Predictive water table modelling in the NAGiS project

Research Study

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1 INTRODUCTION

This report describes the methodology utilized in the NAGiS project for the simulation of groundwater table. The aim of water table modelling was to develop a toolset which can be used for calculation of the water table for various climate conditions. This was done with the goal of facilitating the assessment of climate impact and sensitivity of shallow groundwater resources. This report summarizes the methodology and results of predictive groundwater modelling. Model calibration and natural state modelling are described in another project report. The present study includes essential information on modelling methodology and datasets, and thus can be read as a standalone report.

The present study utilizes the datasets available at the time of the preparation of this work. Model results reflect the inaccuracies and data gaps present in the input databases. The methodology developed within the frameworks of this study makes the recalculation of output products possible making use of updated or completed datasets. The presented outputs are representative of groundwater conditions at the regional scale, and thus cannot be used for local-scale investigations. In order to increase the accuracy of the results, the resolution of the input datasets and applied models need to be increased. The introduced methodology is valid for modelling purposes at various scales and thus represents a versatile tool for the assessment of climate sensitivity of shallow groundwater bodies.

2 METHODOLOGY

A dynamic modular approach was developed in order to quantitatively simulate the groundwater table under various climate conditions:

1. A toolset was developed to calculate climate zonation from climate parameter grids;
2. Recharge zones (Hydrological Response Units, HRU's) were delineated based on geology, land-use and slope conditions;
3. Recharge was calculated for various climate conditions for each recharge zone using 1D analytical hydrological models;
4. Groundwater table was calculated under various climate conditions using numerical groundwater flow models.

The advantage of the above methodology is that

- it provides a quantitative link between climate conditions and shallow groundwater conditions;
- each step of the workflow is replicable and provides coherent results for various climate conditions;
- modular structure provides flexibility and facilitates changes in input data, calculation tools and spatio-temporal resolution at various levels.

The climate data source applied in our calculation comprised interpolated daily climate data of the Central European CarpatClim-Hu database and the results of the ALADIN climate models. Climate zones were determined making use of the THORNTWAITE (1948) climate zonation scheme. Recharge zones (HRU's) were determined based on surface geology, land-use and slope conditions. The HELP hydrological model was used for the calculation of 1D water balance for hydrological response units. The Modflow numerical groundwater modelling code was used for the calculation of the water table under various climate conditions.

The following chapters describe the dataset applied, the calculation tools developed, and the methodology applied throughout the study. Within the frameworks of the NAGiS project groundwater conditions were determined for several time periods representing various climate conditions. Besides the description of the applied methodology, the present report summarises the results of predictive groundwater modelling. Average groundwater table distributions were calculated for the following time periods:

1. 1961–1965
2. 2005–2009
3. 1961–1990

4. 2021–2050
5. 2071–2100

While the simulation of past conditions was undertaken based on measured climate parameter inputs, prediction of future groundwater conditions was undertaken making use of the ALADIN climate model outputs supplied by the National Meteorological Survey (ILLY et al. 2015). Any inaccuracies and uncertainties included in climate model outputs are inherited by the groundwater models and thus increase model uncertainty.

Within this study it was assumed that the 1961–1965 averaged groundwater conditions represent natural state of the shallow groundwater system, without any significant influence from mining or water extraction operations. This time period served as a reference condition, for which model parameters were calibrated against observed groundwater levels. Each predictive simulation was undertaken making use of the initial calibrated parameter set.

3 CLIMATE DATA

3.1 DATABASE

Throughout this study, the CarpatClim-Hu (LAKATOS et al. 2013a) database was applied as a source of the main input parameters. CarpatClim-Hu is a homogenized raster dataset interpolated from climate observations within the Pannonian Basin (JRC 2010).

The dataset was derived from weather observations at 258 climate stations and 727 precipitation stations. In Hungary 37 climatological and 176 precipitation stations were applied (SPINONI 2013). The CarpatClim-Hu project area included 9 countries (Czech Republic, Slovakia, Poland, Ukraine, Romania, Serbia, Croatia, Austria and Hungary).

The database includes 0,1° (about 10×10 km) resolution homogenized and gridded datasets for basic meteorological variables and several climate indicators on different time scales (daily, monthly, yearly) from 1961 to 2010 (KOVÁCS et al. 2013).

Table 1. shows the list of variables analysed by the CarpatClim-Hu project. These include the meteorological parameters required by the weather generator of HELP model to be applied within the frameworks of the NAGiS project.

Meteorological data (daily temperature and precipitation, global radiation, data for evapo-transpiration input, average wind speed, relative humidity) of the CarpatClim-Hu project, generated for each HRU polygon, were used as initial input parameters for hydrological models (HELP) in our calculations.

Table 1. List of CARPATCLIM-HU variables

No.	Indicator Acronym	Description	Frequency
1.	TA	Average mean air temperature	Daily/Monthly/Yearly
2.	TMIN	Average minimum air temperature	Daily/Monthly/Yearly
3.	TMAX	Average maximum air temperature	Daily/Monthly/ Yearly
4.	PREC	Accumulated total precipitation	Daily/Monthly/ Yearly
5.	WS10	Average 10m horizontal wind speed	Daily/Monthly
6.	WS2	Average 2m horizontal wind speed	Daily/Monthly
7.	WD10	10m wind direction	Daily
8.	WMAX10	Maximum 10m horizontal wind speed	Daily
9.	SUN	Sunshine duration	Daily/Monthly/Yearly
10.	CC	Average cloud cover	Daily/Monthly
11.	RG	Global radiation	Daily/Monthly
12.	RH	Average relative humidity	Daily/Monthly
13.	PV	Mean vapour pressure	Daily/Monthly
14.	PA	Mean surface air pressure	Daily/Monthly

The distribution of main climate variables for the investigation periods are indicated in Figure 1 to Figure10 of the Appendix.

3.2 CLIMATE CHANGE

The distributions of average climate variables were calculated for each simulation period. These data served for climate zonation and for the calculation of recharge. Changes in climate parameter distributions are responsible for the changes in recharge distribution and the subsequent modification of the quasi equilibrium groundwater table. Sensitivity of hydrogeological units is proportional to the response (water table change) given to the change in climate parameters.

The changes in primary climate variables such as rainfall and temperature are indicated in Appendix (Figure 11 to Figure 18).

The changes in parameter distributions over the 45 years preceding 2009 indicate a significant rainfall drop in the western parts of the country by up to 100 mm/year and a rainfall increase in the eastern parts by up to 100 mm/year. According to 5 year average data, the temperature increased by up to 1.8 °C in the central parts of the country during this period.

According to the ALADIN climate model simulations, rainfall is predicted to drop by 50–100 mm/year for the majority of the country between the thirty–year averages of 1961–1990 and 2071–2100. Similarly, climate models indicate a temperature increase of up to 3.5 °C for the majority of the country.

Although climate model simulations are affected by significant uncertainties, both past and future conditions indicate dropping rainfall and rising temperature trends for the majority of the country. This trend, together with the predicted decrease in the number of humid days and the increased intensity of rainfall events suggests the overall decrease in recharge and thus falling groundwater levels for most of the country. A detailed qualitative analysis of groundwater level changes is provided in the following chapters.

4 CLIMATE ZONATION

Zonation (discretization) of spatially and temporally distributed climate data was necessary, as one-dimensional modelling tools were applied to calculate soil water balance necessary for the assessment of groundwater conditions.

Climate zones separate geographic areas with different climate characteristics. These zones were analysed separately in the course of hydrological modelling. Out of the internationally accepted biophysical climate classification methods, the Thornthwaite climate classification was chosen for the purpose of the NAGiS project.

The methodology described in ÁCS, BREUER (2013) was applied for the calculation of Thorntwaite climate zonation. A detailed description of the calculation scheme applied in the NAGIS project is provided in KOVÁCS et al. (2015).

Climate zones were determined for the following time periods using average monthly values of climate parameters:

1. 1961–1990
2. 1981–2010
3. 1961–1990
4. 2021–2050
5. 2071–2100

The calculation was undertaken on averaged parameter grids on a cell-by-cell basis. Resulting Thorntwaite grids were converted to polygons for further data processing and visualisation.

Recharge values were calculated for each time period by applying the corresponding Thorntwaite zonation. The climate zonation calculated from the CarpatClim-Hu and ALADIN databases are indicated in Appendix (Figure 19 to Figure 23).

5 RECHARGE ZONATION

Recharge zones used in this study are hydrogeological units, in which recharge conditions are assumed to show an insignificant variability. Recharge zones are also called Hydrological Response Units according to the SWAT modelling methodology (NEITSCH et al. 2002).

Recharge zones were delineated as a superposition of four data layers including:

- surface geology,
- land-use,
- slope,
- climate.

The surface geological map constructed by the MFGI was applied in the first data layer (see later Figure 24).

Geological formations were reclassified into six lithological categories as follows:

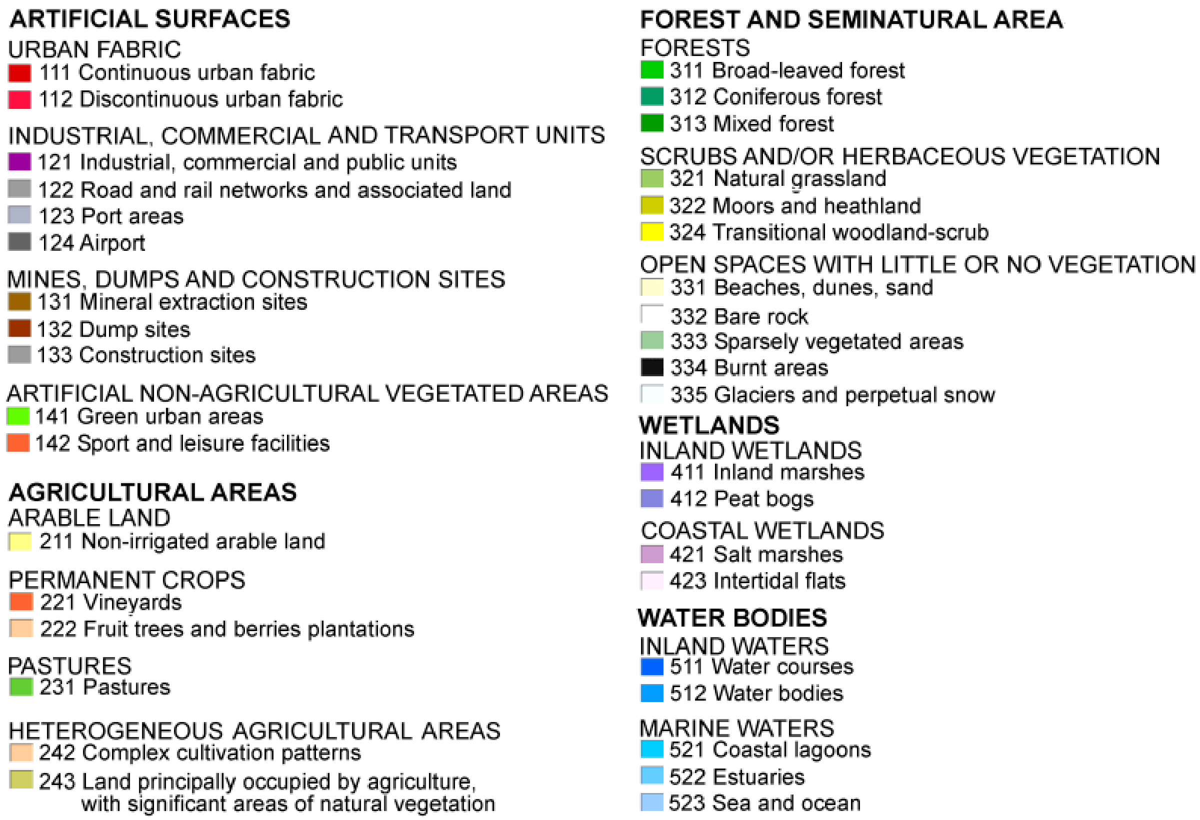
- Fractured (10).
- Dolomite (20).
- Limestone (30).
- Fine porous sediments (40).
- Coarse porous sediments (50).
- Surface waters (60).

A two-digit identifier was assigned to each lithology group as indicated above.

Land-use polygons were derived from the CORINE (EEA 2006) map. The large number of original Corine land-use categories was regrouped into six main classes as follows:

- 111, 112, 121, 122, 123, 124, 131, 132, 133, 141, 142, 331, 332 → Urban areas (1).
- 211, 212, 241 → Arable land (2).
- 231, 321, 333, 334 → Pastures (3).
- 221, 222, 242, 243, 244 → Permanent crops (4).
- 311, 312, 313, 322, 324 → Forest (5).
- 213, 411, 412, 421, 422, 423, 511, 512, 521, 522, 523 → Water bodies (6).

The description of the original CORINE land cover categories is provided in Chart 1.



ARTIFICIAL SURFACES
URBAN FABRIC
111 Continuous urban fabric
112 Discontinuous urban fabric

INDUSTRIAL, COMMERCIAL AND TRANSPORT UNITS
121 Industrial, commercial and public units
122 Road and rail networks and associated land
123 Port areas
124 Airport

MINES, DUMPS AND CONSTRUCTION SITES
131 Mineral extraction sites
132 Dump sites
133 Construction sites

ARTIFICIAL NON-AGRICULTURAL VEGETATED AREAS
141 Green urban areas
142 Sport and leisure facilities

AGRICULTURAL AREAS
ARABLE LAND
211 Non-irrigated arable land

PERMANENT CROPS
221 Vineyards
222 Fruit trees and berries plantations

PASTURES
231 Pastures

HETEROGENEOUS AGRICULTURAL AREAS
242 Complex cultivation patterns
243 Land principally occupied by agriculture, with significant areas of natural vegetation

FOREST AND SEMINATURAL AREA
FORESTS
311 Broad-leaved forest
312 Coniferous forest
313 Mixed forest

SCRUBS AND/OR HERBACEOUS VEGETATION
321 Natural grassland
322 Moors and heathland
324 Transitional woodland-scrub

OPEN SPACES WITH LITTLE OR NO VEGETATION
331 Beaches, dunes, sand
332 Bare rock
333 Sparsely vegetated areas
334 Burnt areas
335 Glaciers and perpetual snow

WETLANDS
INLAND WETLANDS
411 Inland marshes
412 Peat bogs

COASTAL WETLANDS
421 Salt marshes
423 Intertidal flats

WATER BODIES
INLAND WATERS
511 Water courses
512 Water bodies

MARINE WATERS
521 Coastal lagoons
522 Estuaries
523 Sea and ocean

Chart 1. Description of Corine landuse categories (EEA 2006).

The landuse category map applied in the NAGIS project is indicated in Appendix (Figure 25).

Slope categories were determined based on the 50 m resolution Digital Elevation Model of Hungary (HM Zrinyi 2014). Two slope categories were applied as follows:

- 0 – 4,99% → Plain (100).
- > 5% → Slope (200)

The resulting map of slope zones is indicated in Appendix (Figure 26).

Climate zones were determined as described in Chapter 4.

The resulting map of recharge zones is indicated in Appendix (Figure 27). Recharge zone types are indicated by four-digit numbers, where the first digit indicates climate zonation, second digit indicates slope category, the third digit indicates geology, and last digit indicates land-use.

