*R&D Project SP/1a6/108/07*

# "Update of existing estimates of the impacts of climate change in the water, agriculture and forestry sectors, and proposed adaptation measures"

*(Summary)*

## Outline of the project and the use of its results

The Ministry of the Environment issued an invitation for tenders for R&D Project SP/1a6/108/07 in order to support basic and applied research in the field of climate change and the regular monitoring of such changes and their impacts. The period of the project was 2007 to 2011 and the contractor was the Czech Hydrometeorological Institute. The project's results will be used, amongst other purposes, for the preparation of national strategic documents in the field of climate change (the Climate Protection Policy of the Czech Republic, the Climate Change Adaptation Strategy of the Czech Republic).

The other participants involved in the project were the Faculty of Mathematics and Physics of Charles University in Prague, the T. G. Masaryk Water Research Institute, public research institution, CzechGlobe - Global Change Research Centre of the Academy of Sciences of the Czech Republic, public research institution, and the Crop Research Institute, public research institution.

The project focused in particular on the following areas:

- refining and updating climate development scenarios in the Czech Republic using regional climate models to forecast short-term (2010-2039), medium-term (2040-2069) and long-term (2070-2099) developments;
- performing an uncertainty analysis of the results of estimates of the future development of manifestations of climate change in the Czech Republic at cross-sectional time periods with regard to the level of uncertainty in the input data and other parameters;
- archiving and distribution of time series for selected climatological characteristics (air temperature, precipitation, humidity, global radiation, wind speed) with monthly and daily increments for future climate;
- comparison of generated scenarios with the results of the projects EU CECILIA and EU ENSEMBLES;
- analysis of the development of the basic indicators of climate change (temperature and precipitation) in the Czech Republic over the 50-year period from 1961 to 2010;
- a regional analysis of the impacts of climate change on the hydrological balance in the Czech Republic, and evaluation of the basic elements of the hydrological balance, average and minimum flows and the occurrence of droughts;
- a methodology for assessing the impacts of climate change on water management (in particular on the need for water supplies in agriculture and forestry), and an analysis of predicted changes in the statistical characteristics of daily and annual minimum flows and changes in the flood regime;

- an analysis of long-term series of selected agro-climatic elements and their predicted changes;
- an analysis of the effects of abiotic and biotic stressors on forests; and
- proposals for selected types of adaptation measures in the water, agriculture and forestry sectors, including pilot cost-benefit analyses of their probable effectiveness.

THE FINAL REPORT ON THE PROJECT consists of five chapters focusing on a detailed description of the results achieved in the project (available only in Czech). The report is accompanied by annex files on DVD which expand on the information contained in the main text of the report, including time series of the values of the analysed meteorological elements from the reference period 1961-1990 and the values simulated in the regional climate model used - "ALADIN-CLIMATE/CZ" - with a resolution of 25 km (both corrected and uncorrected ) for each of the nodes of the area studied, which users may employ as input data for further research on climate change in regional conditions. The report is also accompanied by an overview of the publications of the principal investigators from the time of the project which has a direct relationship to the themes studied.

## Refining and updating regional climate change scenarios

The basis used in the climate change scenario for the Czech Republic consists of the outputs from the regional climate model ALADIN-CLIMATE/CZ with a resolution of 25 km for the period 1961-2100, corrected for errors in the model which were identified when comparing the model simulation for the reference period with measured values. The basic elements chosen for the scenario were average daily air temperature, daily precipitation, daily sum of global solar radiation, average daily wind speed and relative humidity. These basic climatic elements were chosen on the basis of the requirements of sectors concerned with estimates of impacts, and based on the availability of outputs from regional climate models. From daily values it is possible to calculate a number of other characteristics using ProClimDB software which express, amongst other things, extreme climate features, such as the number of days with limit temperatures (summer, tropical, frost and ice days) or the number of days with limit precipitation etc.

For model estimates of predicted short-term changes the emission scenario IPCC SRES A1B was used, and for the medium and long-term the scenarios SRES B1 and A2.

### *Validation of the model*

The ALADIN-CLIMATE/CZ model outputs for the reference period with a 6-hour time resolution were first converted to daily data. Calculations were then made of the daily average, maximum and minimum air temperatures, the daily precipitation, the daily average relative humidity and the daily sum of global solar radiation. Following this, validation of the obtained fields was performed by making a comparison with the sets of measured station data remapped to the regular grid of the ALADIN-CLIMATE/CZ model.

The deviations of the simulated seasonal average air temperatures from those observed in the reference period are in the range of up to 1 °C for most of the country in the summer and winter. However, in the spring and autumn, the model shows substantially colder values than those observed (in some cases in spring by more than 3 °C). When modelling the development of atmospheric precipitation, the ALADIN-CLIMATE/CZ model on average tends to exceed the observed precipitation in the reference period in all seasons (other regional and global climate models behave similarly) - in the winter and spring by up to 30-40 % in some cases. However, this finding does not apply to the entire country, as there are areas where, conversely, the model precipitation is underestimated, especially in the winter and the autumn. Large deviations from the observed values are found in particular for humidity, which the model overestimates for most of the country, sometimes by as much as 30 %. In the case of global solar radiation, the model overestimates the values in the summer and tends to underestimate them in the winter. The model tends to underestimate wind speed in summer, and to exceed the observed values in winter.

***Post-processing of model outputs***

Since systematic errors in the simulations of the studied climatic elements and characteristics were found during the validation of the ALADIN-CLIMATE/CZ model, for the purpose of estimating impacts a recommendation was made either to use the model outputs for future climate in relative terms (i.e. in the case of air temperature to work with the differences, and for the other elements to use the ratios of the average values for the new and reference periods), or to use data which had passed through a "post-processing" stage (i.e. the application of statistical corrective functions). Due to the small differences in the results of different methods of post-processing compared to other uncertainties, a quantile method was used, where for each climatic element, day and grid point quantile functions were constructed based on the measured and simulated values in the reference period. Correction factors were then calculated by comparing the values of corresponding quantiles, which were subsequently applied to the period describing future climate.

