J6.1 DISTRIBUTED HYDROLOGICAL MODELLING- AND STOCHASTIC WEATHER GENERATOR-BASED COMBINED ESTIMATION TECHNIQUE FOR FUTURE FLOOD FREQUENCY USING REGIONAL CLIMATE MODEL SIMULATION

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1. INTRODUCTION

Regional impacts of global warming are evidently very likely to affect hydrological processes, especially, the characteristics of flood events. In order to provide reasonable estimation for the future trends of flood event frequency, we have developed a combined modelling approach for the target Upper-Tisza Basin (UTB) located in Eastern Europe (Fig. 1). Three countries fall within the basin: Ukraine, Romania, and Hungary.

Fig. 1: Geographic location of the target watershed.

About 30% of the mountainous area of the basin is higher than 1000 m and it is rapidly increasing from this altitude up to 2256 m high, which is the highest point of the UTB.

Climatologically the watershed can be characterized by continental climate. The annual mean temperature varies between 6 °C and 10 °C; higher elevated parts are evidently colder than lower elevated parts. The annual mean precipitation amount is between 500 mm and 1400 mm; the eastern part of the basin is the driest and the north-western part is the wettest. The highest level of rainfall occurs in June and the lowest in January and February. However, the melting of the thick snow cover in spring raises the general level of the rivers and if this combines with high rainfall, a flood wave can (and often does) develop. Within 6-10 hours, the water from such an event reaches the Ukraine-Romanian border and within 12-36 hours it reaches the Ukraine-Hungarian border, with a possible water level rise of 8-10 m. Due to these particular topographic and climate conditions floods are common in spring and summer with river stages increasing 1.5 to 2.5 meters within four or five hours, further intensified by the low infiltration capacity of the soils in the Carpathian Mountains. Rainfall, snowmelt produced and mixed floods all are frequent, and the type of a particular flood wave depends and varies also on the magnitude of the sub-catchment where it originates.

Floods are quite violent, their drainage is significantly influenced by floods of tributaries. During long lasting rainy periods floods can be congested. These floods cause enormous inundation in the vast lowland areas.

During the last 30 years the river caused more than 100 flood events. Moreover, the rate of occurrence and degree of floods have continuously increased and reached its maximum with two catastrophic flood events of 1998 and 2001. The flood in November 1998 resulted in 2984 houses destroyed, 24340 houses evacuated, 12 bridges destroyed, 48 bridges damaged, 96.2 km roads destroyed. In March 2001 a flood peak record was observed and this event also resulted in huge damages: 1674 houses destroyed, 13768 houses evacuated, 17 bridges destroyed, 6 bridges damaged, and 52.7 km roads destroyed.

As a consequence of the floods occurring in recent years, large scale and ever accelerated embankment development works were initialised in Transcarpathia (Ukrainian part of UTB). Based on the results of preliminary analyses (Szabó and Lucza, 2010), it could be concluded that the developments mentioned above would result in a significant reduce in the number of dyke failures, being frequent until now only in Transcarpathia, which could increase the flood volumes and peaks in the downstream reaches of the Tisza by 10-15%, i.e., by 150-200 million m^3, and thus could further enhance the risk of flooding due to sudden collapse of the dykes along the River Tisza. According to this preliminary analyses, due to the ongoing development in Ukraine the peak level of extreme floods could increase by a couple of tens of centimetres, and the travel time could be reduced by 3-6 hours, thus decreasing by 10-20% the time available to organize flood prevention actions in the region. Taking into account the nature of the flood propagation, we can conclude that, such measures and developments - lacking any compensative flood

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prevention system (e.g., flood retention reservoirs, polders) - are kinds of risk relocation to the lower section of the river, in our case to the Hungarian section of the river. As an additional consequence of this large scale embankment development works, that the return periods of extreme hydrological events and its volume will change into an adverse direction in the lower part of the River Tisza.

With regard to design efficient flood management strategy, answering the questions like: what are the present (modified by the embankment development works) characteristics of floods, or will climate change lead to more flooding, are one of the major problems facing flood experts of the UTB Regional Water Directorate. The Upper-Tisza Regional Water Directorate recognized the gravity of the problem, and at the autumn of 2008 applied for the calls for proposals announced within the framework of the Swiss Hungarian Cooperation Programme as agreed by the Swiss Federal Council and the Government of Hungary with an application entitled "*Development of the flood prevention information system in the catchment area of the Upper River Tisza*" that application has won subsidy.