6 RECHARGE CALCULATION

The potential effects of climate change on water budgets and groundwater levels can be approximated with infiltration rate calculations for recharge (hydrological response) units. The HELP model (SCHROEDER et al. 1994) was applied to calculate a water balance for recharge zones (or HRU's) defined in the framework of the NAGiS project as the applicability of this model is well known from the literature (GOGOLEV 2002, JYRKAMA, SYKES 2007) and the methodology has successfully been applied in the country. The outcomes (the generated precipitation infiltration values) of the HELP hydrological model can also be directly imported into the widely applied and accepted Modflow groundwater modelling package, which was used in the NAGiS project to simulate groundwater levels.

HELP (Hydrologic Evaluation of Landfill Performance) is a hydrologic numerical model developed by the United States Environmental Protection Agency for landfills. The model uses a water-balance approach to model evapotranspiration and drainage through soil layers. The model is often used for simulating the effects of various climate scenarios.

The weather generator of the HELP model needs several meteorological variables, such as daily and monthly average mean temperature, daily and monthly accumulated total precipitation, monthly average horizontal wind speed, daily global radiation and monthly relative humidity.

The daily and monthly data were extracted from the CarpatClim-Hu dataset for the Thorntwaite climate polygons, and average polygon values were calculated.

Within the frameworks of the NAGiS project computer codes were developed for the purpose of all data extraction and file conversion calculations. These codes can be applied in the future for the creation of HELP input files from any meteorological data grids.

Besides meteorological input, the HELP code requires the definition of soil profiles for which the 1D transient water balances is calculated. Soil profiles were defined by analyzing grain size distributions of soil samples collected from various geological environments. Grain size data was obtained from the soil logging database of the country. A characteristic soil profile was assigned to each lithological category. As the uppermost three meters of observed soil profiles show negligible vertical variability, homogeneous soil profiles were applied. The applicability of homogeneous profiles was verified through sensitivity analysis.

Simulated percolation rates (recharge) were verified against literature values and were also compared with monitoring well hydrographs. Default soil parameters were fine-tuned through calibration against observed water level fluctuations. Calibrated soil parameters for each profile type are indicated in Table 2.

The effects of land-cover and slope were simulated using a range of runoff curve numbers. Applied curve numbers are indicated in Table 3.

Table 2. Adjusted hydraulic parameters applied for different soil types throughout the HELP simulation of recharge rates

Parameter	Profile				Unit
	Fine porous (Silty Loam)	Coarse porous (Loamy Sand)	Karst (Sand)	Fractured (Fine Sand)	
Total porosity	0.463	0.43	0.437	0.38	vol/vol
Field capacity	0.232	0.2	0.052	0.2	vol/vol
Wilting point	0.116	0.0825	0.024	0.033	vol/vol
Sat.hydr.conductivity	5	1	501.12	8	cm/day
Subsurface inflow	0	0	0	0	cm/day
Evapotranspiration zone depth	115	125	125	125	cm

Table 3. Adjusted curve numbers applied for different soil types and land-use categories throughout the HELP simulation of recharge rates.

Soil category		Fine porosity	Coarse porosity	Karstic	Fractured
Land-use category		Curve Number			
2	Cultivated	94	94	91	94
3	Pasture	93	93	91	93
4	Orchard	92	92	91	92
5	Forest	91	91	91	91

Recharge rates were simulated using the finalised soil profiles for each recharge zone applying averaged climate parameters for the corresponding climate zones. Climate zonation for each simulation was assigned from the relevant Thorntwaite climate time period. The distributions of averaged recharge for the simulated time periods are indicated in Appendix (Figure 28 to Figure 32).

Differences in recharge between the simulated time periods are indicated in Appendix (Figure 33 to 34).

Simulation results indicate that recharge decreased by up to 50 mm/year between 1961–2009 across mountainous areas such as the Alpokalja area and the Northern Mountain Range.

Recharge calculations undertaken on ALADIN model results indicate decreasing recharge rates by up to 50 mm/y in the mountainous areas such as the Northern and Transdanubian Mountain Range and the Mecsek Mountains for the rest of the century. These models do not predict recharge deficiency in the Alpokalja area.

7 GROUNDWATER MODELLING

7.1 MODELLING GOALS

The primary goal of groundwater modelling undertaken within the frameworks of the NAGiS project was to investigate climate impact on shallow groundwater resources. Climate change entails variations in rainfall and temperature patterns which in turn results in the modification of recharge conditions. Recharge is the primary process influencing the distribution of the water table.

The overall aim of the modelling component of the project was to simulate the water table under various climate conditions. The present report summarizes the results of predictive modelling. The results of natural state modelling together with details on model calibration are summarized in another project report (KOVÁCS et al. 2015).

The natural state model simulated average groundwater conditions for the period 1961–1965. It was assumed that shallow groundwater conditions were determined by climatic conditions during this period and that artificial influences were negligible during this period. The natural state model served for calibrating hydraulic properties against measured water levels. Calibrated parameters were applied for simulation of various climate conditions.

7.2 MODELLING METHODOLODY

Groundwater modelling was preceded by the delineation of recharge zones and the calculation of recharge from climatic parameters. In order to ensure numerical efficiency the model area was subdivided into two model domains (West and East Hungary).

The applied model aimed at the simulation of shallow groundwater conditions. For this reason a one-layered two-dimensional model was applied. In mountain areas of open karst terrain, where shallow aquifers are absent, karst water table was simulated, and it was considered to be hydraulically connected to adjacent shallow groundwater bodies.

The main boundary conditions applied in the model comprised surface streams, water bodies and drainage zones. Artificial influences on the groundwater system such as water extractions were not incorporated in the models. Simulated water tables are thus hypothetical distributions which are intended to demonstrate direct effects of climate impacts rather than predict future groundwater levels.

The model was calibrated against water level monitoring stations, spring elevations and surface water bodies. As the aim of the present study was to develop and demonstrate a methodology for the assessment of climate change impact on shallow groundwater bodies, emphasis was put on testing methodological aspects rather than simulation accuracy. Recharge of predictive model scenarios was calculated from climate model outputs which contain significant inaccuracies. The accuracy of the regional scale simulation can be further improved through the application of more accurate input datasets and finer discretization.

The presented methodology can be applied for groundwater table simulation at various scales.

7.3 APPLIED SOFTWARE

The Modflow numerical groundwater flow model has been used for this study, operating under the Visual Modflow v.4.6 software package (Waterloo Hydrogeologic Inc. 2005). Modflow is widely accepted as the industry-leading numerical groundwater flow model as:

1) Verified against a range of analytical solutions.

2) Successfully used to model a wide range of hydrogeological situations throughout the world, and

3) Developed with a modular structure, with the different modules being continuously improved or added.

The degree of model complexity required to meet the project objectives is an important consideration. In this case, it is considered that a model of moderate complexity is appropriate for the study. This is in part due to the regional scale of the model and the shallow depth of groundwater resources targeted by this study. The result of which is that a conservative approach to the interpretation of the model results must be taken. Model results can only be interpreted and utilized at the intended purpose, scale and accuracy of this study.

7.4 MODEL GEOMETRY

The study area (Hungary) was subdivided into two model domains to ensure numerical efficiency. Both model domains had a rectangular geometry. A uniform cell size of 250 meters was applied.

The applied model comprised a two-dimensional one layered finite difference grid. The coordinates of model extent are summarized in Table 4 and Table5.

Table 4. Model extent. Eastern model domain

Boundary	Easting (EOV)	Northing (EOV)
Western boundary	620000	N/A
Eastern bundary	940000	N/A
Northern boundary	N/A	364000
Southern boundary	N/A	54000

Table 5. Model extent. Western model domain

Boundary	Easting (EOV)	Northing (EOV)
Western boundary	426000	N/A
Eastern bundary	458000	N/A
Northern boundary	N/A	41000
Southern boundary	N/A	304000

7.5 MODEL PARAMETERS

The main model parameter to be adjusted through model calibration was hydraulic transmissivity. Transmissivity is the product of hydraulic conductivity and aquifer thickness. In the case of the present study, where shallow groundwater was simulated, the thickness of simulated shallow aquifers is uncertain, and thus transmissivity is a calibration parameter. Shallow aquifers were regrouped into larger hydrogeological units to facilitate calibration. Transmissivity values were adjusted to obtain an acceptable match between measured and simulated heads.

The objective of the model calibration process was to determine model-scale hydraulic parameters that reproduce the hydraulic functioning of the groundwater system. Model calibration was performed by means of automated calibration using PEST. PEST (WNC, 2005) is a nonlinear parameter estimation code. Parameter optimisation is achieved using the Gauss-Marquardt-Levenberg method to drive the differences between model predictions and corresponding field data to a minimum in a weighted least squares sense. Model calibration was undertaken with the assumption that field measured water levels represent steady state (equilibrium) of the groundwater system.

The hydraulic parameters and boundary conditions determined during steady state calibration were applied for predictive model simulations. The calibrated transmissivity distribution is shown in Appendix (Figure 35).

7.6 MODEL LIMITATIONS

The applied model has the following limitations and thus can be used for the intended purpose of the project only:

- The model simulates steady state. It is assumed, that shallow groundwater levels are in equilibrium with climatic conditions during the simulation period of the model.
- Model calibration was based on observations not distributed equally throughout the model domain. For this reason simulated water level incurs spatially varying uncertainty.

- As the model is two-dimensional it only simulates shallow groundwater levels in equilibrium with recharge. Deep regional groundwater flow or groundwater extractions are not represented in the model.
- The cell size of the model is 250 meters. For this reason the model is not suitable for local-scale investigations. The model can only be used for regional scale studies.
- The primary goal of the modelling was to demonstrate the methodology developed for the simulation of climate impacts, instead of providing a precise water table map. Model results must be assessed and utilized considering the general goals of the study.
- Artificial influences on the groundwater system such as water extractions were not incorporated in the model. Simulated water tables are thus hypothetical distributions which are intended to demonstrate direct effects of climate impact rather than predicting future groundwater levels.
- Outputs of the ALADIN climate model were applied for the calculation of recharge in predictive model scenarios. As no information was available on the uncertainty of ALADIN climate models at the time of the preparation of this work, the accuracy of predictive simulations was unknown. For this reason predictive simulations only serve as demonstration tools for methodological aspects of the project.

7.7 MODEL PREDICTIONS

Shallow groundwater levels were calculated from measured (1961–1965 and 2005–2009) and simulated (1961–1990, 2021–2050, 2071–2100) climate parameter distributions for five-and thirty-year averages.

Simulations of the 1961–1965 and 2005–2009 stress periods were undertaken with recharge distributions calculated from measured CarpatClim-Hu five-year average climate parameter distributions. Simulations of the 1961–1990, 2021–2050 and 2071–2100 stress periods were undertaken with recharge distributions calculated from simulated ALADIN thirty-year average climate parameter distributions.

Simulated average water table distributions are indicated in Appendix (Figure 36) **Hiba! A hivatkozási orrás nem található.**. The simulated unsaturated zone thickness (depth to groundwater) distribution for the calibration period 1961–1965 is indicated in Appendix (Figure 41).

The unsaturated zone thickness map indicates that water table depth is generally within three meters below lowland areas such as the Alföld and Kisalföld areas. Under mountain areas simulated groundwater depths can exceed 100 meters; although these values often correspond to karst water bodies rather than shallow groundwater table which might be perched above deep groundwater levels.

In order to demonstrate the potential effects of climate change on shallow groundwater bodies, water table difference maps were constructed (Appendix: Figure 42 to Figure 45). The 45-year water table change calculated from 1961–1965 and 2005–2009 average water levels indicate significant water level drops under highland areas such as the Alpokalja, Transdanubian and Northern Mountain Ranges. A more subtle water level drop was simulated along foothill areas and the Kisalföld zone.

The water table difference maps calculated from ALADIN climate predictions indicate significant water level drops under the Transdanubian, Mecsek and Northern Mountain Range. No significant water table drop is predicted by these models in the Alpokalja area. In contrast moderate water level drops of up to two meters are indicated in the Kisalföld, Danube–Tisza Interfluve and Tiszántúl areas.

8 CLIMATE SENSITIVITY

The main purpose of the groundwater component of the NAGiS project besides developing and demonstrating a methodology for the quantitative simulation of climate impact on groundwater levels was the evaluation of climate sensitivity of shallow groundwater bodies of Hungary.

This was done through the application of a modular methodology developed for this project described in KOVÁCS et al (2015) and previous sections of this report. The final result of water table modelling was the simulation of water table distributions for various climate conditions.

Shallow groundwater levels are sensitive to changes in recharge conditions which are primarily determined by climatic conditions. Water level change is thus a characteristic indicator of climate sensitivity of shallow groundwater bodies.

Sensitivity was characterized qualitatively based on simulated groundwater level changes. Sensitivity maps based on simulated past and future water level changes are provided in Appendix (Figure 46 and Figure 47). The map in Figure 46 was constructed from water table differences between the 2005–2009 and 1961–1965 simulation periods and is thus based on measured data. The map in Figure 47 was constructed from water table differences between the 2071–2100 and 1961–1990 simulation periods and is based on the ALADIN model outputs.

Areas affected by groundwater level rise and areas with water table drops inferior to 0.5 m were classified as low sensitivity areas. Areas with water level drops between 0.5–5 m were classified as medium sensitivity zones. Areas affected by more than 5 meters of water level drop were classified as high sensitivity areas.

Both sensitivity maps suggest that elevated areas such as the Northern and Transdanubian Mountain Range are highly sensitive to climate change and foothill areas of these mountains are of medium sensitivity. The fundamental difference between the two maps is that simulations based on past measurement indicate that the Alpokalja area is highly sensitive while simulations based on the ALADIN model outputs indicate the high sensitivity of the Mecsek mountain area.

9 SUMMARY AND CONCLUSIONS

The present report summarises a methodology developed for the calculation of groundwater table distributions from climate parameters. The aim of water table modelling was to develop a toolset which can be used for calculation of the water table for various climate conditions. This was done with the goal of facilitating the assessment of climate impact and evaluating climate sensitivity of shallow groundwater resources.

A dynamic modular approach was developed in order to quantitatively simulate the groundwater table under various climate conditions. The calculation modules included the following:

1. A toolset to calculate climate zonation from climate parameter grids;
2. Delineation of recharge zones (Hydrological Response Units);
3. Calculation of percolation (recharge) rates using 1D analytical hydrological models;
4. Simulation of the groundwater table using numerical groundwater flow models;

The climate data source applied in our calculation comprised interpolated daily climate data of the Central European CarpatClim-Hu database and the results of the ALADIN climate model. Climate zones were determined making use of the Thorntwaite climate zonation scheme. Recharge zones (HRU's) were determined based on surface geology, land-use and slope conditions. The HELP hydrological model was used for the calculation of 1D water balance for hydrological response units. The Modflow numerical groundwater modelling code was used for the calculation of the water table.

The applied methodology provided a quantitative link between climate conditions and shallow groundwater conditions, and was successfully applied for water table calculation and the assessment of climate sensitivity.

Results of recharge calculation indicate that recharge decreased by up to 50 mm/year between 1961-2009 in mountainous areas such as the Alpokalja area, the Transdanubian and the Northern Mountain Ranges.

Calculated water table changes indicate significant water level drops under highland areas such as the Alpokalja, Mecsek, Transdanubian and Northern Mountain Ranges. A more subtle water level drop was simulated along foothill areas and the Kisalföld zone. Calculations based on climate models also indicate moderate water level drops in the Danube-Tisza Interfluve and Tiszántúl areas.

Calculated sensitivity maps suggest that elevated areas such as the Northern and Transdanubian Mountain Ranges are highly vulnerable to climate change and foothill areas of these mountains are of medium sensitivity. There is a difference in the sensitivity status of the Alpokalja and Mecsek mountain areas between the calculations based on measured and predicted climate data.