***Short-term climate change scenario (2010–2039)***

Only the SRES A1B emission scenario was used in connection with this scenario, as for such a near-term period only minor differences are expected between the various SRES scenarios.

In the short term, the average annual air temperature in the Czech Republic will increase by approximately 1 °C according to the ALADIN-CLIMATE/CZ model. The warming during summer and winter is only marginally less than in spring and autumn. A systematic increase in temperatures can be seen with relatively little spatial variation. In the case of changes in seasonal precipitation the situation is more complicated. At most nodes, the simulation shows a decrease in future precipitation in winter (depending on the specific location by up to 20 %), and an increase in spring (from 2 % to around 16 %). In summer, and particularly in the autumn, the situation in different parts of the Czech Republic varies (in the case of autumn, a slight decrease by a few percent can be seen in several places, in other areas an increase of up to 20-26 %, while in the case of summer there is predominantly a marginal decrease, although in a few locations (e.g. western Bohemia) there is an increase by up to 10 %). At the same time, relatively significant spatial variability can be seen in the changes. It is therefore possible that in this near-term period any climate change signal may be concealed by natural (interannual) fluctuations in precipitation.

Due to the weak signal for predicted changes in relative humidity, and not least of all the fact that the measured values of relative humidity did not change over the period 1961-2000, it was recommended that the measured values of relative humidity from the reference period be used when estimating impacts for this period. The simulated changes in the seasonal averages for daily sums of global solar radiation are greatest in winter (up to more than

10 %), while in the other seasons they are in the range of up to 4 % at most locations. However, compared with the errors of the model the changes in global radiation reaching the Earth’s surface are small. For practical work with these files, the same recommendation applies as in the case of relative humidity.

***Medium-term (2040-2069) and long-term (2070-2099) climate change scenarios***

In the case of the medium-term outlook, the simulated level of warming is already more significant. The air temperature will increase the most in the summer (by 2.7 °C) and the least in the winter (by 1.8 °C). Worthy of note is the increase in temperatures in August by nearly 3.9 °C. At particular grid points the values of the changes in the spring and summer may range from 2.3 °C to up to 3.2 °C, in the autumn from 1.7 °C to up to 2.1 °C, and in the winter from 1.5 °C to 2.0 °C. In the long term the increase in summer temperature reaches approximately 4 °C (3.5 to 4.7 °C), while in autumn and winter the temperature increase is less, namely 2.8 °C (2.6 to 3.1 °C).

In the medium term, a decrease can already be seen in winter precipitation (e.g. in the Krkonoše Mts., Českomoravská Vysočina (the Bohemian-Moravian Highlands) and the Beskydy area by up to 20 %), and an increase in precipitation in the autumn. In the summer a decrease in precipitation begins to dominate in the Czech Republic, which will be even more pronounced in the long term, whereas the decrease in winter precipitation will be smaller than in the preceding period.

Changes in relative humidity are small, but the model nonetheless indicates a drop for all seasons and time periods - in winter by as much as 5 %, in summer 5-10 %, and at the end of the 21st century in some places by as much as 15 % (part of Central Bohemia, Vysočina). This finding is consistent with the projected increase in air temperature and the decrease in precipitation. A recommendation has been made that users of the output data for both time periods work with the corrected data, or, potentially, that they apply the relative changes between the future and the reference period to the time series of observed values in the reference period 1961-1990 (incremental method or delta approach). If the simulations of predicted future developments in global radiation are used, the same applies as was stated in relation to the short-term period.

The values stated apply for the SRES A1B emission scenario. However, for these two cross-sectional time periods the project also involved simulations according to the emission scenarios SRES B1 and A2.

***Assessment of the level of confidence for regional climate change scenarios***

The ability of the ALADIN-CLIMATE/CZ model to capture the essential features of the regional climate was also compared with the level of success of other simulations of regional climate; particularly those of the EU project ENSEMBLES. Using a selected type of skill score, a ranking was made of regional models according to their success at simulating selected climate characteristics in the reference period. In this ordering, the ALADIN-CLIMATE/CZ model was ranked in the first half of the group of selected regional climate models for most of the evaluated characteristics.

The uncertainties in the scenario-based model simulations carried out in the project essentially arise from three sources:

- emission scenario uncertainty

- driving global model uncertainty, and
- nested regional model uncertainty.

The simulations made using the ALADIN-CLIMATE/CZ model were performed for the emission scenario SRES A1B, which is regarded as one of the middle-of-the-range scenarios. In addition to this, the differences between the scenarios are not especially apparent in the model outputs for the short-term outlook or, to a great extent, for the medium-term outlook. Emission scenario dependence is visible only in the long-term outlook, and even then almost only in the case of temperatures (the biggest changes in the assessed scenarios being for A2, smaller changes for A1B and the smallest for B2). In the case of precipitation changes there is no particularly visible dependence on emission scenario (assessed using the outputs of global climate models).

The variance of the changes in the different regional climate models, similarly as in the different global climate models, progressively increases with time. For the most part, the growth in this variance can be seen similarly in both the regional and the global models (for emission scenario A1B). Analyses have shown that global models generally introduce more uncertainty into the scenarios than the associated regional models.

In comparison with other regional models, for the A1B scenario the results derived from application of the ALADIN-CLIMATE/CZ model to estimate climate change in the short term do not especially deviate from the context of other regional models (except in the case of winter, where, unlike most other models, it indicates a marginal decrease in precipitation). However, the results of its application for the medium- and long-term outlooks differ more from the characteristics of the other models, especially in the case of the winter period. It systematically indicates a smaller temperature increase, a general decline in precipitation and an increase in global radiation, which is totally at odds with the context of the other models. The cause may be the greater level of simulated anticyclonicity in the winter period compared with the other regional models. For this reason, the scenarios of the ALADIN-CLIMATE/CZ model display a greater degree of uncertainty for the winter period than for the other seasons.