In accordance with the winner proposal, one of the specific aims of our research was to develop and implement an adequate modelling framework to estimate the distribution of the extremes of different return period (100 and 200 years) flood events for both present and future climate variability, referring to the Tiszabecs outlet gauging station of the UTB.

2. METHODOLOGY

2.1 *Background of the concept*

Virtually all hydraulic and hydrologic designs require estimating and analyzing a certain return period flow with special regard to the extreme flood events. Among others, reliable estimates of expected extreme flood events and their frequency distribution are required for design and operation of vital importance infrastructures such as flood defences, bridges, and also for flood risk management and planning, and for defining flood insurance premiums, etc. In practice, this information is obtained through the use of one of the flood frequency estimation techniques based on the principle of analyzing series of observed events to infer a probabilistic behaviour, which is then extrapolated to provide estimations of the likely magnitude of future extreme events (i.e., flood magnitude associated with the recurrence interval T, T-year flood). By nature, extreme flood events are seldom observed locally and hydrologists have little or no chance of gathering an adequate sample of catastrophes. This raises the question of how best to extrapolate to extreme events when no or only short series of recent events are available, or – as is often the case – the land uses of the watershed and/or the morphology of stream channels and floodplains has been changed (drastically/slightly) in recent decades.

Design flood techniques (flood frequency estimation methods) can be divided into two basic categories: streamflow-based and rainfall-based.

- The main characteristic of *streamflow-based approaches* is the primary reliance on observed streamflow data. The approach assumes that a series of independent observations of flood characteristics (peak flow, flood volume) fits an underlying probability distribution. Due to the limited homogeneous data availability for streamflow-based approach flood frequency analysis and taking the recent land-use and stream channel morphology changes into account, such methods are unusable for our aims.
- *Rainfall-based approaches* rely on the ability of a model to convert rainfall into streamflow. This approach relies on the assumption that the model employed preserves the probabilistic relationship between the input rainfall and the resultant flood. Basically there are two types of rainfall-based approaches:
  - *Discrete event modelling approach*, which produce a complete design flood hydrograph from a design rainfall event using rainfall-runoff model;
  - *Continuous simulation modelling (CSM) approach*, which is the most powerful technique to determine reliable flood frequency curves. Estimation of design floods using CSM has emerged as a very active research topic across academic institutions in Europe and everywhere in the world. CSM is based on the use of precipitation-runoff models (lumped or distributed), of various complexities, for transforming precipitation data into river flows. By coupling a precipitation-runoff model with a stochastic rainfall model, Monte Carlo simulations can generate very long series (even more thousand of years) of synthetic daily rainfall, which can be transformed into river flow from which the flood frequency characteristics can be deducted.

2.2 *The framework of our modelling concept*

The flood runoff analysis can be best achieved by a distributed analysis that provides the design values of the structural and non-structural protection measures across the entire river basin, with special regard to the Tiszabecs outlet gauging station.

We accomplished this objective by means of a modelling framework, which was based on continuous simulation of the river system response subject to stochastically generated meteorological forcings. This approach allowed to overcome the limitations of conventional statistical analysis "at site" or regional analyses, in that it provided design values for virtually any level of risk, and supplied in addition to the peak flows also other key variables such as the flood volume and duration associated with each simulated peak, thus allowing to assess the risk of failure of engineered dykes due to prolonged submersion times and the design of retention basins.

In order to achieve the specific objectives of the analysis, combined modelling technique has been developed as follows:

- a stochastic weather generator (SWG) to simulate the meteorological forcings at daily temporal resolution;
- a continuous in time and distributed in space precipitation-runoff (P-R) model, which accounted for the relevant hydrological processes and was explicit in the soil-vegetation-atmosphere components, and could be used to generate synthetic flood frequency curves, from which the discharge design values could be computed.

Such modelling framework allowed a much higher flexibility than conventional (streamflow-based) flood frequency analyses based on the use of statistical models and complied with the requirements needed to achieve the objectives described in section 1. Specifically,

- the stochastic nature of the modelling approach allowed the use of Monte Carlo techniques, which provided a basis for a probabilistic nature of the risk assessment, for uncertainty analyses, and for the generation of climate change driven meteorological forcing scenarios;
- the distributed and physically based nature of the P-R model allowed
    - to simulate explicitly the key hydrological processes for the generation of flood runoff,
    - to investigate the local and basin scale effects of non-stationarities induced by diffused and localized land-use changes,
    - to model the flood wave propagation along the river network, thus identifying the potential additional risk due to synchronous occurrence of flood peaks at critical junctions of the tributaries with the main stream.