The presented outputs are representative of groundwater conditions at the regional scale, and thus cannot be used for local-scale investigations. In order to increase the accuracy of the results, the accuracy of input datasets and the resolution of applied models need to be increased. The introduced methodology is valid for modelling purposes at various scales and thus represents a versatile tool for the assessment of climate sensitivity of shallow groundwater bodies.

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APPENDIX

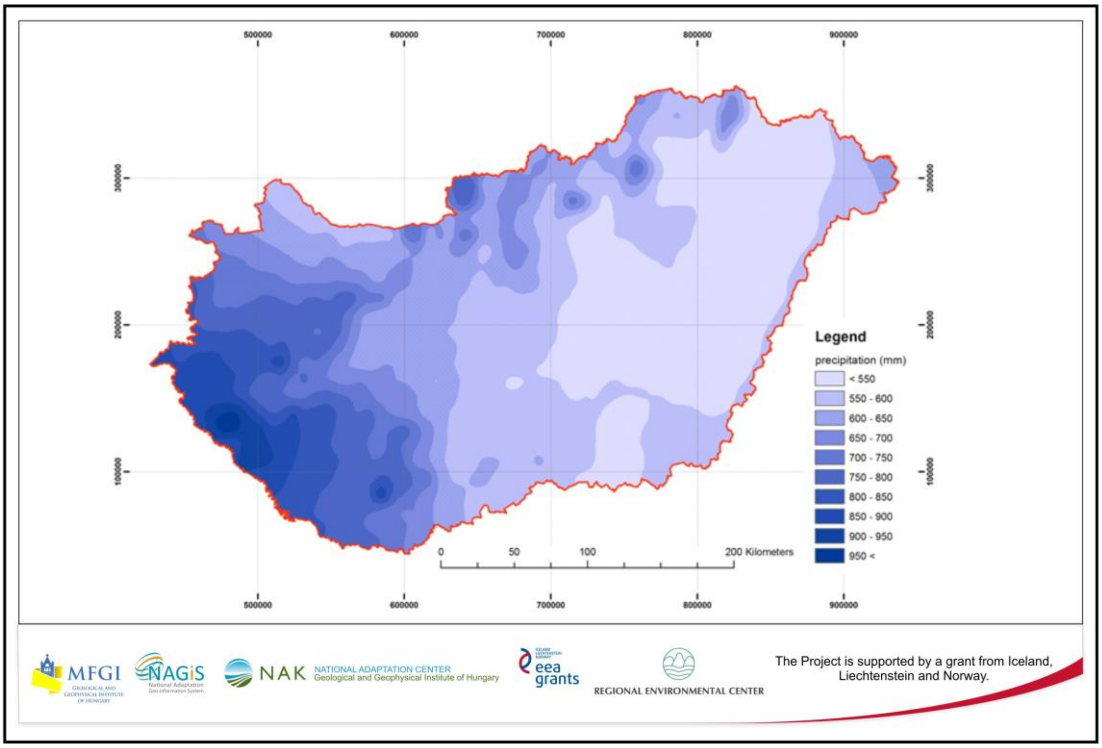

Figure 1. Distribution of averaged annual precipitation for the period 1961–1965 based on the CarpatClim-Hu database

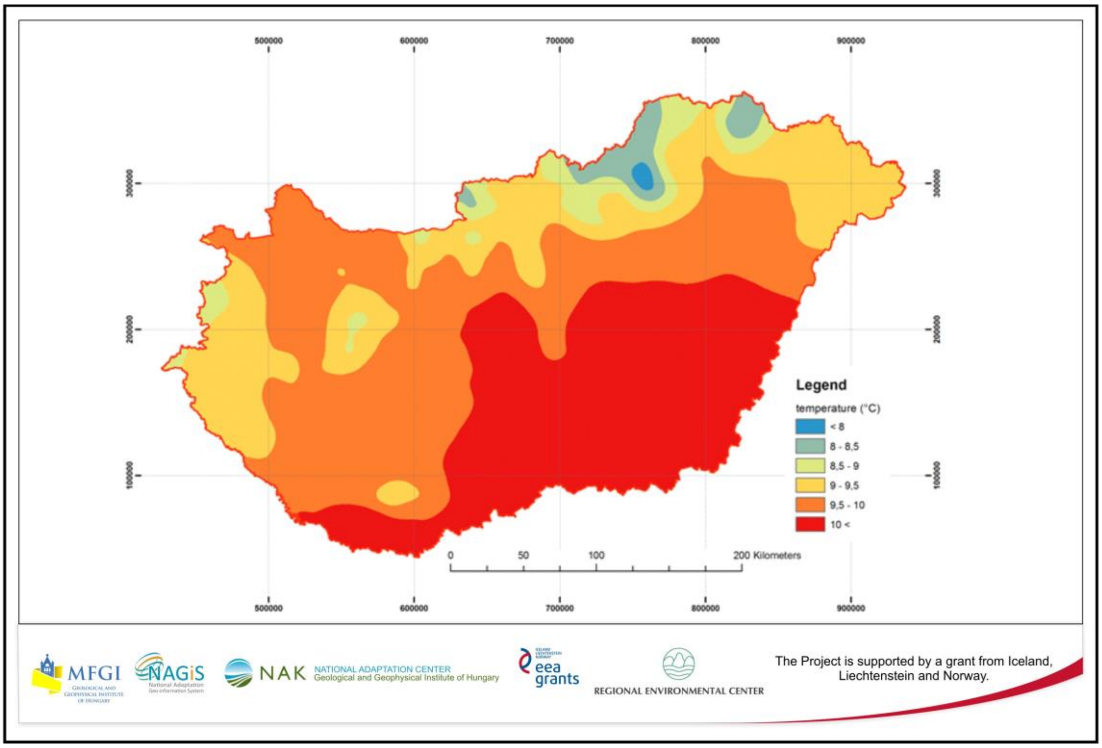

Figure 2. Distribution of averaged annual temperature for the period 1961-1965 based on the CarpatClim-Hu database

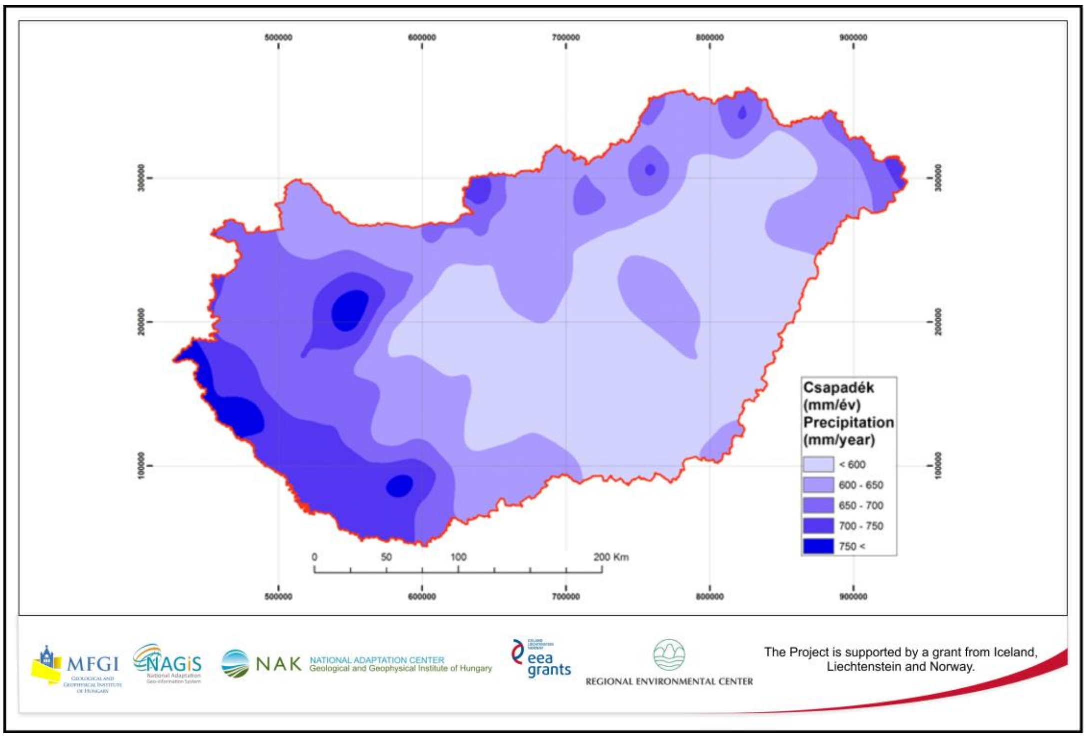

Figure 3. Distribution of averaged annual precipitation for the period 2005–2009 based on the CarpatClim-Hu database

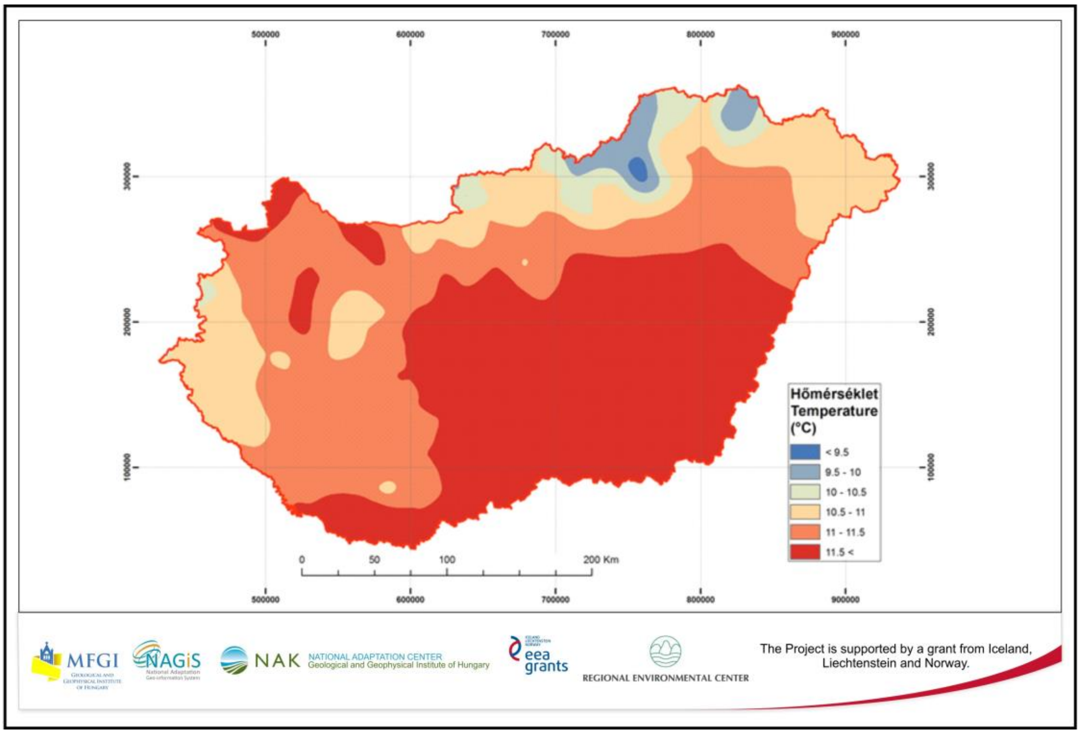

Figure 4. Distribution of averaged annual temperature for the period 2005–2009 based on the CarpatClim-Hu database

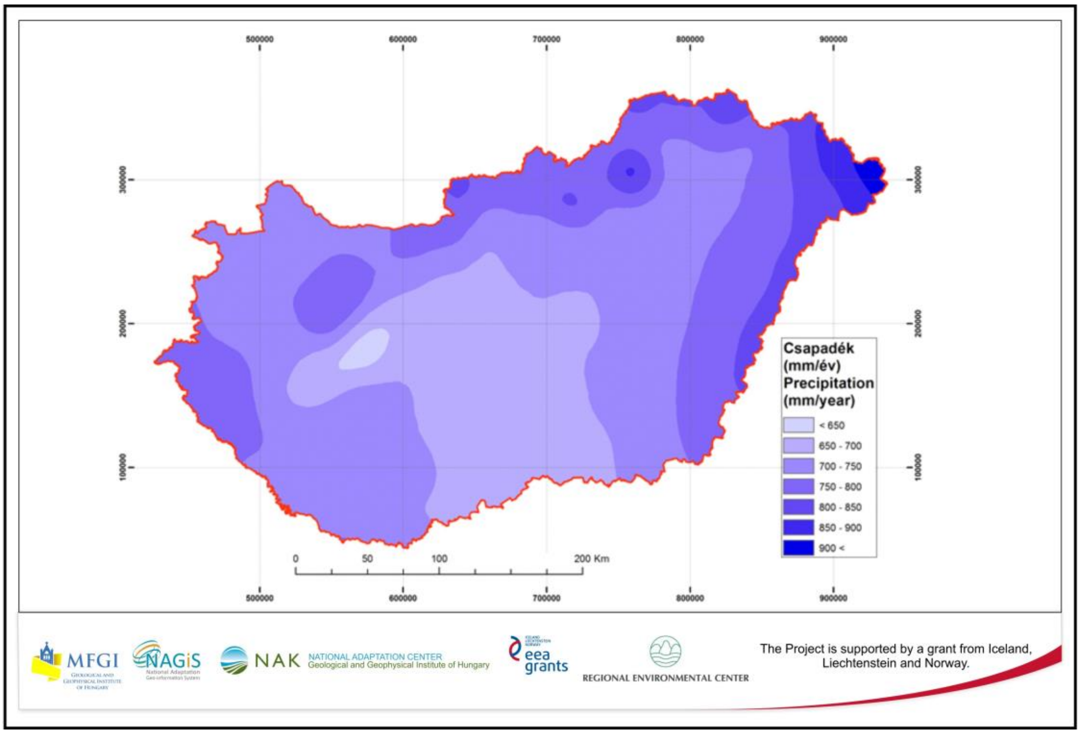

Figure 5. Distribution of averaged annual precipitation for the period 1961–1990 based on ALADIN simulation results

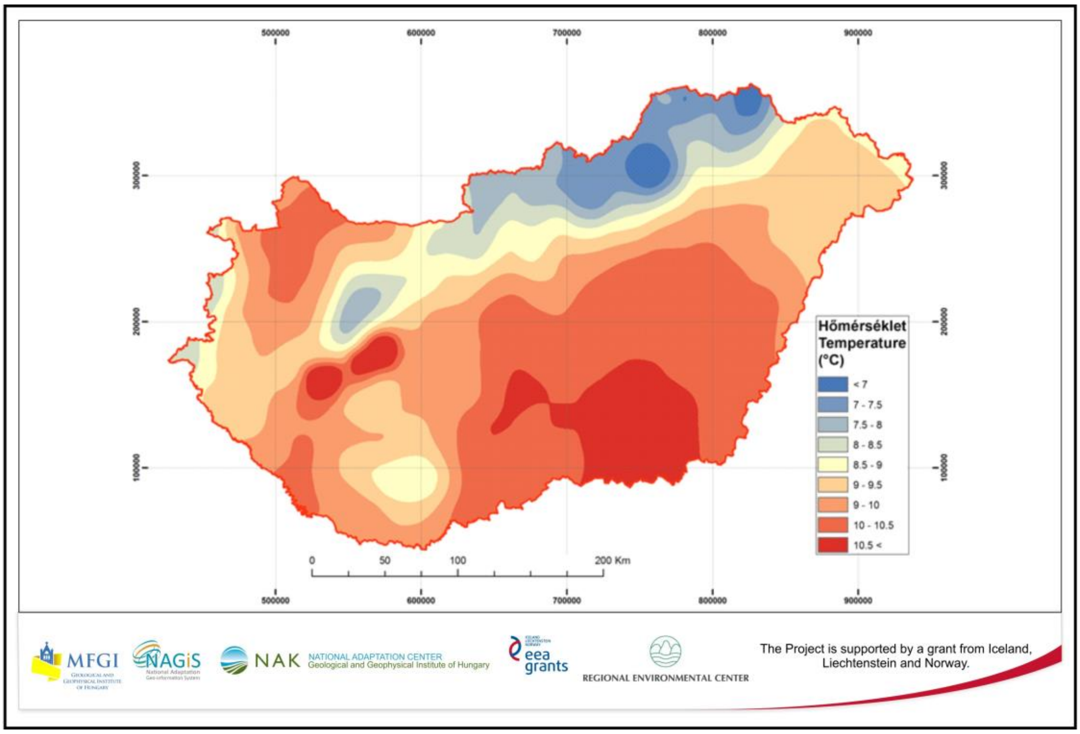

Figure 6. Distribution of averaged annual temperature for the period 1961–1990 based on ALADIN simulation results