## Impacts of climate change on the hydrological balance and water resources, and proposed adaptation measures in the water sector

Climate change can cause or exacerbate problems at both extremes of the hydrological regime, i.e. during periods of hydrological drought and during flooding. In such situations the needs of the population are not met - in the case of drought, mainly the need for water supplies and the dilution of discharged wastewater; in the case of flooding, the need for protection for the public and property used thereby (lying within the range of effect of the floods). Both extremes can cause widespread damage to ecosystems across the whole landscape, although ecosystems directly associated with watercourses are particularly affected. An important point to note is that periods of water shortage are expected to be more likely than increases in the intensity and frequency of torrential rainfall causing floods.

Temperature is a major factor influencing the hydrological balance, because as temperature increases so also does potential evapotranspiration (and if there is water available in the basin, also evaporation). There is therefore a faster rate of water loss from the basin. The observed increase in temperature leads to an increase in potential evapotranspiration by approximately 5-10 % as an annual average, and the same increase can also be seen for both spring and summer. The most significant increase in evapotranspiration occurs in winter (by up to more than 20 %), as a result of the greater number of days with positive air temperatures. On the other hand, no major changes in potential evapotranspiration occur in the autumn, because there is no observed increase in air temperature.

In the Czech Republic, the increase in potential evapotranspiration is to a large degree offset by the growth in precipitation. This will increase by up to 10 % in terms of the annual balance. Over the course of year we can see a relatively significant increase in autumn precipitation (by up to 20 %, particularly in the southern part of the country). The exception is the area of Central Bohemia, where instead of this growth in precipitation there is a decrease in spring by as much as 20 %. It is evident from the difference between the changes in precipitation and potential evapotranspiration that in the annual balance the growth in potential evapotranspiration is effectively offset by increased precipitation for a large part of the Czech Republic. However, in the central part of the country there are basins where changes in precipitation cannot compensate for the increase in potential evapotranspiration, so that there is a hydrological imbalance in these areas in the long-term.

***Estimation of the impacts of climate change on the hydrological balance of basins, and the respective degree of uncertainty***

For the purposes of the project, extensive modelling was performed of the impacts of climate change on the hydrological regime at 250 basins using the hydrological model BILAN. A consistent set of fifteen simulations of regional climate models was considered. These all had a comparable horizontal resolution (approximately 25 km x 25 km) and covered the same time period, i.e. the period from 1961 to 2099. The regional models were driven by various global climate models based on the SRES A1B emission scenario. An assessment was made of the changes between the reference period and individual cross-sectional periods.

The fundamental basis for potential changes in the hydrological balance in the Czech Republic is derived from the precipitation and temperature projections for Europe, i.e. a gradual increase in temperature over the whole year and a decrease in summer precipitation, an increase in winter precipitation, and stagnation in overall annual precipitation. The Czech Republic is situated in a transitional area between the anticipated growth in precipitation in the north and the drop in precipitation in the south of Europe. This fact contributes significantly to the uncertainty in estimating changes in the annual balance of precipitation, and thus also runoff and other components of the hydrological cycle. Uneven distribution of the projected changes in precipitation over the year is one of the features common to a large number of simulations of climate models.

In the period from early autumn to early summer there is an increase in precipitation, which is accompanied by an increase in evaporation of roughly the same order of magnitude caused by the increase in temperature. In the summer precipitation decreases and due to the drop in water supply in the basin there can be no significant increase in evaporation. An important factor influencing changes in runoff is the shift in the time of snow and ice melting from approximately April to January-February due to the higher temperature. The changes in runoff in the period from January to May are therefore primarily determined precisely by the different dynamics of snow water storage, while changes in the summer period are determined primarily by the decrease in precipitation.

Based on the set of regional climate models considered, the average changes in runoff for the individual seasons are consistent for all the time periods assessed. In general terms, we see a growth in runoff in winter and a decrease in runoff for the rest of the year, and for a large part of the Czech Republic also in terms of the annual balance. The largest decreases are generally found in the southern half of the country. The near-term outlook slightly deviates from this trend, as even in summer or autumn basins may be found where in exceptional cases runoff may also increase. In the annual balance we can therefore expect stagnation as regards runoff in the northern and western parts of the Czech Republic, and a drop (in most areas of up to 10 %) in the southern and southeastern parts of the country. Over the medium and long term it is possible to clearly distinguish a growth period as regards runoff in winter (mostly 5-10 %, in some cases up to 20 %), and a decrease in other seasons, most of all in the summer (20-40 %). In terms of the annual balance, a decrease in runoff can be predicted in the range of between 5 and 20 %. However, for most of the country the projected changes of annual runoff balances in particular are affected by a considerable degree of uncertainty for all the outlooks.

***Assessment of the level of confidence for estimates of the impacts of climate change on the water sector***

Generally, the level of confidence for particular projections of a climate model can be evaluated from two different perspectives: (i) according to its ability to simulate a control climate, and (ii) according to the deviation of the projections of the given climate model from the projections of other climate models for future climate. The deviations in precipitation and temperature between the climate model simulations and the observed data are not insignificant - in the set of models considered, the average error in temperature for individual seasons is in the range of 0 to 1 °C, while for particular models it can even be as much as between -2 and +5 °C. Precipitation is generally overestimated in the climate models (except in the case of summer). In winter the error reaches up to 50 %. The smallest differences are in regard to summer precipitation. It clearly follows that the uncorrected simulations are not directly usable for hydrological modelling, and therefore various forms of "post-processing" are applied (see above).