By generating in a Monte Carlo fashion several hundreds of simulation years we envisaged thus to generate synthetically.

2.3 *The DIWA-SWG stochastic weather generator*

Many stochastic weather generators (SWGs) have been proposed in the scientific literature. However, most of them allow the simulation of meteorological variables, particularly precipitation and temperature at a daily scale resolution. Often they are also confined to a single site and hardly allow for the generation of meteorological variables in space. Due to the fast nature of the Tisza river basin response and the need for a spatially explicit meteorological forcings that is compatible with the distributed nature of the P-R model, we put to use the recent developed DIWA-SWG model (Szabó et al., 2010), which allows the generation of time series of rainfall and temperature fields at the daily temporal scale. Despite the physically based nature of the P-R model, it may in principle require additional variables such as radiation and wind speed, the absence of adequate historical series to validate other components of the SWG suggests to limit the SWG generated variables to temperature and precipitation and proceed with physically based parameterizations of the P-R model that do not require the explicit input of other variables than temperature and precipitation.

Temperature: We modelled the temperature using autoregressive models of appropriate order, which are able to model correctly the process correlation structure in time and allow a relatively simple extension to preserve the correlation structure also in space, thus allowing to overcome the limitation of lapse rate based interpolations. This class of models has been extensively used in the literature and has proved to provide reliable results. Because of the importance of snow driven processes in the catchment the simulation of both the minimum and maximum temperature will be required.

Precipitation: Our DIWA-SWG model produces time series of rainfall fields by a two-step procedure:

i. first, time series is generated at locations where historical data are available,
ii. then, a spatial interpolation of the generated series is carried out to produce the precipitation rainfall maps at the scale required by the P-R model.

DIWA-SWG model is a generation of the temporal process by a multi-level modelling approach, according to the following basic steps:

1 First, the alternating process of storm-interstorm process is modelled by simulating the length of the dry and wet spells respectively using the daily scale as reference.
2 For each storm period a randomly generated precipitation amount is simulated for the length of the wet spell.
3 Finally, a disaggregation procedure is applied to the wet spell to simulate the daily precipitation.

The length of the storm-interstorm process is modelled on the basis of a seasonally parameterized Markov chain approach, to account for the significant differences characterizing the precipitation patterns across the year. The precipitation amounts can be sampled from random values generated by probability distributions fitted to the daily precipitation amounts available from historical series.

The spatial interpolation of the time series randomly generated at each rain gauge station which is consistent with the observed spatial variability. Thus, the procedure considers the cross-correlation patterns observed among the stations present in the catchment. The interpolation is based on block-kriging techniques based on the available observations.

2.4 *The DIWA distributed precipitation-runoff model*

As already mentioned above, the P-R model must allow the simulation of the river flows and of the key hydrological processes that are responsible for flood runoff generation. The latter point is particularly important due to the complexity of the flood nature in the Tisza river. Indeed, severe floods were observed that were both snowmelt and storm rainfall driven, as well as floods that were predominantly or only due to storm rainfall.

Accordingly, an appropriate simulation of the snow accumulation and melting processes, as well as explicit and physically based modelling of the soil water balance are mandatory, in order to investigate the risks associated with the two different natures of floods, to account explicitly for the role played by the basin wetness with respect to the onset of a flood event and to account for the non-linearities in the basin response, which are induced by the soil water dynamics. Moreover, due to the need of a detailed analysis of the risk along the entire river network, the P-R model must allow an explicit simulation of the channel flood wave propagation.

With most emphasis on the recent years of extensive scientific development HYDROInform Ltd developed the large-scale high resolution distributed hydrological model **DIWA** (**DI**stributed **WA**tershed) which is a dynamic water-balance hydrological model that distributed both in space and its parameters, and which was developed along combined principles but its mostly based on physical foundations (Szabó, 2007). According to the philosophy of the distributed model approach the catchment is divided into basic elements, cells (see Fig. 2) where the basin characteristics, parameters, physical properties, and the boundary conditions are applied in the centre of the cell, and the cell is supposed to be homogenous between the block boundaries.