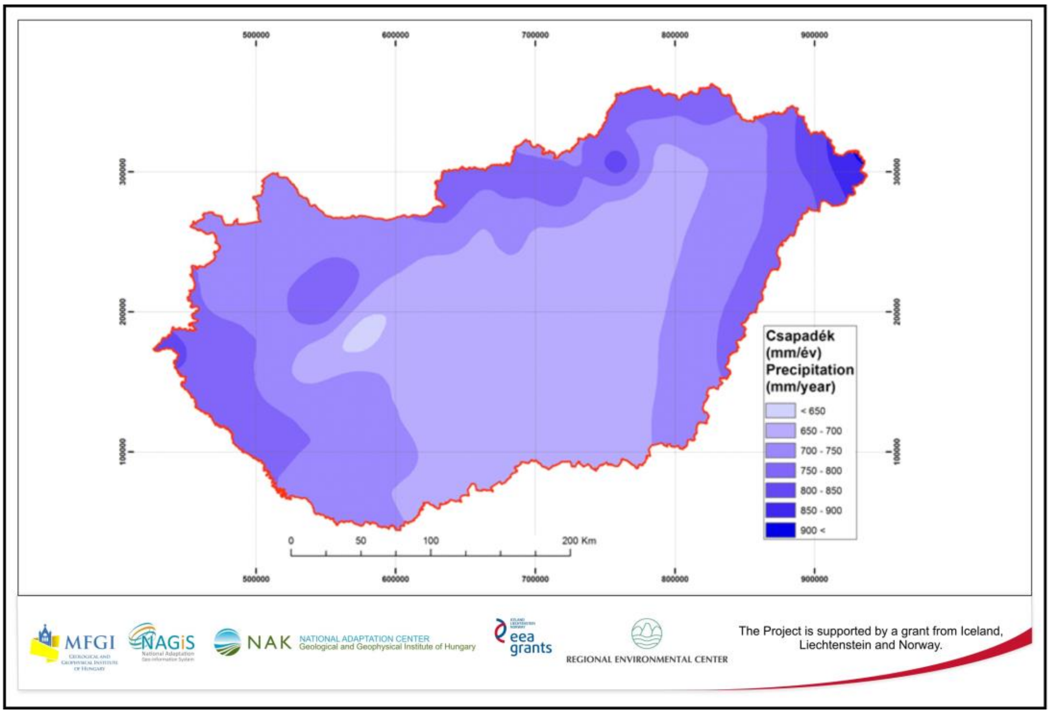

Figure 7. Distribution of averaged annual precipitation for the period 2021–2050 based on ALADIN simulation results

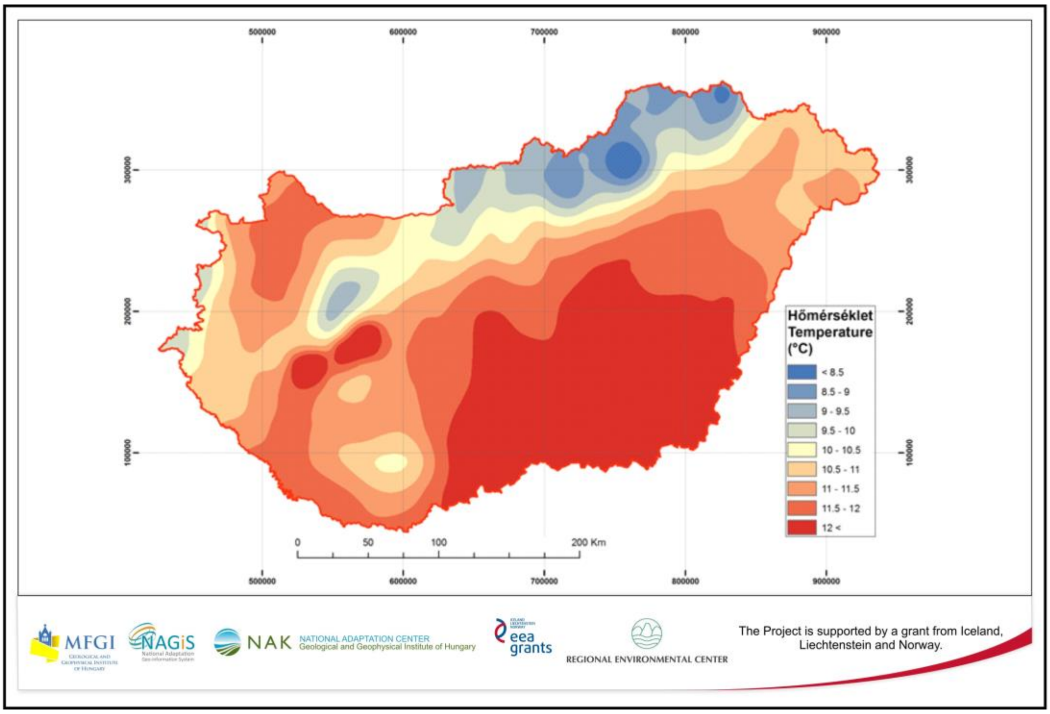

Figure 8. Distribution of averaged annual temperature for the period 2021–2050 based on ALADIN simulation results

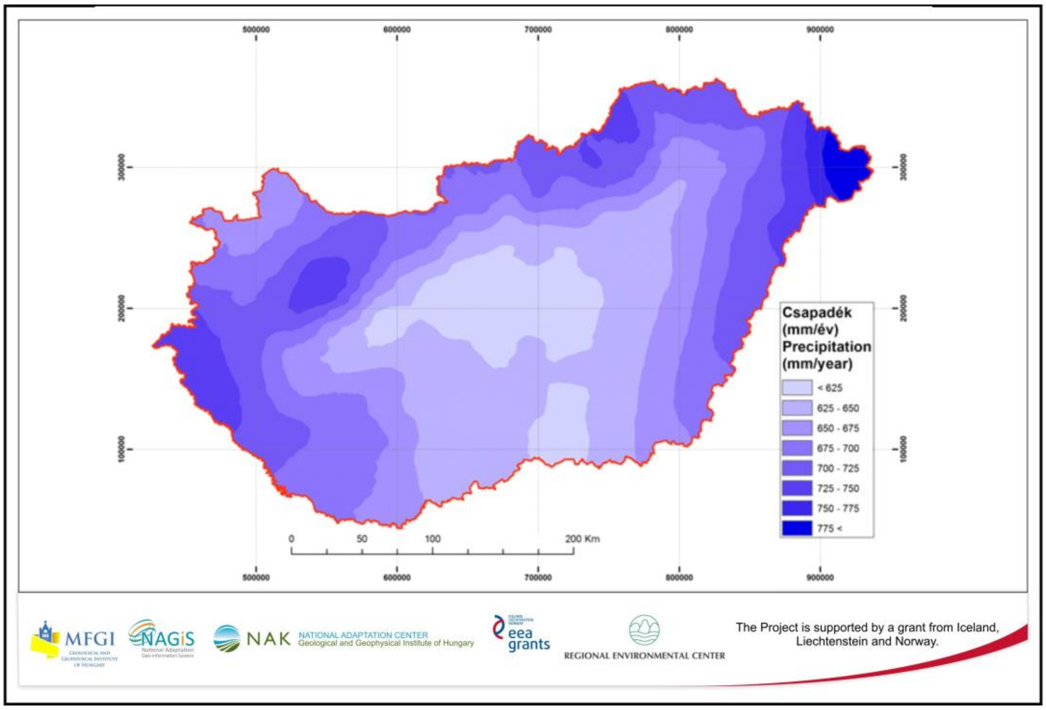

Figure 9. Distribution of averaged annual precipitation for the period 2071–2100 based on ALADIN simulation results

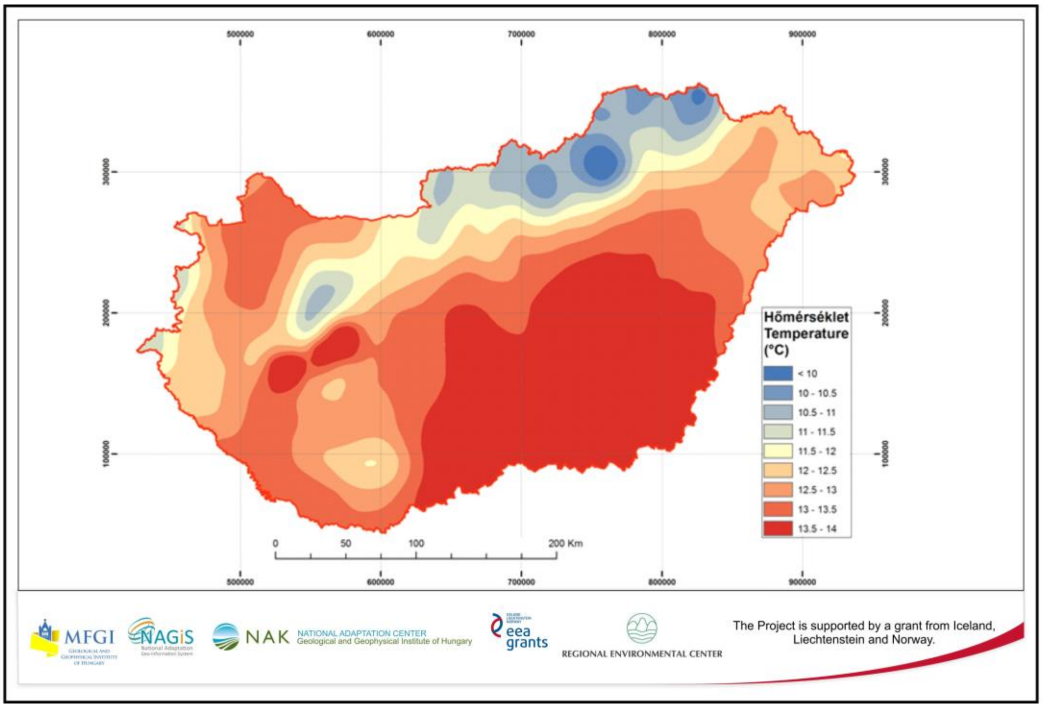

Figure 10. Distribution of averaged annual temperature for the period 2071–2100 based on ALADIN simulation results

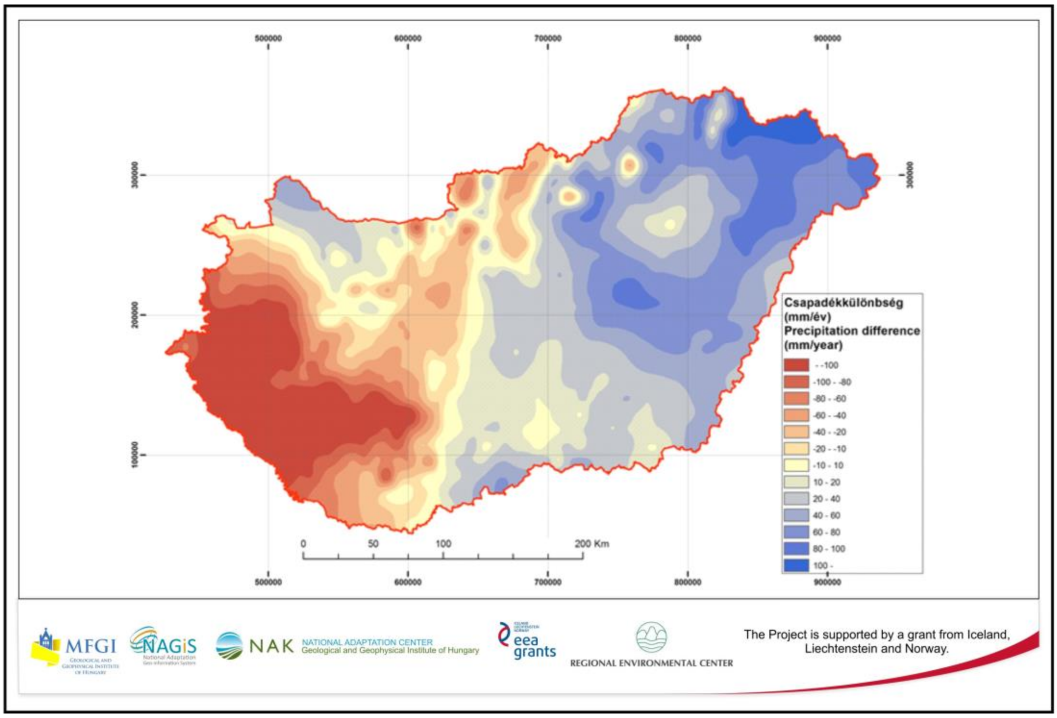

Figure 11. Rainfall difference between the 2005–2009 and 1961–1965 periods based on the CarpatClim-Hu database

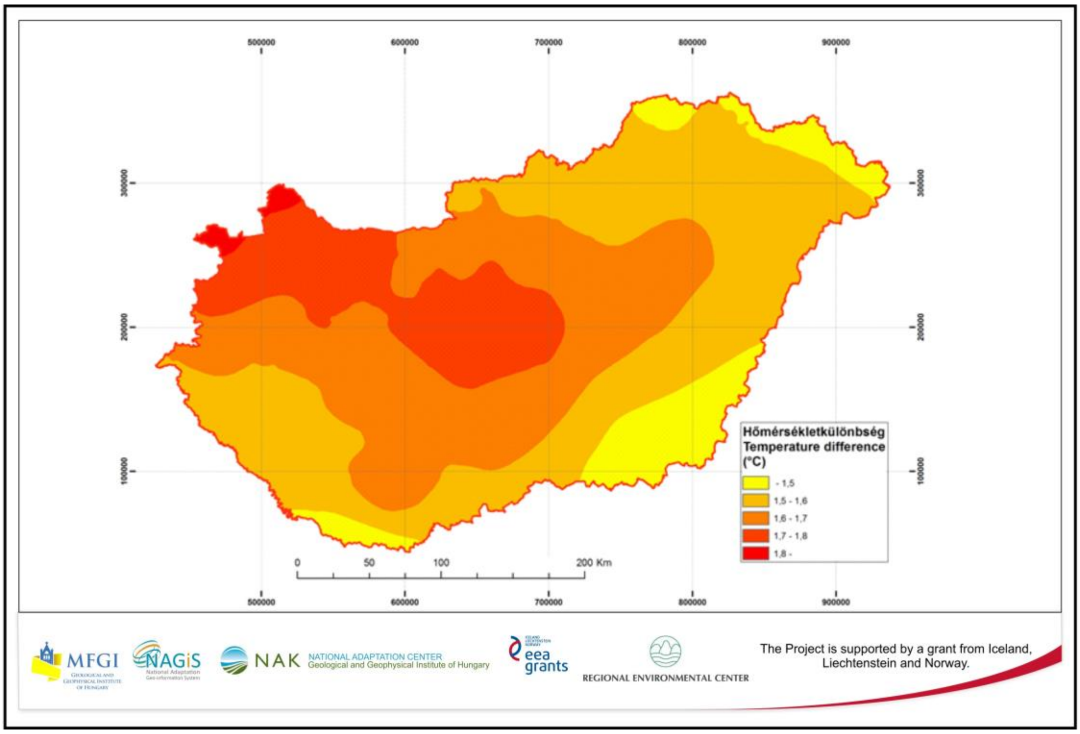

Figure 12. Temperature difference between the 2005–2009 and 1961–1965 periods based on the CarpatClim-Hu database