The range of variation of the projections across the individual simulations of the climate models is considerable, and this leads to significant uncertainty in the conclusions derived from hydrological modelling of climate change impacts. When climate model outputs are then used for hydrological modelling, further uncertainties are added to these. These include, in particular, the uncertainty associated with the choice of method for converting climate model outputs to the scale of individual basins (downscaling), the methodology for creating climate change scenarios, and the structure of the hydrological model itself and its parameters. In fact, the uncertainty associated with the choice of climate model considerably exceeds the uncertainty associated with the choice of emission scenario or the uncertainty arising from hydrological modelling. At the scale of individual basins we can generally note that a decrease in runoff in the period from April to October is common to the overwhelming majority of the models, and the degree and likelihood of this decline increases as time goes on.

***Options for adaptation to climate change in the water sector***

Adaptation measures aimed at preventing and mitigating the adverse impacts of climate change are based either on reducing requirements (on water resources, land use etc.) or mitigating effects (compensating for the shortage of water resources, flood control measures). At the European level, a number of more or less detailed catalogues of possible adaptation measures have been drawn up. However, not all of the possible adaptation measures are appropriate and applicable to the Czech Republic as a whole. In the project an overview was therefore prepared of key adaptation measures that can be considered in the Czech environment. These include:

- measures in the landscape focusing on organisational approaches (promoting widespread diversity within the framework of comprehensive land consolidation, promotion of afforestation and grassing, limiting the cultivation of crops below which an impermeable crust is formed, e.g. maize), agricultural approaches (cropping patterns supporting infiltration) and biotech approaches (contour furrows, drainage ditches etc.);
- measures carried out on watercourses and floodplains focusing on watercourse revitalization (modifications to riverbeds to slow runoff and to improve communication with near-surface aquifers), removing obstructions on floodplains for floodwater flows;
- measures in urban areas focused on improving rainwater infiltration (retention and drainage facilities), collection and use of stormwater;
- renovation of old reservoirs or the establishment of new reservoirs;
- raising the efficiency of water resource management (transfers of water between river basins and water supply systems, reverse transfers of water within basins, temporary use of static groundwater supplies, artificial recharge, multiple use of water, improvement and reallocation of the capacities of water resources);
- reduction of water consumption (minimising losses in water supply systems, rationalising the determination of minimum flows, setting priorities for critical water shortage situations); and
- improved wastewater treatment.

Measures in the landscape are important mainly because they improve the hydrological regime in the landscape and reduce floodwater runoff during flash floods and associated adverse effects (e.g. erosion). On the other hand, however, improved water use in the landscape results in increased evapotranspiration, so that less water is left for precipitation runoff in times of drought. The realistically feasible measures in the landscape have no noticeable importance for increasing flows and groundwater supplies during periods of hydrological drought (especially in view of the size of the areas of land on which it is possible to implement such measures). Similarly, measures on watercourses and floodplains mainly have an impact on reducing runoff during floods. Their importance for improving hydrological conditions during periods of drought is marginal.

In terms of measures to mitigate the impacts of hydrological drought, great potential exists in particular in water management measures of various types, including both measures already known and used (use of reservoirs, water transfers) and measures whose effect, although promising, has not yet been fully quantified (recycling of flows, managed multiple use of water). As regards reducing runoff from urbanised areas, the potential offered by collection and subsequent use of rainwater should not be overlooked. Means for rationalising the use and protection of water resources must also be sought in legislative measures and the reduction of water consumption requirements.

Each of the proposed adaptation measures is applicable, and has an adequate effect, under a different set of conditions. The fundamental limitations on the effectiveness / feasibility of these adaptation measures include, in particular, problems with resolving property relations, restrictions due to natural conditions (e.g. precipitation-runoff conditions and also hydrogeological conditions etc.), unsuitable channel morphology, and the size of the area on which it is possible to implement such adaptation measures. Selection of measures can be guided by a general assessment of the effectiveness and the limits of the individual measures which are described in detail in the final report. It is difficult to further generalise because of the uniqueness of each particular solution. Similarly, it is not possible to generally quantify the financial costs of the individual measures or their combinations, and each proposed adaptation measure must be assessed independently.

Hypothetically, it would be possible to identify appropriate adaptation measures for given areas on the basis of the regional diversification of anticipated impacts of climate change. In a standard risk analysis, the risk is the product of the likelihood of an adverse event (e.g. flood, hydrological drought) and the level of vulnerability. In terms of the projections of climate models it is not possible to regionally determine areas with a greater likelihood of an increased level of intensity or frequency of extreme precipitation events or flash floods.

In the case of hydrological drought the situation is similar, but the climate model simulations suggest that decreases in runoff will be greater and more likely in the southern part of the Czech Republic, in Bohemia rather than Moravia. If the current trend of warming and stagnation of precipitation in central Bohemia continues, the problems with water shortages can be expected to worsen and spread in this area in the near term. On the other hand, hydrological drought is an event with a wide range of effect, and in the case of severe drought a significant part of the Czech Republic is likely to be affected. For future periods also, therefore, the risks are largely determined more by the vulnerabilities of the individual basins than by the increasing likelihood of adverse events. (Although nevertheless, both in the case of flooding and, in particular, in the case of hydrological drought, these likelihoods increase in the future). This also relates to the selection of adaptation measures.

Making a general estimate of the costs of adaptation measures in the water sector (albeit only approximate) is very complex, and as a rule every problem requires a specific study addressing the particular conditions in the given area with consideration to the primary purpose of the adaptation measures assessed. In terms of the direct costs, the most effective measures are generally those aimed at optimising the management of water resources, which do not necessarily require huge investments. In simple terms, however, it can be said that the costs of measures are to some degree at least roughly proportional to their effectiveness and scope. The most expensive (and most effective) measures thus include the construction of new reservoirs and other large-scale water infrastructure, and therefore it is always vital to clearly define the purpose and priorities of the particular measures, and then subsequently to consider their potential and affordability.