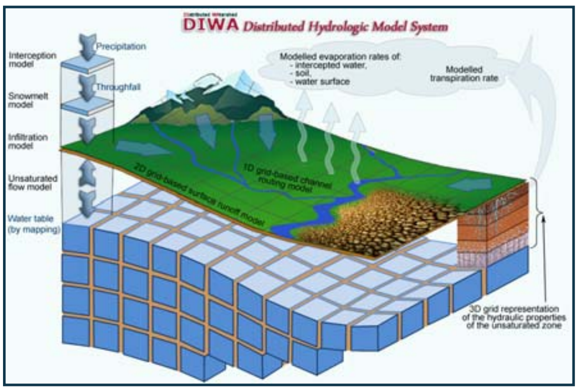

Fig. 2: 3D schematic description of the DIWA distributed hydrological model.

The neighbouring cells are connected to each other according to runoff hierarchy (local drain direction). Applying the hydrological mass balance and the adequate dynamic equations to these cells, the result is a 3D distributed description of the runoff.

The fundamental processes that are simulated by the model include interception of rainfall, snow accumulation/melt, soil frozen, surface runoff, infiltration, evapotranspiration, exchange of soil moisture between the soil layers (percolation and capillary rise) and drainage to the groundwater, sub-surface flow, and flow through river channels.

A user-friendly, Windows-based software system with fully graphical user interface for DIWA model also has been developed including some useful optional pre-processing functions, such as: a hydrodynamic submodel to simulate reservoir operation; automatic calibration routine based on a derivate-free, efficient hybrid combined method of globally convergent adaptive partition-based search and downhill simplex algorithm (Szabó, 2008); a software package of stochastic-based algorithms to perform distributed climatologic data from station data to a certain grid for a range of variables (precipitation, temperature, vapour pressure, potential evaporation) (Szabó, 2011).

2.5 *Setting up the models*

Before using DIWA-SWG model, the following steps of analysis were executed to parameterize and test the model:

1. *Data collection* - observed daily climatological data for the variables and sites of interest were collected, quality controlled and correctly formatted for the 1983-2011 baseline period.
2. *Parameterization* - the parameters of the model are estimated using the built-in automatic procedures for parameter estimation.
3. *Model testing* - time series of weather are generated and their statistics analyzed and compared with the observed data on which they were based. The significance of any discrepancies between the DIWA-SWG-derived and observed series was more than acceptable.

Then the DIWA model was calibrated against time series of discharges for the periods of 01.05.1991–30.04.1995 and 01.05.1995–30.04.2001 selected for calibration and validation, respectively.

Fig. 3 shows the scatter plot diagrams of simulated versus observed discharge for both periods: calibration and validation, which graphically compares the distribution of the discharge to the "perfect" model. The straight line represents what our data would look like if the simulation was perfect. The discharge data is represented by the squares plotted along this line

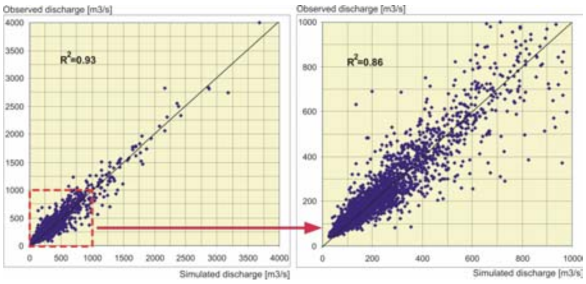

Fig. 3: Scatter plots of simulated versus observed discharge at Tiszabecs gauge for periods, _calibration_ and _validation_: 01.05.1991–30.04.2001.

Then, the climate change has been estimated in order to analyze the effects on the wanted flood frequency characteristics. For this purpose, simulation of regional climate model PRECIS has been used. This hydrostatic model has been developed by the Hadley Centre of the UK MetOffice (Wilson et al., 2010), and adapted for the Central/Eastern European region by the Department of Meteorology Eötvös Loránd University (Bartholy et al., 2009). The applied horizontal resolution is 0.22° (~25 km), and the model contains 19 atmospheric vertical levels with sigma coordinates. The necessary initial and lateral boundary conditions are provided by the global climate model HadCM3 (Gordon et al., 2000; Rowell, 2005). For the future, the intermediate SRES A1B emission scenario (Nakicenovic and Swart, 2000) was taken into account, according to which the estimated CO_2 concentration level by 2050 is 532 ppm.

