of view, the size of the river basin is a vital information. Also important are changes in water reserves in the snow cover and the period of snow melting, which in combination with liquid precipitation is in the spring period in many river basins a major factor for the occurrence of floods.

This work showed increases in Q_{100} at most stations. Decreases are estimated only at Chmeľnica, Banská Bystrica and Janík stations. The Danube basin (to the gauge in Bratislava) and the Morava river basin (to the gauge Moravský Sv. Ján) are the largest river basins in this study. An increase in Q_{100} is indicated in both stations, although in Moravský Sv. Ján only mild. The estimates of Q_{100} from the members of the ensembles are relatively consistent for both stations, i.e. the variability of the average Q_{100} is satisfactory and the hydrolo-

Table 3. Evaluation of the number of increases, decreases or no change in average *CCQ_{100}* for individual hydrological models and the whole ensemble of models (highlighted in grey)

	No. of increase (>5%)			No. of decrease (<-5%)			without change (-5% < x <5%)		
gauging station	**HYPE**	**LISFLOOD**	**ansambel**	**HYPE**	**LISFLOOD**	**ansambel**	**HYPE**	**LISFLOOD**	**ansambel**
Bratislava	8	9	17	0	0	0	3	2	5
Moravský sv. Ján	5	5	10	2	5	7	4	1	5
Vlkyňa	-	7	7	-	1	1	-	3	3
Ipeľský Sokolec	8	0	8	0	11	11	3	0	3
Chmeľnica	0	7	7	11	3	14	0	1	1
Streda nad Bodrogom	10	4	14	0	6	6	1	1	2
Veľké Kapušany	10	2	12	0	9	9	1	0	1
	No. of increase (>5%)			**No. of decrease (<-5%)**			**without change (-5% < x <5%)**		
gauging station	**HBV**			**HBV**			**HBV**		
Liptovský Mikuláš	7	-	-	1	-	-	3	-	-
Banská Bystrica	0	-	-	10	-	-	1	-	-
Spišské Vlachy	4	-	-	5	-	-	2	-	-
Janík	0	-	-	11	-	-	0	-	-

gical models give comparable outputs for individual climatic ensembles in terms of the number of increases or decreases. The third largest catchment is the Bodrog catchment (to the gauge Streda n. Bodrogom), where an increase in Q_{100} is also indicated, but data from hydrological models are not completely consistent (HYPE model estimates increases from all 11 members of the ensemble, LISFLOOD model indicates 6 decreases out of 11).

A decrease in Q_{100} was indicated at Banská Bystrica (Hron), Janík (Bodva) and Chmeľnica (Poprad) stations. The uncertainty of the Q_{100} estimation for the Banská Bystrica and Janík stations may be increased due to the fact that only one hydrological model was available for these stations.

Stations with high uncertainty of Q_{100} estimation according to the CCQ_{100} interquartile range 59–91% are Veľké Kapušany (Latorica), Ipeľský Sokolec (Ipeľ) and Chmeľnica (Poprad). A closer analysis of the results from these stations shows that this uncertainty results from the inconsistency of outputs from hydrological models. At the Veľké Kapušany and Ipeľský Sokolec stations, the HYPE model indicates more increases, while LISFLOOD indicates decreases. At the Chmeľnica station, the situation is the opposite, with declines from the HYPE model and increases from the LISFLOOD model prevailing. The choice of hydrological model and the uncertainty associated with it is probably higher in this case than the uncertainty arising from climate models.

Furthermore, another uncertainty in the Q_{100} estimation may be the narrowed ensemble of hydrological models at some stations (Banská Bystrica, Janík, Liptovský Mikuláš, Spišské Vlachy and Vlkyňa). As the outputs from the SWICCA database of hydrological models for the mentioned stations did not meet the required criteria for the reference period, it was necessary to look for an alternative solution in form of the HBV hydrological model. Here, arises a need to verify the estimated Q_{100} by other hydrological models in terms of the ensemble predictions philosophy as it is commonly used in climate models or by another suitable method, e.g. by correcting climatic ensemble data for hydrological data (Hakala et al., 2019).

The catchments with the smallest area are Spišské Vlachy (Hornád) and Janík (Ida, Bodva basin). Depending on the size of the river basin, it would seem that these river basins should provide data with the highest degree of uncertainty. It is true that hydrological data from the SWICCA database (outputs from the LISFLOOD and HYPE models) were not applicable for these river basins, probably also due to the coarse resolution of hydrological models to a small area of these river basins (775 and 378 km^2). However, the calibrated HBV model provided relatively consistent results for the individual climatic ensembles, and according to the CCQ_{100} interquartile range, these two stations are among the stations with the least and medium uncertainty of the Q_{100} estimate.