## Impacts of climate change on extreme hydrological events

The increased incidence of flooding and increased flood risk (and similarly the increased frequency of low flows) are commonly anticipated consequences of predicted climate change. In the case of floods in particular, however, existing studies have not yet been able to provide a clear and methodologically correctly derived conclusion as to whether the level of flood risk and the flood regime will change in Central Europe.

The objective of this part of the project was to model the potential impacts of the changed climatic conditions predicted by the models in terms of changes in the flood regime, as well as to determine the effect of anticipated climate change on low flows. For this purpose not only was an analysis performed of simulated runoff series in the changed conditions, but a statistical assessment was also carried out of long-term observed series in order to identify whether the current air temperature increase during the second half of the 20th century was reflected in the measured flow data. The final objective was to perform an analysis of the existing experimental base in the Jizerské hory Mts. and to modify it for the purpose of measuring elements of the hydrological cycle in order to identify possible impacts of climate change.

### *Trends of selected flow characteristics*

For 150 hydrometric stations, trends were computed for selected flow characteristics (average and minimum flows) for the period 1961-2005. An analysis was made of series of daily average flows observed mainly at stations where flows are not significantly affected by reservoir operation. An evaluation was made of M-day discharges determined from series of daily average flows and from series of daily flows smoothed using 7-day moving averages. To make a more detailed analysis of the trends of minimum flows, use was made of selected discharges $Q_{330d}$, $Q_{355d}$ and $Q_{364d}$, whose values computed by both procedures were compared against each other. For selected profiles an evaluation was also made of the size and duration of deficit volumes below the level of $Q_{330d}$. Trends were evaluated from the perspectives both of the entire year and individual calendar months. The results showed that although there are no significant changes in average annual runoff, some changes are observed in average monthly flows. A statistically significant increasing trend can be seen in January, February and March, and, conversely, a statistically significant decreasing trend in the months of May and June. In the case of minimum flow characteristics and deficit volumes, however, significant trends were identified only in exceptional cases.

### *Simulation of flow characteristics for the evaluated periods*

Simulations of future flow series (for the basins of the rivers Orlice, Výrovka, Jizera, the upper Vltava, Otava, Smědá and Bečva, all cross-sectional periods and the emission scenarios IPCC SRES A1B, A2 and B1) were carried out on the basis of selected climate scenarios of the best performing climate models (MIROC3_2_M; MPI_ECHAM5; UKMO_HADCM3; ALADIN-CLIMATE/CZ) and the median of an ensemble of the eight most successful global climate models assessed. Modelling of hydrological responses to driving climate variables was carried out using the hydrological modelling system AQUALOG. For the purposes of the simulations, the parameters of the individual models were adjusted in order to achieve a good match between simulated and observed runoff in the calibration and verification period 2000-2008 and the most accurate representation of the hydrological balance, including the rate of evapotranspiration.

Simulations were then performed with a computational increment of 6 hours or 1 day for a period of one thousand years. These simulated 1000-year series of average daily flows were used to perform an analysis of minimum flows based on the exceedance curve of M-day discharges ($Q_a$, $Q_{330d}$, $Q_{355d}$ and $Q_{364d}$) and minimum seven-day discharges, and together with the 6-hour-increment simulation to perform an analysis of the changes in empirical curves of return periods of flood flows.

***Use of the results of the model simulations***

From the analysis of the results of the model simulations it is clear that there is significant variation, and therefore also uncertainty, in the characteristics of the series of the modelled average and minimum flows. Nevertheless, a predominant signal can be seen pointing towards decline (except in the case of the scenarios based on MIROC3_2_M, which predict an increase in precipitation in summer and thus also in minimum flows). For the 2010-2039 outlook, the results show relatively small changes in the discharges $Q_a$, $Q_{330d}$, $Q_{355d}$ and $Q_{364d}$, namely by up to -5 %. In the following period (2040-2069), however, discharges already show more significant decreases. The average value of the decrease in the discharge $Q_a$ is approximately -5 %. For $Q_{355d}$ it is about -13 %. For the 2070-2099 outlook, even greater decreases in flows were found. The average value of the decrease in the discharge $Q_a$ is approximately -13 %. For $Q_{355d}$ it is around -23 %. If we compare the behaviour of the average values of the relative changes in the minimum discharges $Q_{330d}$, $Q_{355d}$ and $Q_{364d}$, we find that at the majority of stations during the studied periods the most significant decreases occur in relation to the minimum discharge $Q_{364d}$.

In the case of the evaluation of minimum seven-day discharges (both averages and 100-year seven-day minima $Q_{100min7d}$), in the 2010-2039 outlook the averages hardly differ and the $Q_{100min7d}$ values fall by 2 % compared to the reference period for all the evaluated stations and alternative models. For 2040-2069 the average falls by 8 % and $Q_{100min7d}$ by 11 %, and for 2070-2099 the average falls by 15 % and $Q_{100min7d}$ by 18 %. In the case of the evaluation of minimum discharges based on the exceedance curve of M-day discharges and minimum seven-day discharges, on average decreases in discharges result for all the evaluated stations and alternative models, which become more pronounced as time goes on.

The results show that the predicted response of the flood regime to changing climatic conditions varies considerably depending on the driving climate scenario. While scenarios based on the MPI_ECHAM5 model generally gave reductions in flood flows for all the studied time periods, scenarios based on the MIROC3_2_M model, on the other hand, mostly predicted a significant increase in flood risk. Meanwhile, it appears that a major influence on the simulated flood regime, particularly in the case of longer return periods for flows, comes from the predicted level of precipitation in the summer.

The simulation for the reference period is close to the median in terms of the variance of the ensemble of all the simulations performed. It is therefore not possible to identify a clear trend. However, most of the simulations - especially for the A1B scenario - tend to show a decrease in the floods magnitude for more distant time periods, while for the nearest simulated period the signals obtained are ambiguous, with both increases and decreases in flood peaks appearing in the evaluated profiles. Only in the case of emission scenario A2 does increase predominate as time goes on into the future. Compared to the reference scenario, the simulated differences are mostly relatively small (with an average change of ± 5 %). The ambiguity in the trend is due to the antagonistic influence of precipitation (less frequent but more extreme) and the lower average initial soil saturation (as a result of greater potential evapotranspiration and a longer period of drought episodes during the summer half-year).