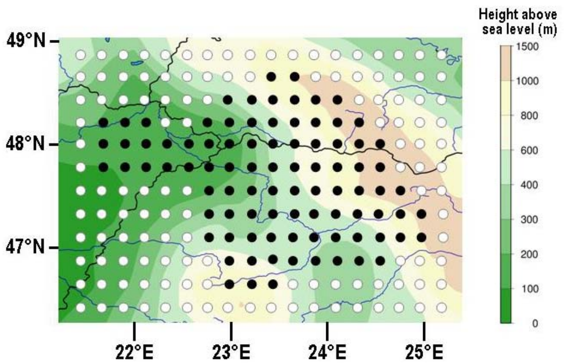

Fig. 4: The selected target area in the PRECIS model: the Upper-Tisza watershed area is represented by 90 grid cell centers indicated with black circles.

In order to eliminate the bias of the climate model experiment (Pieczka et al., 2010), the raw daily output data (i.e., precipitation, minimum and mean temperature) has been corrected using the quantile matching technique for each grid cell located within the target area. In this process, the monthly empirical distribution functions of simulated raw data in each grid cell (Fig. 4) are fitted to the observed monthly distributions (Formayer and Haas, 2010) using the calibration period of 1983-2010. Then, the correction factors are applied to the entire gridded daily time series (e.g., 1961-2050). The corrected outputs enable us to build a stochastic weather generator for each grid cell using DIWA-SWG model embedded into Monte Carlo simulations, and result in a very large ensemble of possible future hydrometeorological conditions on daily scale.

3. REGIONAL CLIMATE CHANGE PROJECTIONS

A multi-model climate projection for the entire Carpathian Basin is discussed by Pongracz et al. (2011), here the projected changes are discussed only for the target subregion, the Upper-Tisza watershed area.

3.1 *Estimation for temperature changes*

The projected monthly mean temperature changes are shown in Fig. 5. The graph suggests clear, significant warming signals for both temperature variables (the projected annual mean increase is 2.3 °C), the largest and the smallest temperature increases are projected in January (>3 °C) and in November (1.0-1.1 °C), respectively.

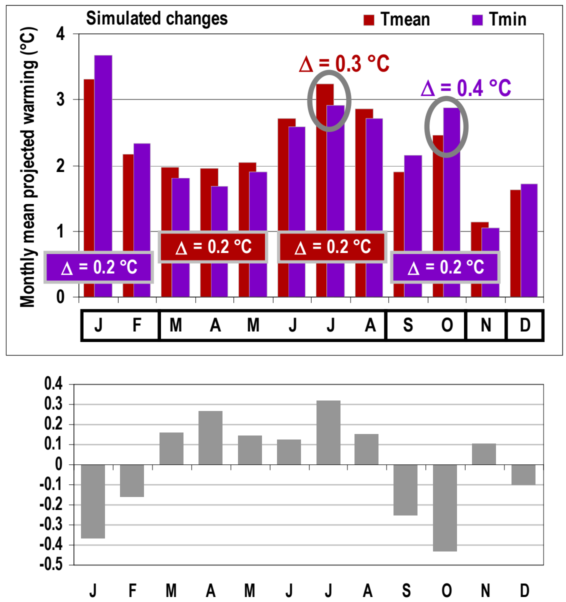

Fig. 5: Projected mean monthly change of daily minimum and mean temperature by 2021-2050, reference period: 1961-1990. The values are spatial averages of the 90 grid cells representing the Upper-Tisza watershed area. All the estimations are statistically significant at 0.05 level.

The largest differences between monthly mean projected increases of daily mean and minimum temperature are found in October ($\Delta T_{min} > \Delta T_{mean}$) and July ($\Delta T_{min} < \Delta T_{mean}$). The daily mean temperature is likely to increase more than the daily minimum temperature by ~0.2 °C in spring and summer, whereas it is likely to increase less than T_{min} by ~0.2 °C in winter and autumn.

Table I: Projected mean seasonal and annual change of daily minimum and mean temperature (T_{min} and T_{mean}, respectively) by 2021-2050, reference period: 1961-1990. The values are spatial averages of the 90 grid cells representing the Upper-Tisza watershed area. All the estimations are statistically significant at 0.05 level.