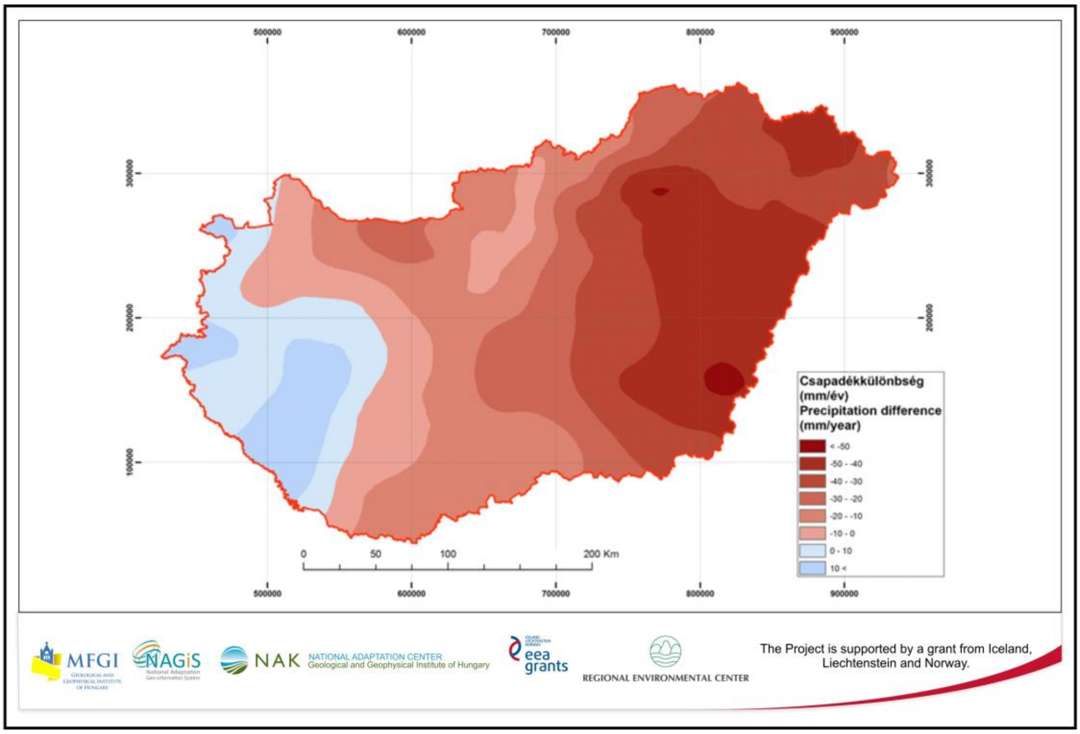

Figure 13. Rainfall difference between the 2021–2050 and 1961–1990 periods based on ALADIN simulation results

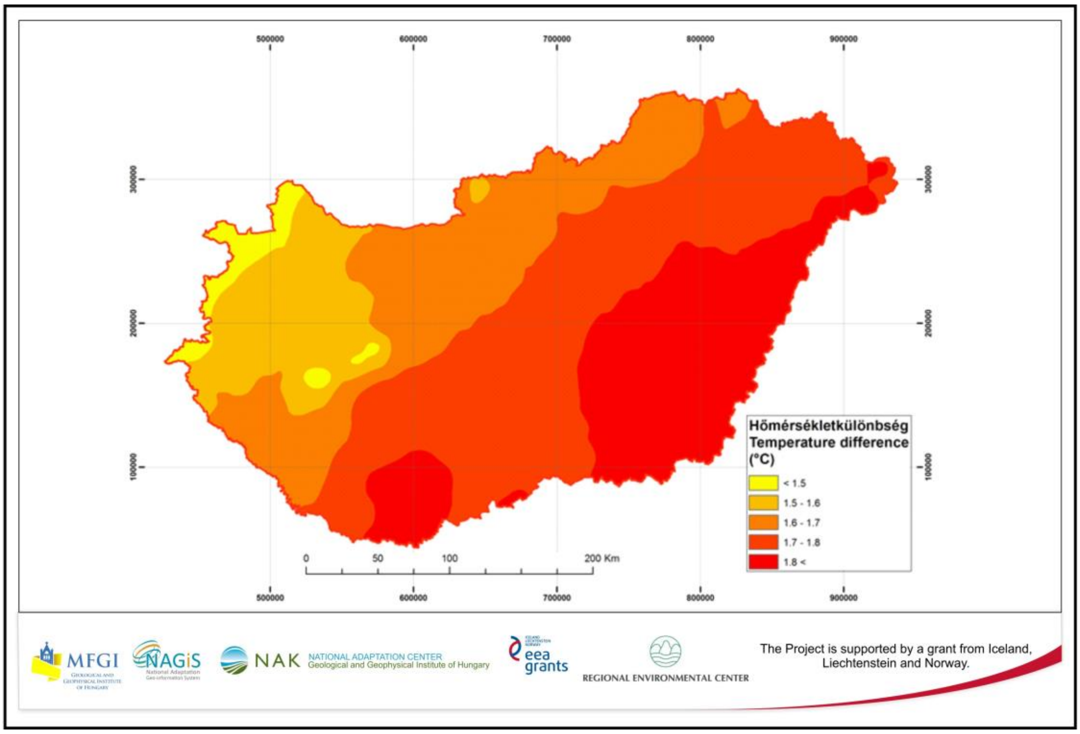

Figure 14. Temperature difference between the 2021–2050 and 1961–1990 periods based on ALADIN simulation results

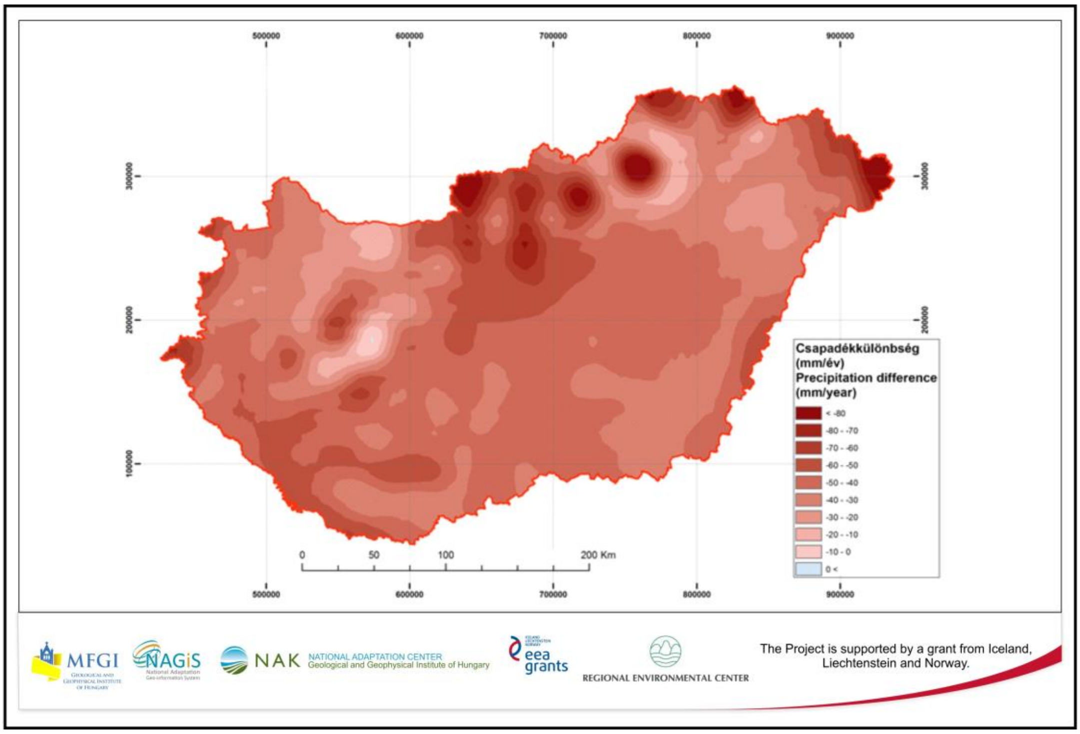

Figure 15. Rainfall difference between the 2071–2100 and 2021–2050 periods based on ALADIN simulation results

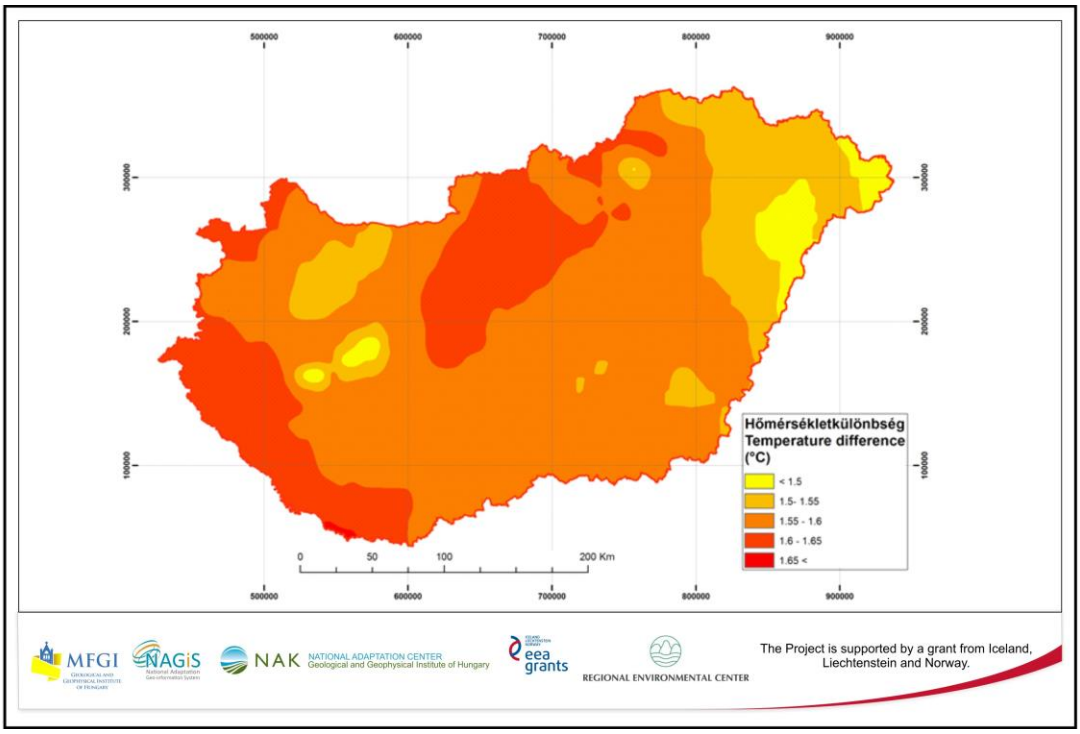

Figure 16. Temperature difference between the 2071–2100 and 2021–2050 periods based on ALADIN simulation results

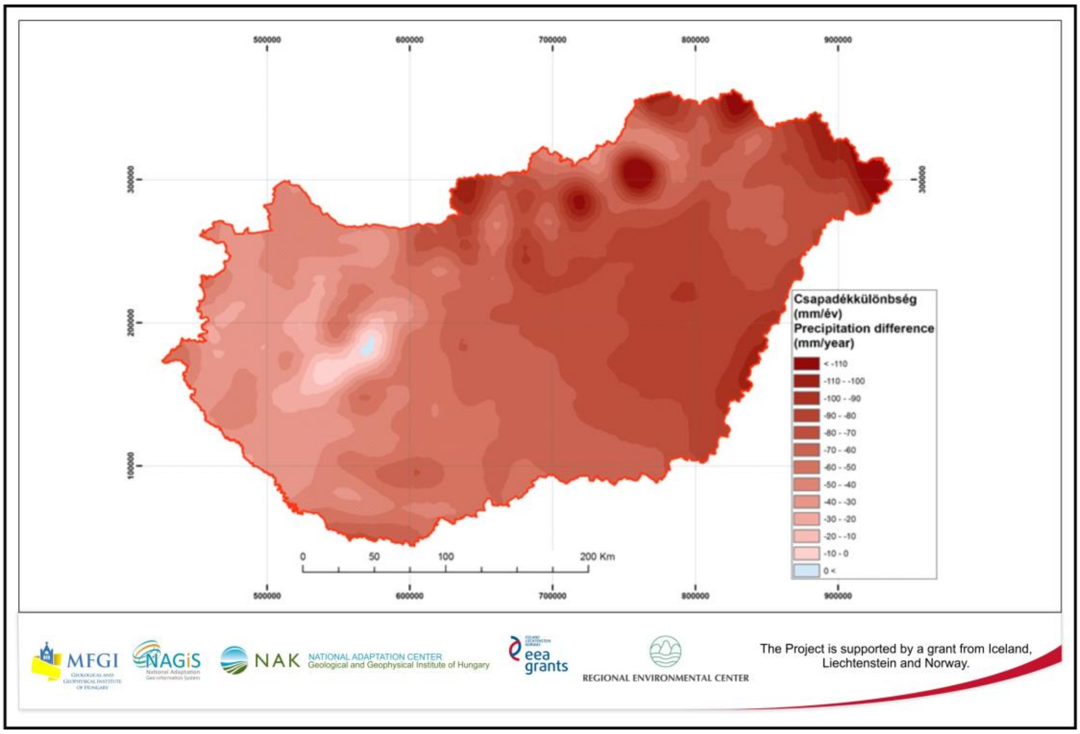

Figure 17. Rainfall difference between the 2071–2100 and 1961–1990 periods based on ALADIN simulation results