***Level of confidence of estimates of the impacts of climate change on extreme hydrological events***

In view of the results of research for the short term outlook, where the resultant decreases in flows compared with the reference period are relatively small, we do not propose any special measures during the provision of long-term average and M-day flows.

Since no clear and robust trend was shown in changes in flood peaks in the future period of the 21st century, it can be assumed that the potential impact of climate change on the flood regime in Central Europe will not entail major changes in the size of design flows. As regards adaptation measures, therefore, a probable appropriate measure may, for example, be to reduce the level of confidence for the data (rather than changing them) during the derivation of design flows incorporating the potential impact of climate change.

## Impacts of climate change and proposed adaptation measures in agriculture

Crop yields are significantly limited by natural conditions. In interaction with soil and agrotechnical factors, weather is the main cause of the interannual variability of their amount. In exceptional cases, there are impacts of extreme events. In the case of temperatures these largely involve occurrences of minimum air temperatures, especially black frosts. In the case of precipitation, these involve occurrences of drought, and major damage is also caused by floods. This “year” effect acts on different crops and their varieties in differing ways, and is further modified by phytopathological influences. It is extremely difficult to define and interpret the influence of meteorological variables on yields in operating conditions. This does not only involve the direct impact of climate on crops, but also the influence of other conditions, such as the incidence of diseases and pests, the use of environmentally sound technologies etc.

***Impacts of climate change on agroclimatological conditions***

Increasing average air temperatures extend the growing season. It is predicted that in the long-term outlook the average length of the major growing season in the Czech Republic will be 41 days longer than in the reference period. In the short term (and at elevations ranging from 300 to 400 m) the length of the growing season will be 234 days, and in the medium term 246 days. The predicted precipitation for each of the cross-sectional time periods shows greater variability. The number of days in each period without precipitation will increase.

Higher air and soil temperatures will result in a whole complex of influences on agroclimatological conditions. The temperature cycle determines the development of crops, and thus also the timing of most agrotechnical operations. An increase in temperature brings both new opportunities and risks for certain groups of crops. Higher temperatures result in the faster development of crops, which also affects the organisation of work (e.g. the sowing of rape is limited by the timely harvesting of the preceding crop). At the same time certain risks also appear, such as shorter growth periods, the premature development of winter crops in autumn along with a higher risk of diseases (viral diseases), the insufficient development of cold resistance in winter crops and damage by episodes of cold air incursion in the winter and the spring. Potential problems with pollen fertility, the effects of high temperatures on seed development and the different dynamics of disease, pest and weed development can also be considered significant. The predicted increase in temperature variability is a decidedly adverse effect for farming, as agricultural engineering, planning and the organisation of work on farms will have to be adapted accordingly. Operational management based on local conditions, yearly conditions and weather forecasts will have to be more flexible, with technical reserves to cope with agrotechnical operations in short periods of time. Advantages will include the expanded cultivation of new species of thermophilic crops, vegetables and fruit trees, as well as improved conditions for year-round grazing.

In winter, the soil freezing depth will decrease from 20 cm in the reference period to 15 cm in the middle of the 21st century, and in the long term outlook the zero degree thermoisopleth should not even appear in the warmest areas. With increasing temperature the beginning of the major growing season will move back one month (from March 31 to March 1), and there will be an extension of the end of the main growing season by approximately 10 days (from October 30 to November 10). The length of growing seasons and their geographic distribution is an indicator for the delimitation of crops and various agricultural activities. The regionalisation of crops, varieties and agricultural technologies (tillage systems) is based on productive sectors and climatic regions, and will have to be updated more frequently. The length of the growing season, along with other indicators, can be used to determine which types of heat-demanding crops it will prospectively be possible to cultivate in the Czech Republic in the future. A longer growing season also suggests the possibility of growing even two crops each year. However, this potential may be significantly limited by the amount of available water.

Precipitation is essentially the only real source of water for agriculture. Its amount in the near future should be marginally higher, and in the more distant future roughly comparable to the amount of precipitation in the reference period. In the case of precipitation we can expect to see a significantly greater level of variability in the future than for air temperature. For this reason, it is entirely justifiable to predict an increase in the length of periods without precipitation.

Agricultural soil moisture conditions will correspond to the difference between precipitation and evapotranspiration. The climate change scenario thus signals that there will continue to be a decrease in the amount of water in the soil, reducing its moisture content so that at the peak of summer the water deficit in the soil may even be critical. It can also be expected that in the early autumn, i.e. at the time of sowing winter crop varieties, the soil is likely to be significantly drier than in the reference period. A clear deterioration in the conditions for cultivating agricultural crops can be expected in the second half of our century.

In the lower altitudinal belts, the conditions for agricultural production will generally worsen in view of drought. A positive effect may come from the earlier onset of the growing season, as following winter the soil will still tend to have a relatively good water content. However, at the peak of summer, the conditions for the cultivation of most crops will be noticeably worse.

***Level of confidence of estimates of the impacts of climate change on agriculture***

Developments in agricultural crop production do not depend only on climatic conditions but also on the evolution of other factors such as the incidence of diseases and pests or resistant weeds, as well as the results of breeding, the development of technological processes, and discoveries in the field of plant physiology. Absolutely certain findings resulting from current studies are that the diversity of cultivated agricultural crops is decreasing, the organic matter content of soil is falling, and soil erosion is increasing.