Season	T_{min}	T_{mean}
Winter (DJF)	+2.6 °C	+2.4 °C
Spring (MAM)	+1.8 °C	+2.0 °C
Summer (JJA)	+2.7 °C	+2.9 °C
Autumn (SON)	+2.0 °C	+1.8 °C
Annual	+2.3 °C	+2.3 °C

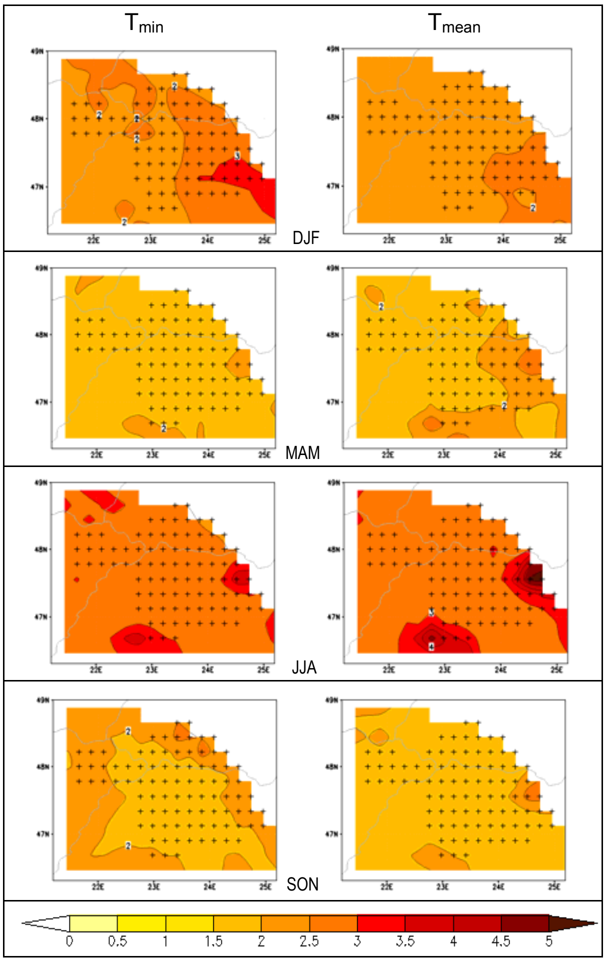

Fig. 6: Projected mean seasonal change of daily minimum and mean temperature (°C) by 2021-2050, reference period: 1961-1990.

The projected mean seasonal temperature increase by 2021-2050 is summarized in Table I, the spatial structure of the projected seasonal warming rates are illustrated in Fig. 6. For all the four seasonal and the annual bias-corrected simulated time series clear, significant warming signal with positive trend coefficients can be foreseen. The fitted annual trend is 0.4 °C/decade, the fitted seasonal trend is 0.3-0.5 °C/decade, the largest and the smallest trend coefficients are projected in summer and autumn, respectively. The largest monthly fitted trend coefficient is 0.6 °C/decade in January.

3.2 *Estimation for precipitation changes*

Projected precipitation changes do not show so clear significant trends as projected temperature changes.

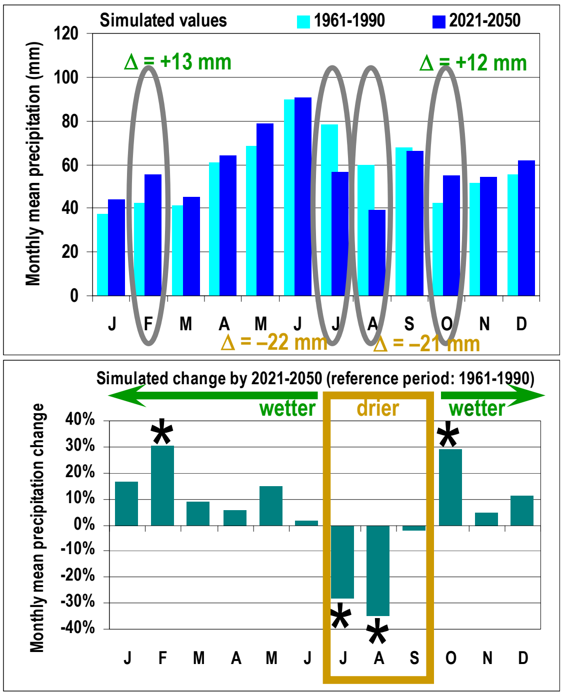

Fig. 7: Simulated mean monthly precipitation amounts for 2021-2050 and 1961-1990 (upper), and the projected mean change of monthly precipitation by 2021-2050, reference period: 1961-1990 (lower). Asterisk (*) near the histogram column indicates statistically significant projected change at 0.05 level. All the values are spatial averages of the 90 grid cells representing the Upper-Tisza watershed area.