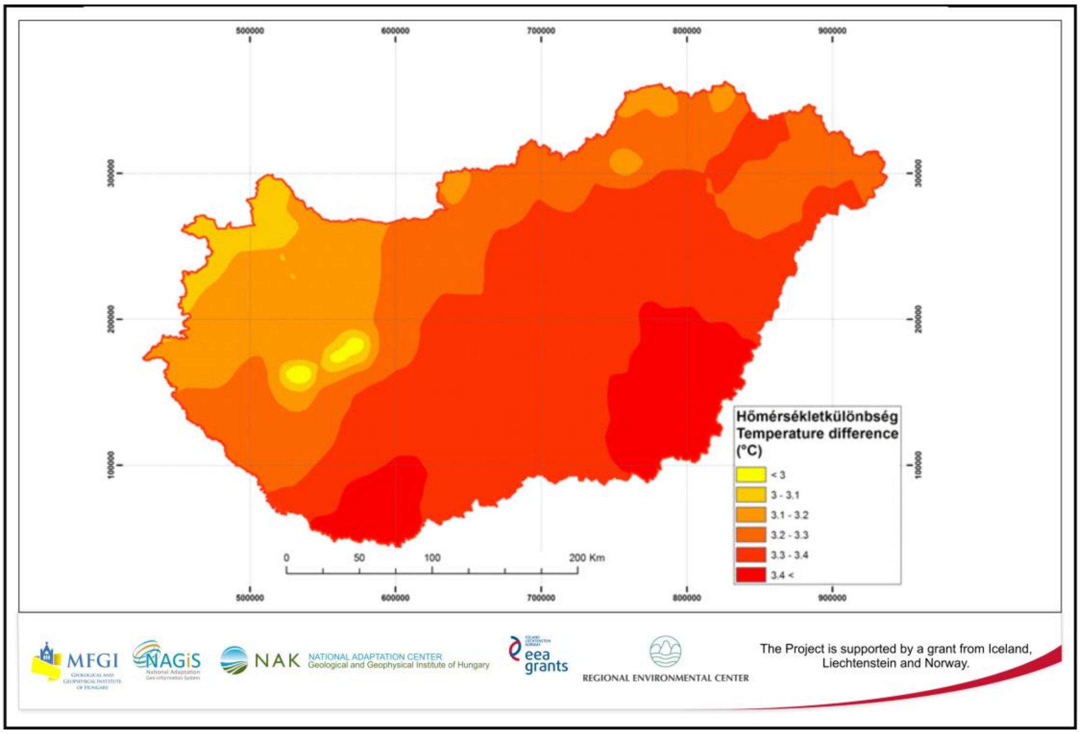

Figure 18. Temperature difference between the 2071–2100 and 1961–1990 periods based on ALADIN simulation results

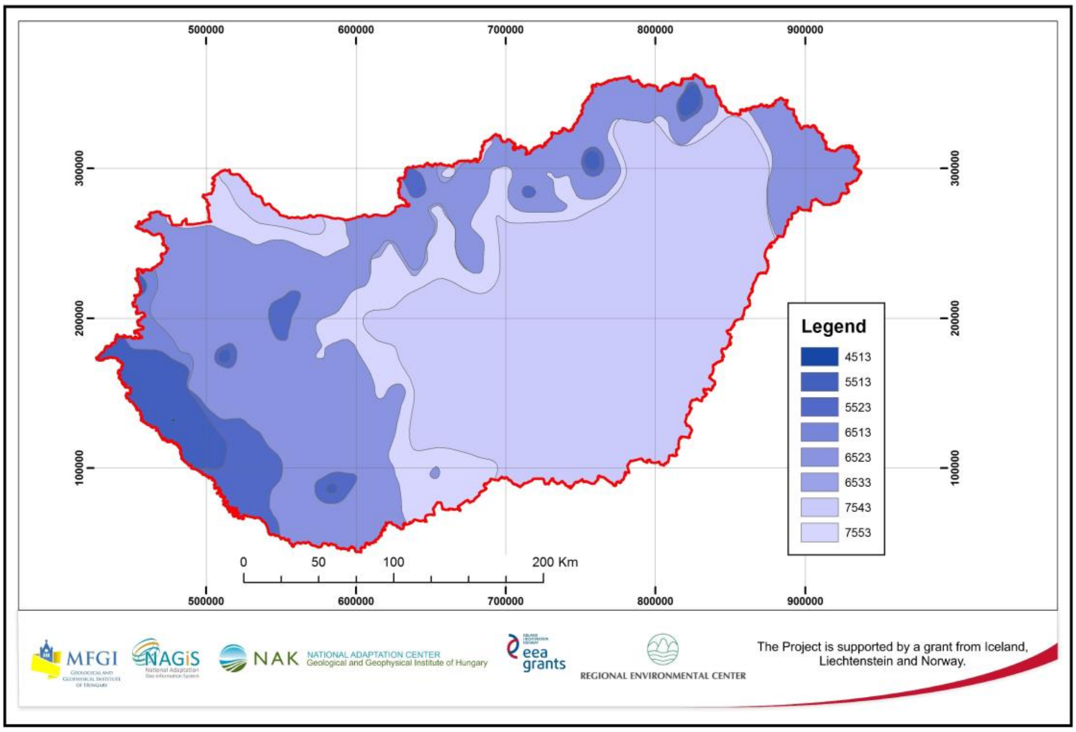

Figure 19. Climate classification based on the Thorntwaite method for the period of 1961–1990 based on CarpatClim-Hu data

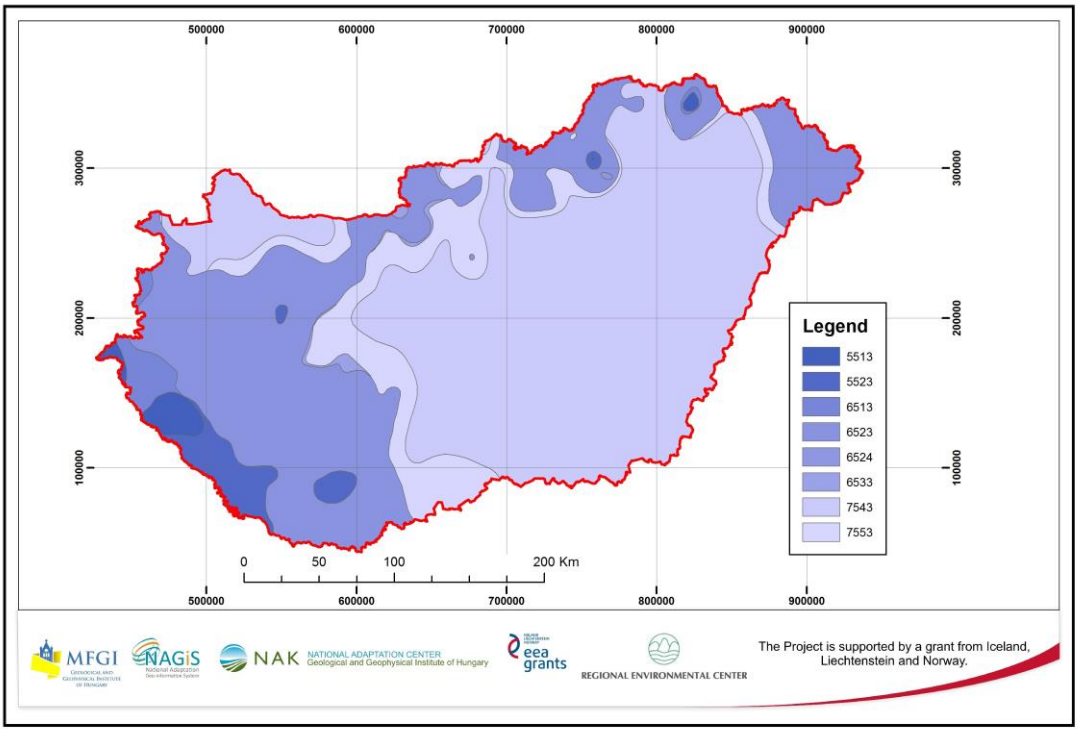

Figure 20. Climate classification based on the Thorntwaite method for the period of 1981–2010 based on CarpatClim-Hu data

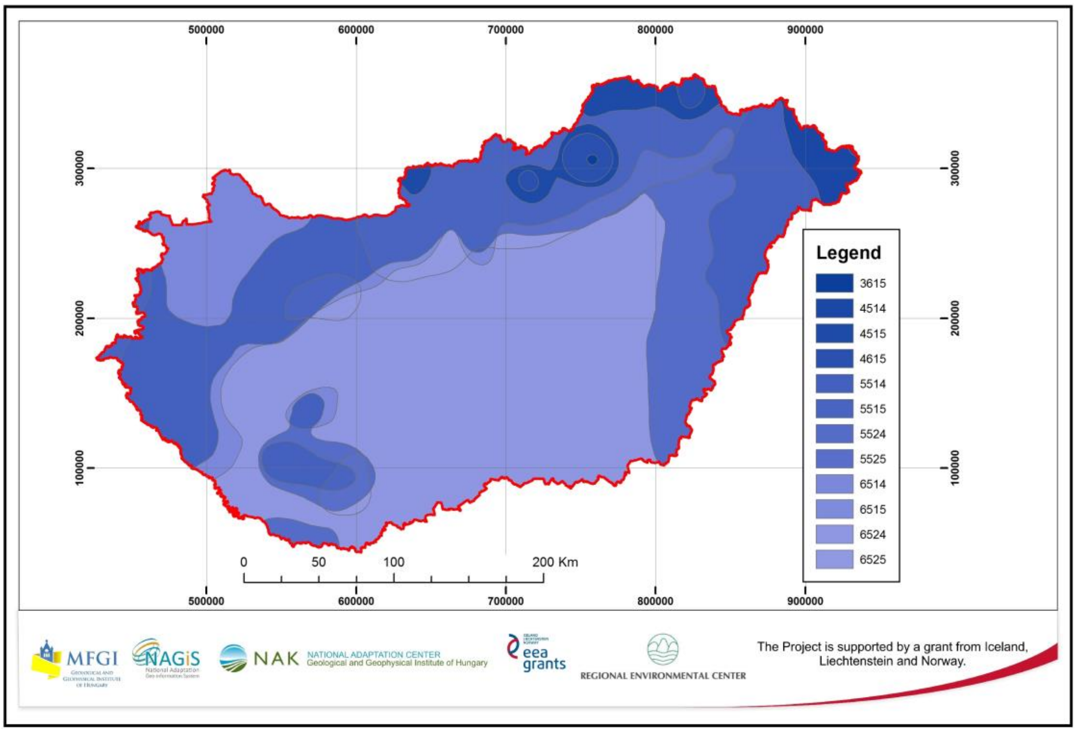

Figure 21. Climate classification based on the Thorntwaite method for the period of 1961–1990 based on ALADIN model outputs

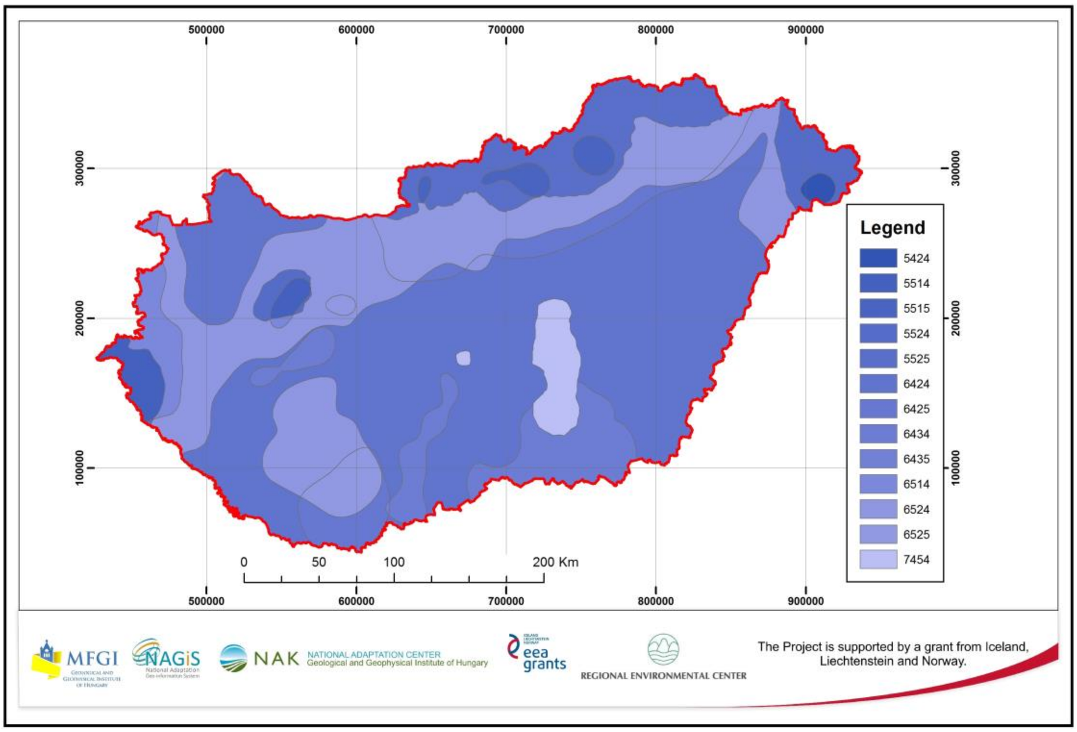

Figure 22. Climate classification based on the Thorntwaite method for the period of 2021–2050 based on ALADIN model outputs

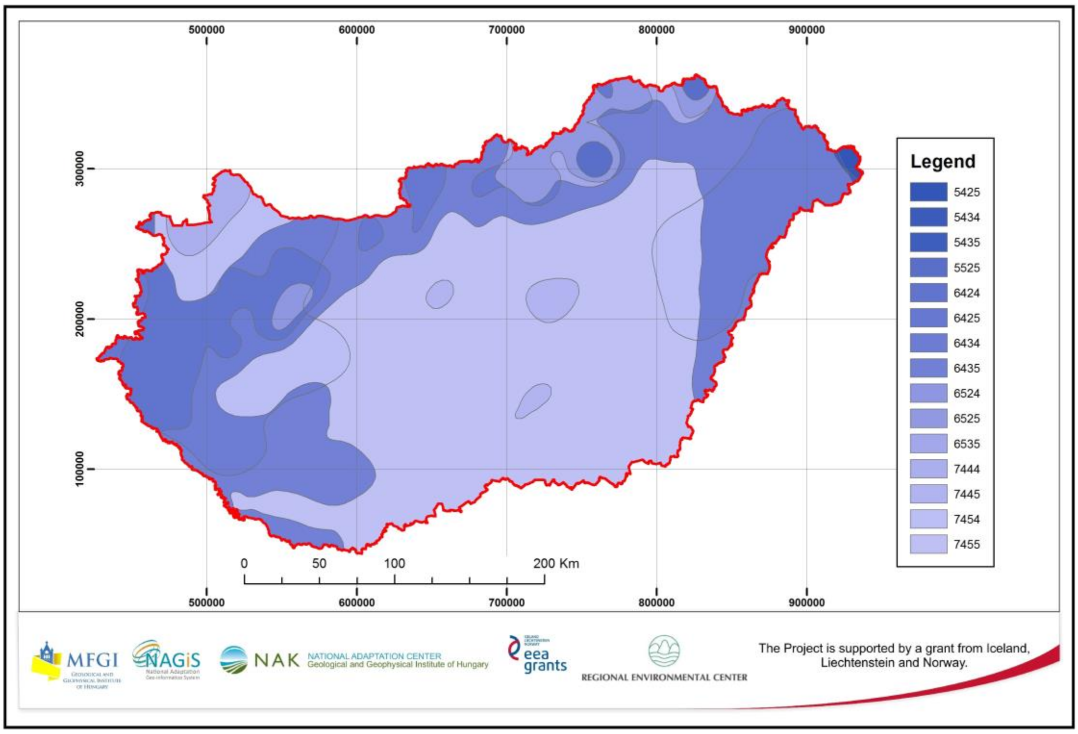

Figure 23. Climate classification based on the Thorntwaite method for the period of 2071–2100 based on ALADIN model outputs