As regards the mechanism by which various meteorological factors influence growth and yields, uncertainties in estimates arise not only in the prediction of average and summary values, but also their extremes, variability and distribution over the course of the year, or in relation to the critical periods for particular crops. In view of both the direct and the indirect influences of meteorological factors on crops, it is possible to say that the uncertainties in further developments correspond to the uncertainties in predicting future climate. It is highly likely that there will be a shortage of water in the landscape, i.e. also in the soil. Based on the "principle of uniformitarianism", at the end of the century droughts will occur almost every other year. From this perspective, it is therefore clearly necessary to devote attention to measures aimed at increasing the capacity of the landscape to retain water in the soil.

***Options for adaptation to climate change in agriculture***

Findings made in regard to the anticipated development of climate change and its consequences for agriculture in the Czech Republic indicate that appropriate adaptation measures should be aimed at:

- adaptation of agricultural activities;
- application of agrotechnical measures;
- maintaining soil fertility;
- change of cultivation practices;
- optimisation of irrigation systems and setting irrigation doses;
- protection against increased pressure from infectious diseases and pests.

Agricultural activity must be focused cultivating crops so as to ensure that diversity is not lost. It is necessary to promote the simultaneous selection not only of varieties and species of field crops, but also of technical crop species, vegetables and ornamental plants, including breeding them for changed conditions. Agro-technology must be based on the predicted increase in dryness in the Czech climate. It is therefore necessary to select techniques to reduce the loss of soil moisture (e.g. minimising tillage). In view of the decreasing availability of organic fertilisers, maintaining or increasing soil fertility must form the essential basis for adaptation measures, as compensating for the decline in natural soil fertility by means of increased inputs (e.g. energy intensive mineral fertilisers) is economically unsustainable in the long term, and only leads to the destabilisation of the system.

A crucial measure in limiting the risk of wind erosion (erosion primarily affects dried out sandy soils), and thereby reducing the aridisation of the landscape, consists of windbreaks, which, if properly located, provide a significant anti-deflation effect. Adaptation measures focusing on improved water management in areas of vegetation also function as one of the tools for improving the resistance of plants to episodes of high temperatures with subsequent, often very severe, impacts on yield.

Adaptation measures require funding in connection both with their preparation and, in particular, with their practical implementation. In many cases it is difficult to prove that the costs for their implementation will be demonstrably recovered in terms of reducing the amount of damage caused by the negative impacts of climate change.

An example of one attempt may be seen in the introduction of agrometeorological models forecasting the incidence of pests, and the subsequent timely use of spraying techniques. Approximate calculations (and feedback from farms) indicate that the return on the use of agrometeorological models is sufficiently high. Similarly, it is possible to make a rough estimate of the costs of fertiliser, which are entirely ineffective in the case of the occurrence of summer drought.

## Impacts of climate change and proposed adaptation measures in forestry

The outputs from the part focusing on the forestry sector provide a comprehensive methodological procedure for estimating both the current and the future environmental risks of disrupting existing forest ecosystems with a predominance of spruce. They also focus on estimating their probable future development, evaluating changes in the value of forest ecosystem services as a consequence of their disruption, and proposing structured adaptation measures to increase the adaptation potential of forests, including an estimate of their financial cost. The methods used are applicable at various spatial scales - ranging from the whole country, through individual natural forest areas, to individual forest districts (and even at the level of stands or specific groups of trees).

### *Estimation of the environmental risks of disrupting the development of existing forest ecosystems*

In the process of making an estimate of the environmental risks of disrupting the development of existing forest ecosystems with a predominance of spruce for a selected climate development scenario, including an estimate of their probable future development, the main emphasis was placed on making an estimate of the development of climate stressors through to the end of the 21st century. Spatial averages of basic climatic characteristics (average daily temperature, daily precipitation, average daily wind speed, humidity and solar radiation) were calculated for all forest vegetation zones occurring in areas of natural forest. The degree of occurrence of three climate extremes was then found - the number of days with daily precipitation of less than 1 mm which occurred in periods of longer than 10 consecutive days in the growing season, the number of days in the growing season when the average daily temperature was above 30 °C, and the number of temperature reversals in the early spring (periods in the winter when the average daily temperature was above 5 °C for at least 5 consecutive days and then fell below freezing again).

The analyses carried out indicate that a significant decrease will occur in the area of land with suitable conditions for growing Norway spruce - in the short term outlook to 67.2 %, in the medium term to about a half, and in the long term to only a third of the current area.

This can be seen in the declining state of health of stands of predominantly Norway spruce in these areas.

***Evaluation of the current state of forest stands and estimation of their probable further development***

This part of the report focuses on an evaluation of tree species, in particular as regards the adaptation potential of forest stands, the risks posed by fungal pathogens and destructive insects etc. The synergistic effects of extreme climatic fluctuations, the long-term natural acidification of the soil and anthropogenic impacts - especially the impacts of ambient air quality and economic activities - will decrease the vitality of forest stands. In the decline of spruce, abiotic or initiating stressors have an absolutely fundamental level of importance. One of the most important abiotic stressors is drought, especially in spring and early spring. Short periods of drought in the summer are a significant factor predisposing trees to the development of root rot. A significant risk in the case of spruce is the combination of abiotic stressors in the form of periods of summer drought and high temperatures combined with high humidity, which can act as a mortality stressor by causing the overheating of tissues. Climatic extremes in winter are a risk for spruce primarily in terms of the disruption of dormancy by relatively warm periods followed by a sudden drop in temperatures below freezing. Biotic factors are involved mainly as initiating stressors (e.g. sucking and leaf-eating insects). In combination with the effects of abiotic predisposing stressors they may act as mortality stressors. In the case of the combined effect of the European spruce bark beetle and the wind, windthrow can provide suitable conditions to trigger an outbreak, threatening the surrounding forest.

The results of an analysis performed for the entire Czech Republic show that in the short term outlook there should not be any shift in forest vegetation zones. On the contrary, the values of stressors are in some cases surprisingly lower than in the period 1991-2009. In the medium and long term, on the basis of the analyses performed it is even possible to foresee a downward shift in forest vegetation zones (generally two zones down).