The upper panel of Fig. 7 compares the annual distribution of simulated monthly mean precipitation amounts for the future period 2021-2050 and the reference period 1961-1990. The difference between them, which is the projected change, is shown in the lower panel of Fig. 7 (the difference is expressed as the relative change in %). Statistically significant monthly projected changes are emphasized by asterisks. In February and October the precipitation is likely to increase by about 30% in the Upper-Tisza watershed area. Similar rates but opposite sign are projected in July and August when drier conditions are likely to occur in the future.

The estimated annual and seasonal mean precipitation changes by 2021-2050 are summarized in Table II. The spatial structures of the seasonal mean projected changes are shown in Fig. 8. The maps suggest that the projected summer drying is larger in the western part of the watershed than in the eastern part. The winter and spring precipitation increase is projected to reach the largest change in the southern and northeastern parts of the watershed. The smallest changes are projected for autumn.

Table II: Projected mean changes of seasonal and annual precipitation amounts by 2021-2050, reference period: 1961-1990. The values are spatial averages of the 90 grid cells representing the Upper-Tisza watershed area. Grey background indicates statistically significant projected change at 0.05 level.

Season	Absolute change	Relative change
Winter (DJF)	+25 mm	+19%
Spring (MAM)	+18 mm	+10%
Summer (JJA)	-41 mm	-18%
Autumn (SON)	+13 mm	+8%
Annual	+15 mm	+2%

The projected annual mean precipitation change is +2%, which is quite small and not significant at 0.05 level. Monthly mean precipitation is likely to increase mostly, except in July, August, and September (when drier conditions are projected for the mid-century). The projected monthly changes are significant at 0.05 level only in February and October (increase by ~30%), July and August (decrease by 28% and 35%, respesctively).

Trend analysis of bias-corrected simulated annual, seasonal, and monthly time series for the spatial average of the 90 grid cells representing the Upper-Tisza watershed area suggests the following conclusions: (1) Fitted linear trend coefficient for annual sum is 0.4 mm/decade, which is not significant. (2) Significant drying trend is projected for summer, the estimated trend coefficient is -7 mm/decade. (3) Significant positive trend implying wetter conditions is projected for winter, the estimated trend coefficient is +3 mm/decade. (4) Fitted linear trend in spring and autumn are not significant. (5) Significant drying trends are projected for July and August, the estimated trend coefficients are -4 mm/decade and -3 mm/decade, respectively. (6) Significant positive trend implying wetter conditions is projected for February, the estimated trend coefficient is +2 mm/decade. (7) Fitted linear trend in other months are not significant.

The main conclusion of the study for the selected watershed is that the regional climate change results in favourable hydrological changes, i.e., the flood threat in the region will significantly decrease if the SRES A1B scenario realizes in the future.