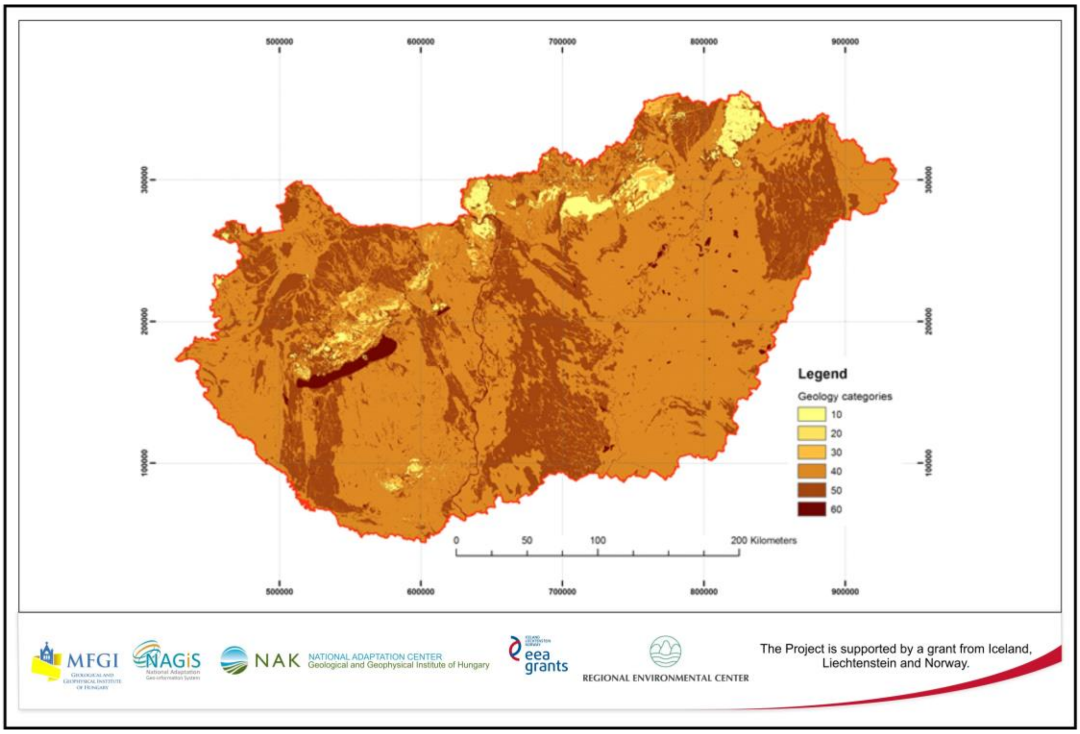

Figure 24. Geology categories applied in the NAGIS project

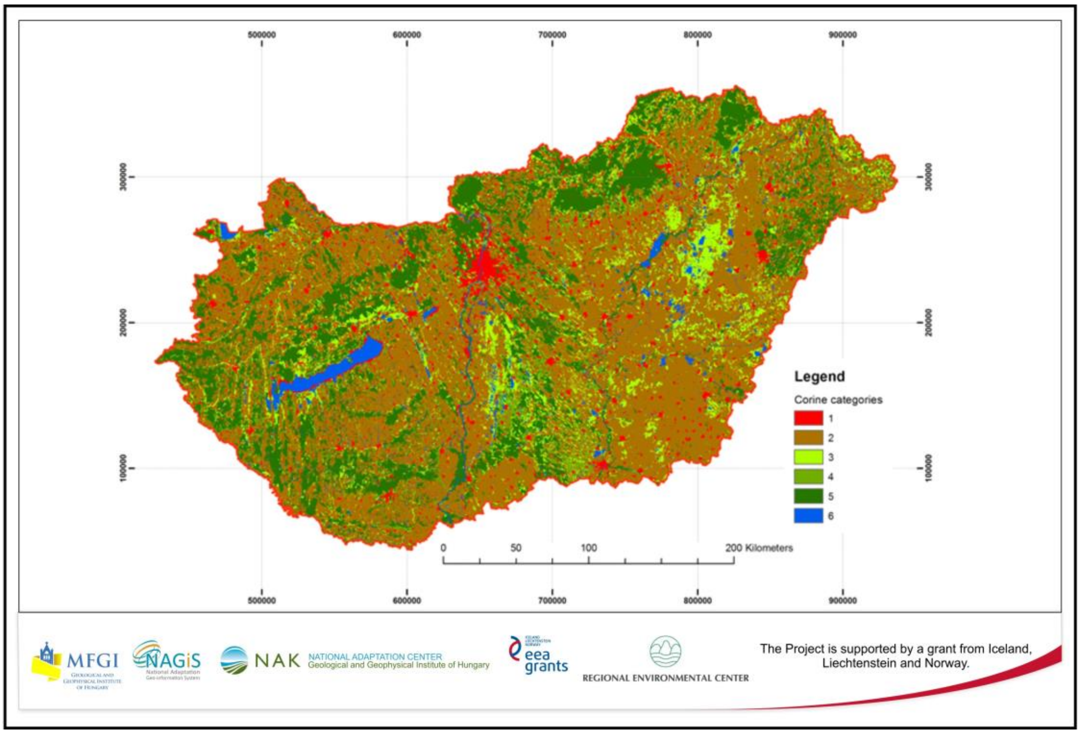

Figure 24. Land-use category map applied in the NAGIS project

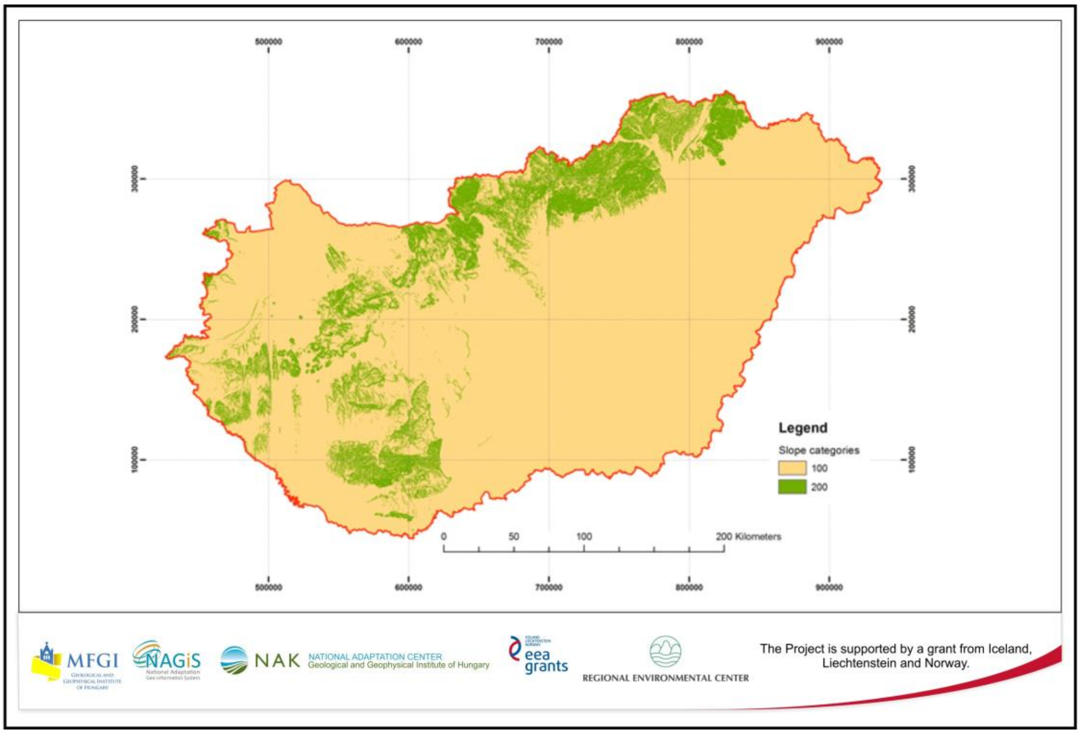

Figure 25. Map of slope categories

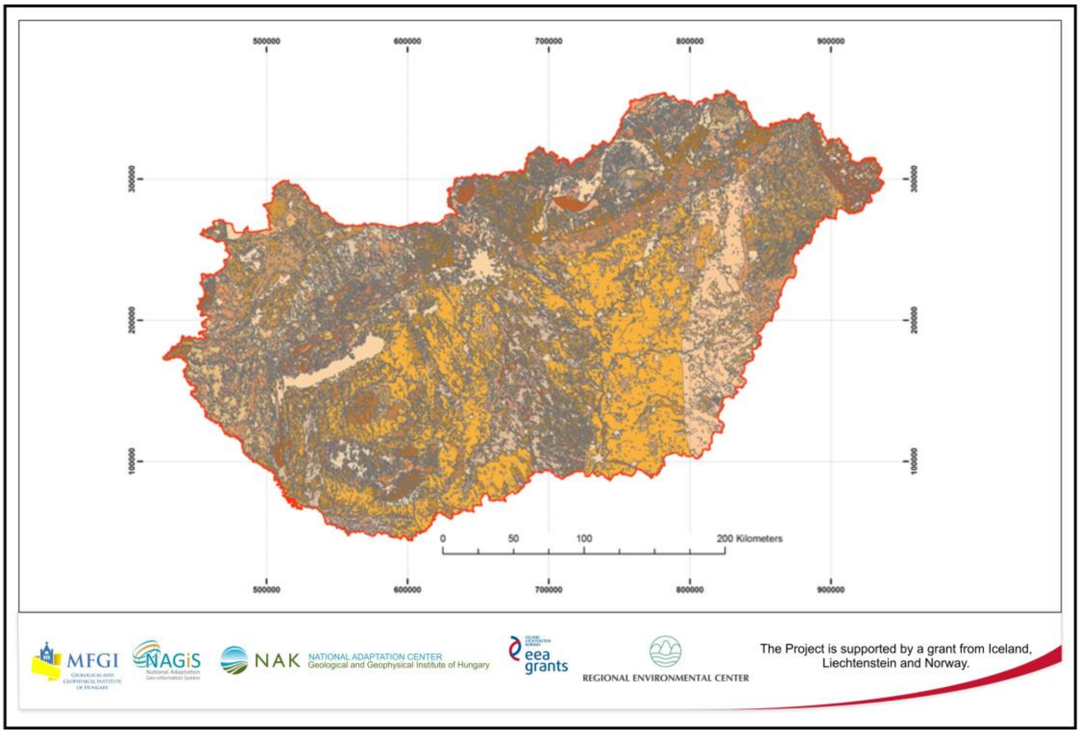

Figure 26. Recharge zones applied in the NAGIS project

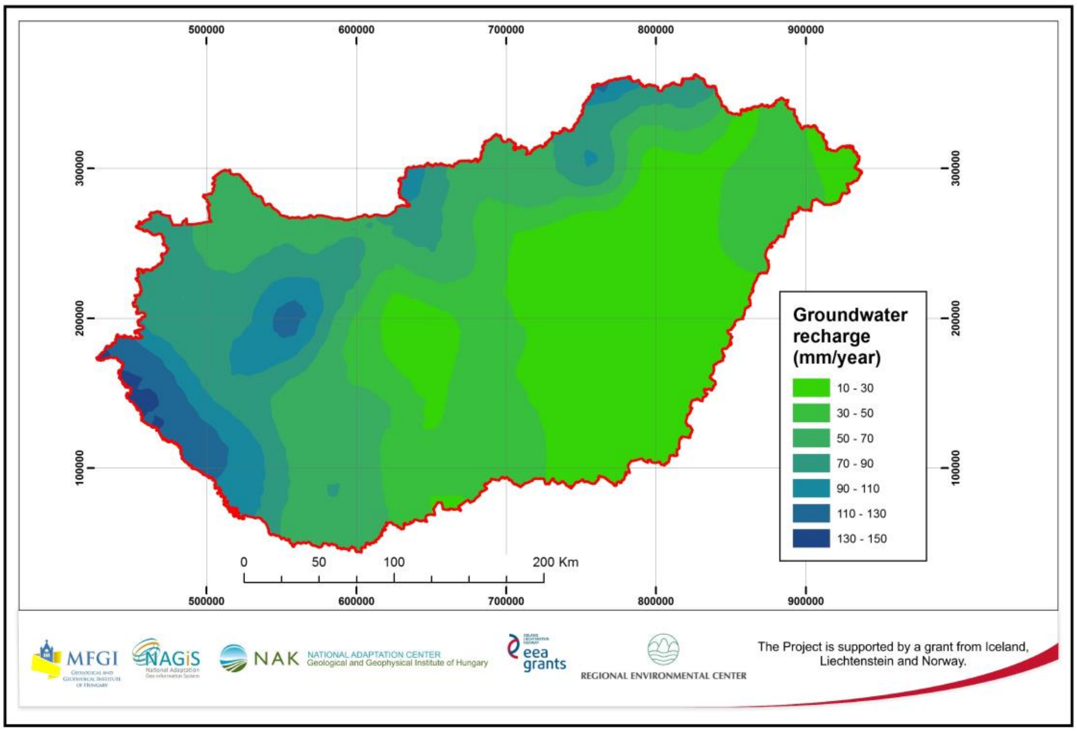

Figure 27. Simulated average recharge distribution for the 1961–1965 period based on CarpatClim-Hu data

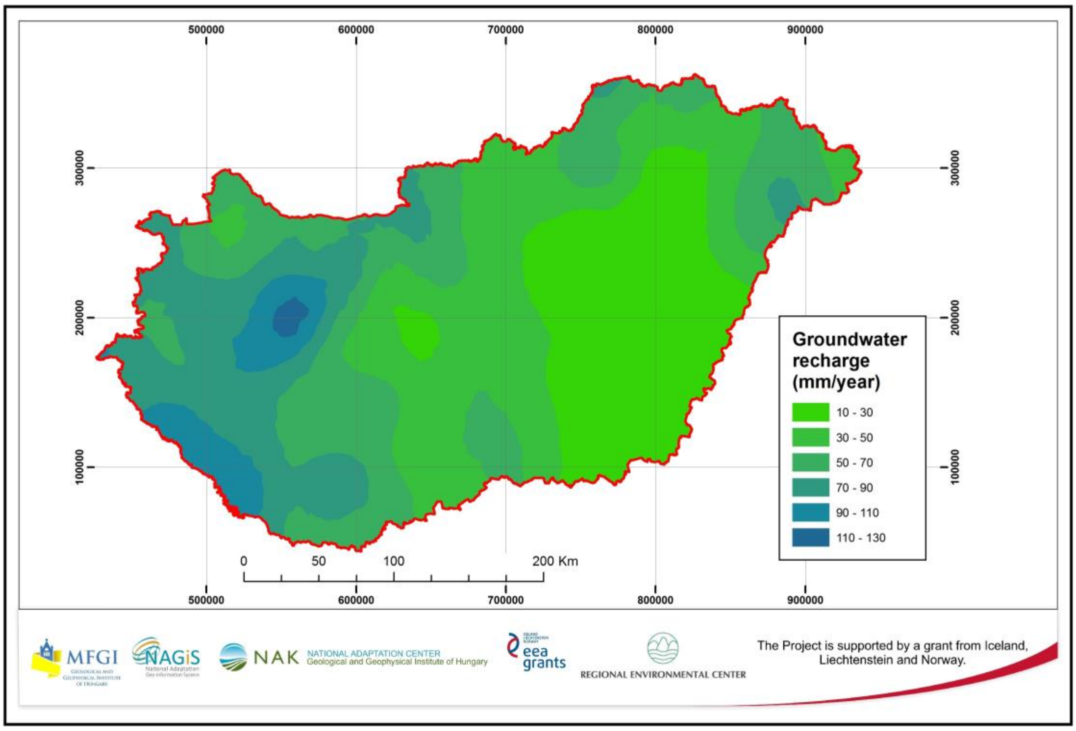

Figure 28. Simulated average recharge distribution for the 2005–2009 period based on CarpatClim-Hu data