***Options for adaptation to climate change in forestry***

The impacts of climate change on forest ecosystems are, and will be, very regionally variable. Therefore adaptation measures must be the result of long-term planning at the level of individual forest areas. Decisions whether or not to implement measures must be made for specific forest stands of a particular quality, and according to local predictions of potential risks.

In the Czech environment, relevant adaptation measures should be directed primarily at

- increasing the adaptation potential of forests;
- a shift from the clearcutting method of management to shelterwood cutting; and
- changing the species composition of forest stands.

Increasing the adaptation potential of forests by means of the species, genetic and age diversification of trees can be considered to be the most important measure overall. Although the shelterwood method of silvicultural management, which creates favourable conditions for the cultivation of richly structured forests, entails higher extraction costs, the regeneration costs will be lower and the overall production of the forest higher. The most dramatic measure is the forced change of the species composition of forest stands - i.e. of those which are not withstanding climate change in their respective habitats. This would mainly involve the premature clearing of stands of conifers, especially spruce, and replacement of these stands with a mixture of trees of higher stability, i.e. with a proportion of stabilising and amelioration trees in spruce stands of greater than 50 %.

The adaptation measures themselves should be carried out in two parallel steps. The first of these has a markedly preventive nature, as it is necessary to more or less immediately begin making a change towards the target species compositions of forest stands or represented groups of forest types in the various forest management categories. Since, according to analyses performed, about half of the rotation period remains until the start of the 2070-2099 period, there is still relatively sufficient time to undertake a timely response to the change in climatic conditions.

The second step consists of measures of a rehabilitation nature in individual forest management categories, forest vegetation zones or in the structures of individual forest stand types. In the forest vegetation zones at risk, spruce forests are already endangered, and therefore their progressive rehabilitation must be commenced as soon as possible. This step would result in a significant reduction in the area covered by the highest risk monocultures.

## Development of basic climate indicators in the period 1961-2010

Air temperature and precipitation are two basic climatological characteristics which are among the most important indicators of the development of regional climate and its changes. The development of these basic indicators in the Czech Republic over the last fifty years was evaluated mainly on the basis of an analysis of series of “local temperatures” and precipitation, which represent their characteristic values, taking into account the results of measurements from our entire network of stations (with temperature converted to median elevation). In order to estimate the variability of the indicators and their changes, daily temperature / precipitation series were used from 30 stations in the Czech Republic from the period 1961-2010.

Supplementary information is provided in the form of data obtained by processing a series of measurements of average monthly and annual air temperatures and precipitation levels taken at the Prague-Klementinum station, which has at its disposal the longest series of observations in the Czech Republic (in the case of temperature dating from 1775, and for precipitation from 1805) and one of the longest series in Europe. With certain limitations (the station is located in a built-up urban area), these can also be used for the purpose of a general description of the long term evolution of the climate in the Czech Republic.

***Temperature regime***

- average annual temperature shows a long-term upward trend, which has been increasing over the last few decades;
- average annual local temperatures have been subject to significant interannual changes over the last 50 years; nonetheless, they show an increasing trend (of just under 0.3 °C/10 years); temperatures increase more markedly in the summer (0.4 °C/10 years), and more slowly in the autumn (less than 0.1 °C/10 years);

- in the last two decades the average annual temperature increased by 0.8 °C compared to the reference period; larger changes were observed in the summer months, smaller ones in the autumn; in the summer temperature is increasing slightly faster in Moravia, in the winter and spring in Bohemia, but the differences are minimal;
- in parallel with the gradual increase in temperature and the increasing temperature extremes over the last two decades, an increase has also occurred in the average number of days with high temperatures (summer and tropical days, tropical nights and days with maximum daily temperatures above 35 °C) and a reduction has occurred in the average number of days with low temperatures (frost, ice and arctic days); in this area the differences between Bohemia and Moravia are not significant;
- the temporal variability of average daily temperatures shows a clear annual cycle (higher in winter, lower in summer), increasing in the cool half and decreasing in the warm half of the year, while the differences in the changes in Bohemia and Moravia are not significant;
- the spatial variability of the temporal variability of average daily temperatures and their changes does not change significantly during the year.

**Precipitation regime**

- average annual precipitation shows very marked interannual variability in the last fifty years (2002 had the highest precipitation, the subsequent year 2003 the lowest), with a very slightly increasing trend;
- in the last two decades, average annual precipitation increased by approximately 5 % compared to the reference period;
- the main features of the annual cycle of precipitation remain unchanged (maximum in summer and minimum in winter); however there is a redistribution of monthly precipitation over the year (a drop in the period from April to June, an increase from July to September). The differences between Bohemia and Moravia are not significant;
- the warm period of the year is noticeably more susceptible to greater changes in the precipitation regime than the cold period, and the most significant changes in both directions take place at the turning point between the summer and the autumn, and respectively between the winter and the spring; however, Moravia generally shows a greater tendency towards changes leading to higher precipitation than Bohemia;
- the number of days with snow cover of 1 cm or more varies considerably interannually both at lower and at higher elevations; however, in the last fifty years their number has been falling, especially in connection with the increase of average temperature;
- the temporal variability of average daily precipitation shows an even more marked annual cycle than the variability of average daily temperatures (higher in summer and lower in winter); however, in general it is higher in Moravia;
- in the last two decades, the temporal variability of average daily precipitation in the warm half of the year has increased, and in the cold half of the year decreased; the regime of the changes is considerably more pronounced in Bohemia, while in Moravia the changes are more balanced;
- the spatial variability of the temporal variability of precipitation is markedly higher than that of temperature, which is the main cause of the statistically insignificant

differences in the findings for the average numbers of days with daily precipitation exceeding the specified limits at individual stations; however no particularly significant differences in spatial variability between Bohemia and Moravia can be seen.