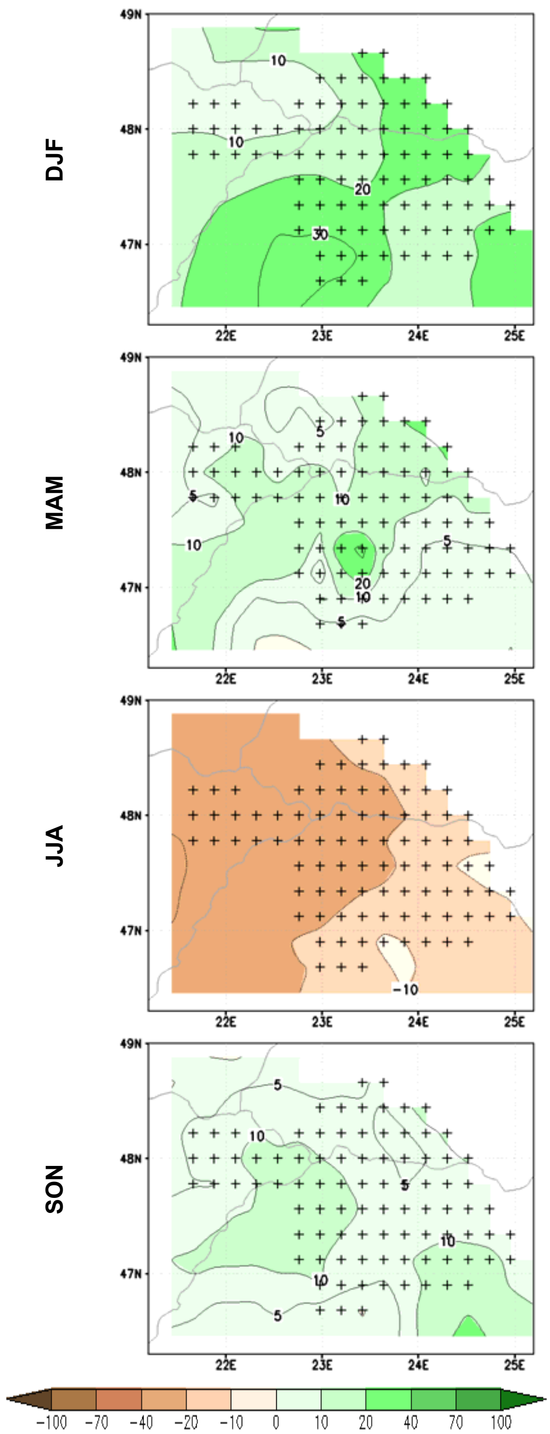

Fig. 8: Projected mean seasonal change (%) of precipitation by 2021-2050, reference period: 1961-1990.

4. RESULTS

Finally, we ran the calibrated DIWA hydrologic model using 900 times 100/200 years independent synthetic, stochastically generated daily sequences of weather conditions on the basis for both present and future climatic conditions, referring to the Tiszabecs outlet gauging station of the UTB, with the purpose to estimate the frequency of the extreme flood events for the return periods of 100 and 200 years. The scenarios are evaluated:

I. Present conditions:
- current conditions of the riverbed and the overbanks,
- current land-use,
- meteorological data for the past 30 years.

II. Predicted climatic conditions:
- current conditions of the riverbed and the overbanks,
- current land-use,
- projected climate data for the future period of 2021-2050.

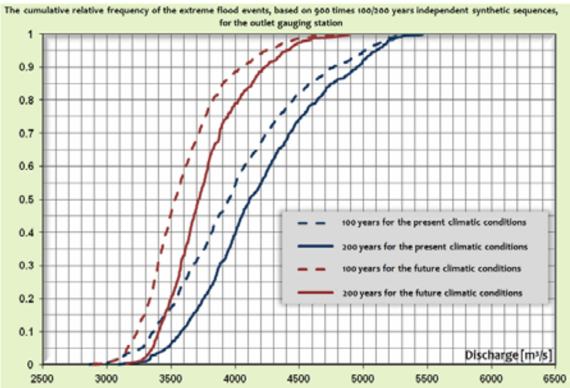

Fig. 9: The cumulative frequency of the extreme flood events for the outlet gauging station of UTB. Blue/red lines indicate the present/future. Dashed/continuous lines indicate 100/200 years.

I. Evaluation of the simulation for present conditions

As a result of the integrated simulations, the cumulative frequency curve of the extreme flood events for the outlet gauging station of UTB of 100- and 200-year recurrence interval were made, which was considered as reference for the evaluation of scenario II. The results are shown in the Fig. 9.

II. Evaluation of the simulation for predicted climatic conditions

According to the results of the simulations we can conclude (see Fig. 9.), that the flood threat in the region will significantly decrease on the UTB according to the applied climate change scenario (A1B). This can be happen in spite of the fact that the increase of 10% of the winter precipitation is predicted. Our conclusion can be explained by two essential conditions mentioned below:

1. First, it is important to point out that nearly 60% of the maximums of the 900 runs of 100 years were given by flood waves originating from conjoint rainfall and snowmelt. In spite of the fact that the increase of 10% of the winter precipitation was predicted by the climate models, through the predicted average increase of 4 °C of the daily mean temperature the rate of rain/snow in winter will be increased on the project area. Hence the majority of the precipitation in winter will fall as rain, not snow that leads the snow accumulation to drop and the winter run-off to increase. As a result the volume of flood waves originating from conjoint snowmelt and rainfall will significantly decrease and so will the frequency of the extreme flood events.
2. The relative invariability of the annual precipitation and the increase of the intensity of the precipitation will result in the increase of the rate of the dry/wet days. As a result of the longer period of days without rain the riverbeds will be filled with less water when the rain begins to fall. The conditions mentioned above will result in a situation where the frequency of flash-floods on the area of the foot of mountain will increase due to the increase of the intensity of the precipitation, while the flood waves in the larger rivers (like river Tisza) will run down with lower water levels.

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