No significant differences between individual climate scenarios (RCPs) were identified in this work. Probably these were masked by uncertainties related to climatic and hydrological models. This may also be due to the fact that the data period was analysed as a whole (2011–2100) for the purposes of the Q_{100} estimation as opposed to the more typical 30 years sections.

Conclusions

This impact study provides the results of estimating the impact of climate change on Q_{100} for 11 gauging stations in Slovakia. In the first phase of the work, at least 572 time series of average daily flows for 26 stations were analysed. Relationships between peak and maximum average daily flows were derived (Hlaváčiková et al., 2019). For 242 time series, trends were analysed and frequency analysis was performed fitting the GEV distribution function. Data from climate projections as well as from hydrological models available in the SWICCA database were used to analyse the impact of climate change. Such an extensive analysis of data from the C3S database has probably not yet been implemented in Slovakia, despite the fact that some reputable organizations, such as the International Association of Hydrological Sciences (IAHS) recommended it. The results of this work can lead to a discussion regarding the usability of climate data from the C3S database for Slovak river basins, their limits, but also other perspectives.

The results of the whole work can be summarized in several points:

1 – The results indicate an increase in Q_{100} for seven gauging stations: Bratislava (Dunaj), Moravský Sv. Ján (Morava), Liptovský Mikuláš (Váh), Vlkyňa (Slaná), Ipeľský Sokolec (Ipeľ), Streda n. Bodrogom (Bodrog), Veľké Kapušany (Latorica), in the range of percentage change of Q_{100} (CCQ_{100}) 5.48–34.12%. A decrease in Q_{100} is indicated for stations Chmeľnica (Poprad), Banská Bystrica (Hron) and Janík (Ida, Bodva river basin) in the range of -17.99 to -47.03%. For the station Spišské Vlachy (Hornád) no significant change in Q_{100} was indicated (change more than ± 5%),

2 – the largest river basins in the analysis (Danube upto the Bratislava station and Morava upto Moravský Sv. Ján) provided results that fell into the group with the least degree of uncertainty in terms of CCQ_{100} impact variability and had the most consistent results for the two hydrological models used,

3 – the higher estimate uncertainty at stations Veľké Kapušany (Latorica), Ipeľský Sokolec (Ipeľ) and Chmeľnica (Poprad) resulted from conflicting outputs of hydrological models HYPE and LISFLOOD. Here, the use of a larger ensemble of hydrological models should be considered,

4 – the impact of climate change on the smallest river basins Janík (Bodva) and Spišské Vlachy (Hornád) could not be satisfactorily estimated with the hydrological outputs from the SWICCA database probably due to the rough resolution of models in relation to these river basins. The impact of climate change for these river basins was modeled by a calibrated HBV model using climate inputs from the SWICCA database. The impact of climate change for the Hron (Banská Bystrica) and Váh (Liptovský Mikuláš) river basins was estimated in a similar way. We assume that the complex orography and runoff formation in these river basins needs a finer resolution of climatic and hydrological models,

5 – in this work, it was not possible to clearly identify significant differences between individual climate scenarios (RCP) and their impact on Q_{100}. We assume that these were masked by uncertainties carried by climatic and hydrological models themselves.

The advantage of the SWICCA database is the availability of a large number of climatic and hydrological model outputs for a number of European river basins, as well as the latest knowledge on the state of the climate and modelled estimates of its development in one place. Not every user of a hydrological model has all the relevant meteorological data needed to calibrate the hydrological model and climatic data on the future climate. Another advantage is the time saved having ready to use calibrated data from the hydrological model that has been run for individual climatic inputs. The SWICCA database is constantly evolving and supplemented by necessary data. Its ambition is to provide users with a finer resolution of the outputs from the RCM models and to extend the reference period from 30 years to the longest possible period in the past. To achieve this, the necessary climatic and hydrological data in a sufficiently dense network of measurements provided by individual European countries are also indispensable.

The climate change is ongoing and its impacts are visible already. Therefore, an effort is made to best understand the ongoing processes and to use different methods to estimate the final impact of these changes in the field of water management. From this point of view, this work offers possibilities for a promising way in which it is possible to estimate the impact of climate change on extreme flows on the basis of currently available data. There is a strong presumption that the future will require more frequent and in-depth analyses of the impacts of climate change on design high flows, which will need to be taken into account in individual EU countries. That is why we consider this work to be an initial step towards solving this urgent and serious task in Slovakia.

The EU Working Group on Floods (WGF) is currently calling on the professional institutions of all Member States to be involved in addressing the effects of climate change on the occurrence of floods. Interdepartmental, interdisciplinary communication and data exchange is an essential part of mastering this task at both domestic and international levels.

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