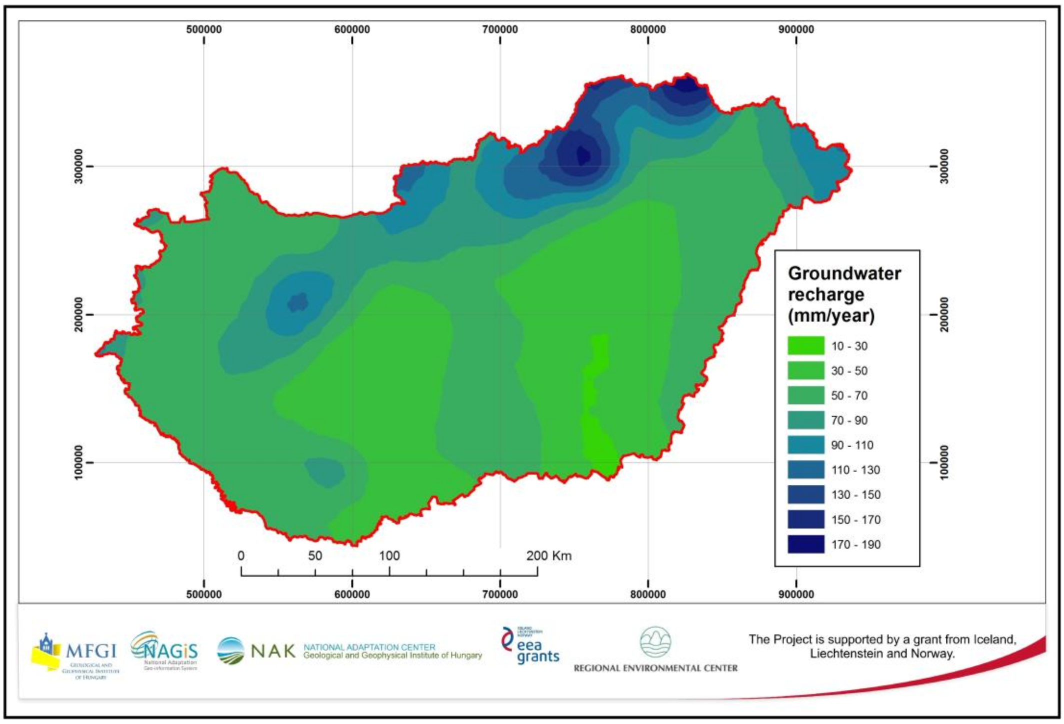

Figure 29. Simulated average recharge distribution for the 1961–1990 period based on ALADIN model results

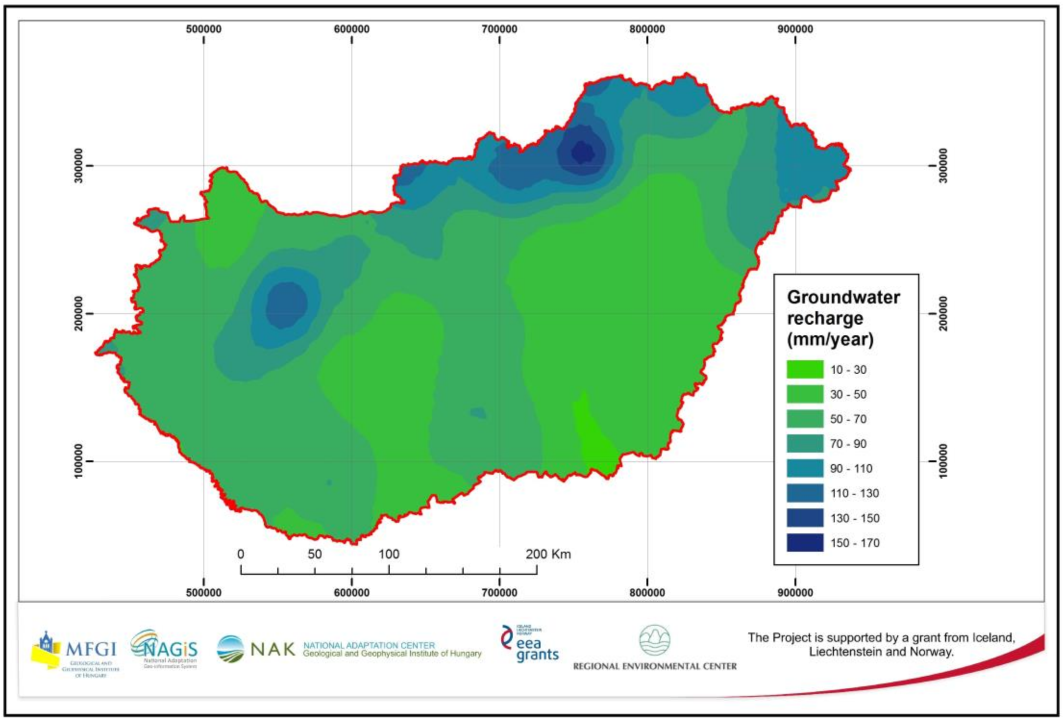

Figure 30. Simulated average recharge distribution for the 2021–2050 period based on ALADIN model results

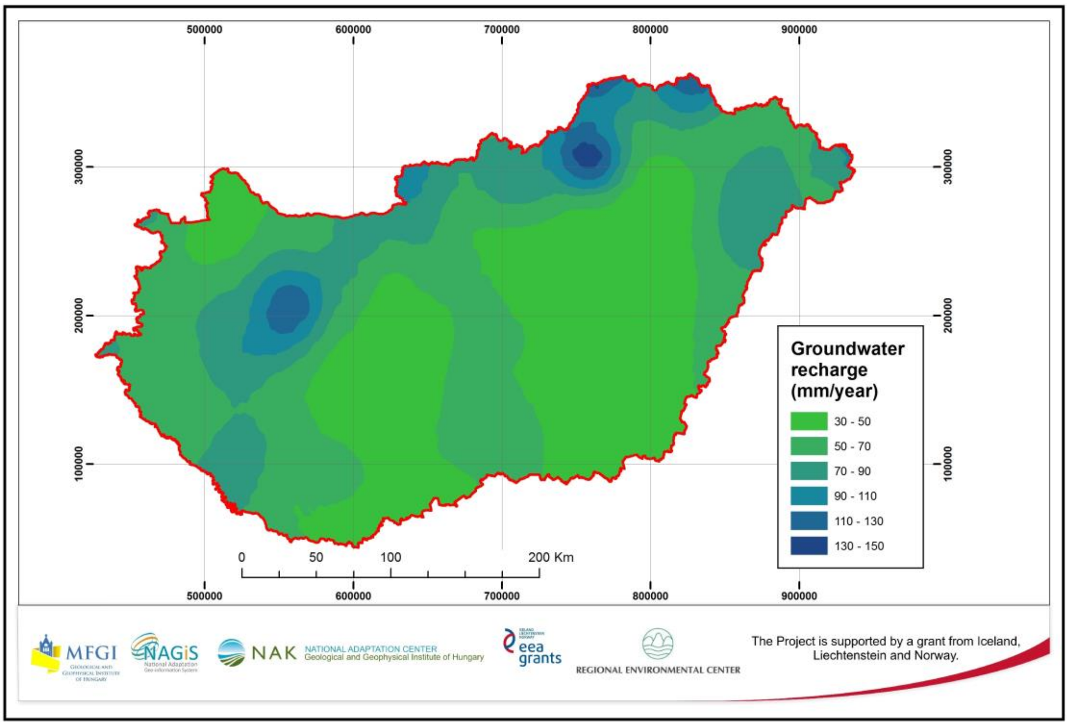

Figure 31. Simulated average recharge distribution for the 2071–2100 period based on ALADIN model results

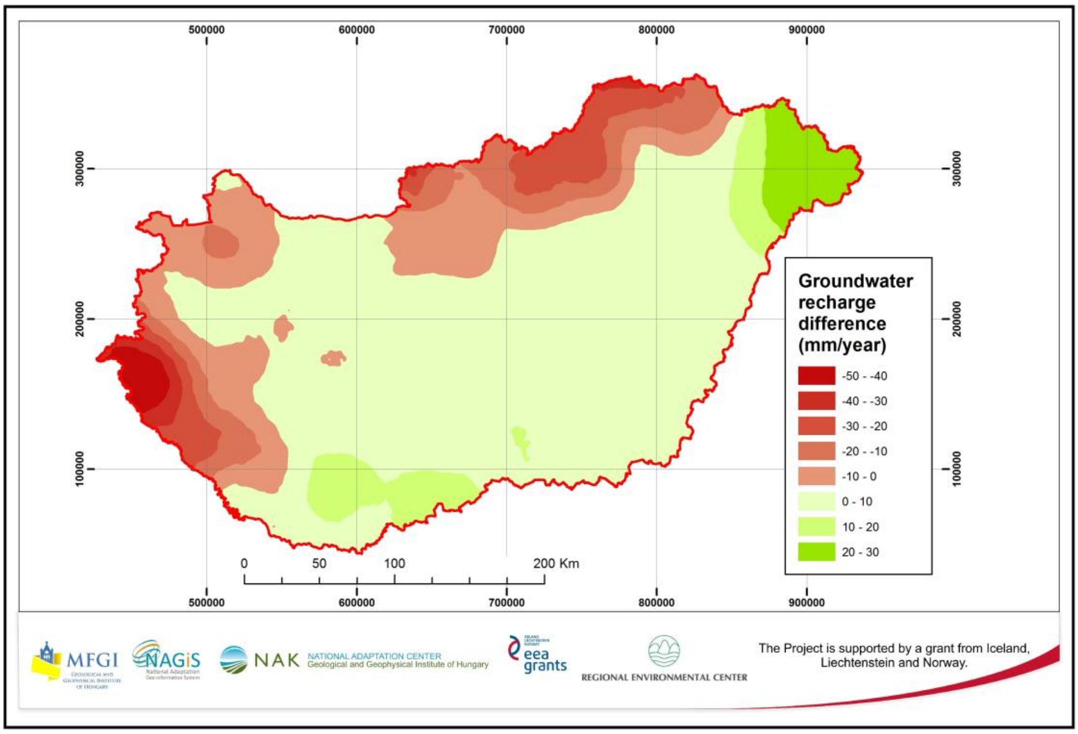

Figure 32. Recharge difference between the 2005–2009 and 1961–1965 simulation periods based on CarpatClim-Hu data

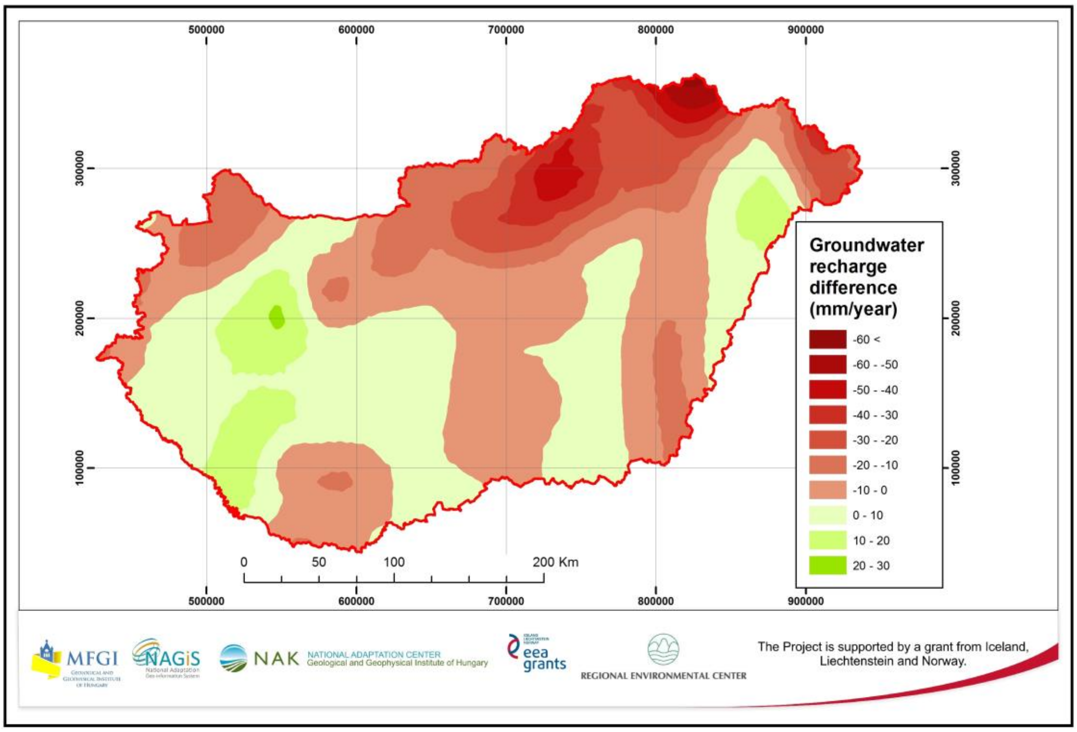

Figure 34. Recharge difference between the 2071–2100 and 1961–1990 simulation periods based on ALADIN data

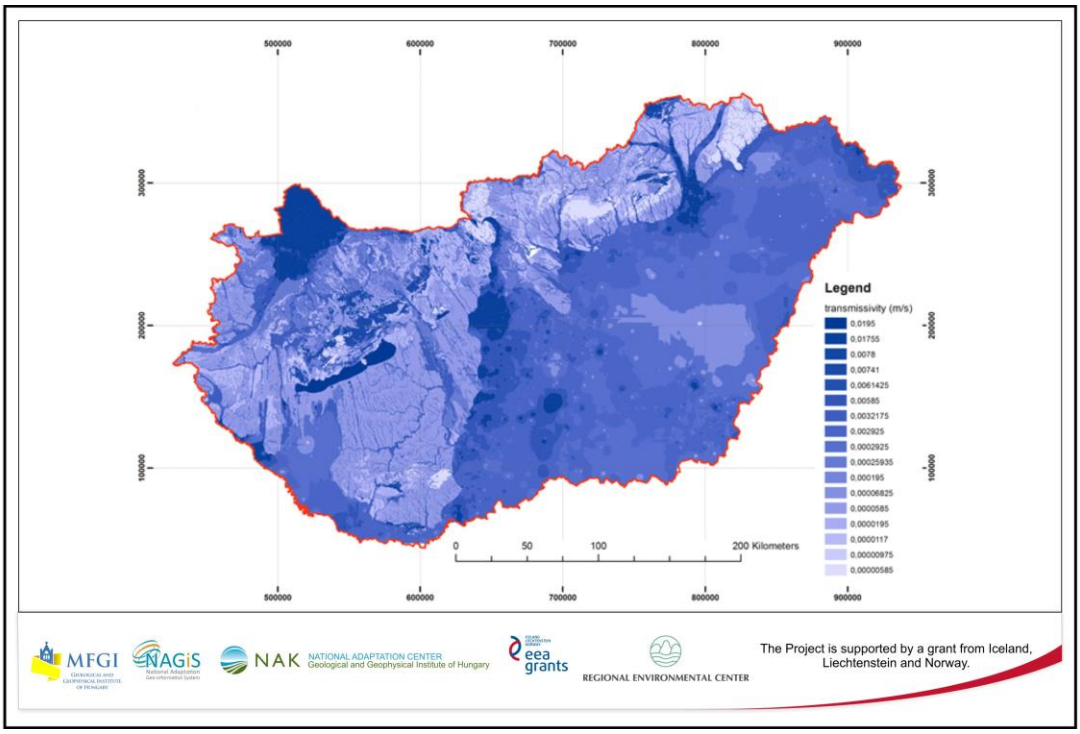

Figure 35. Calibrated transmissivity distribution

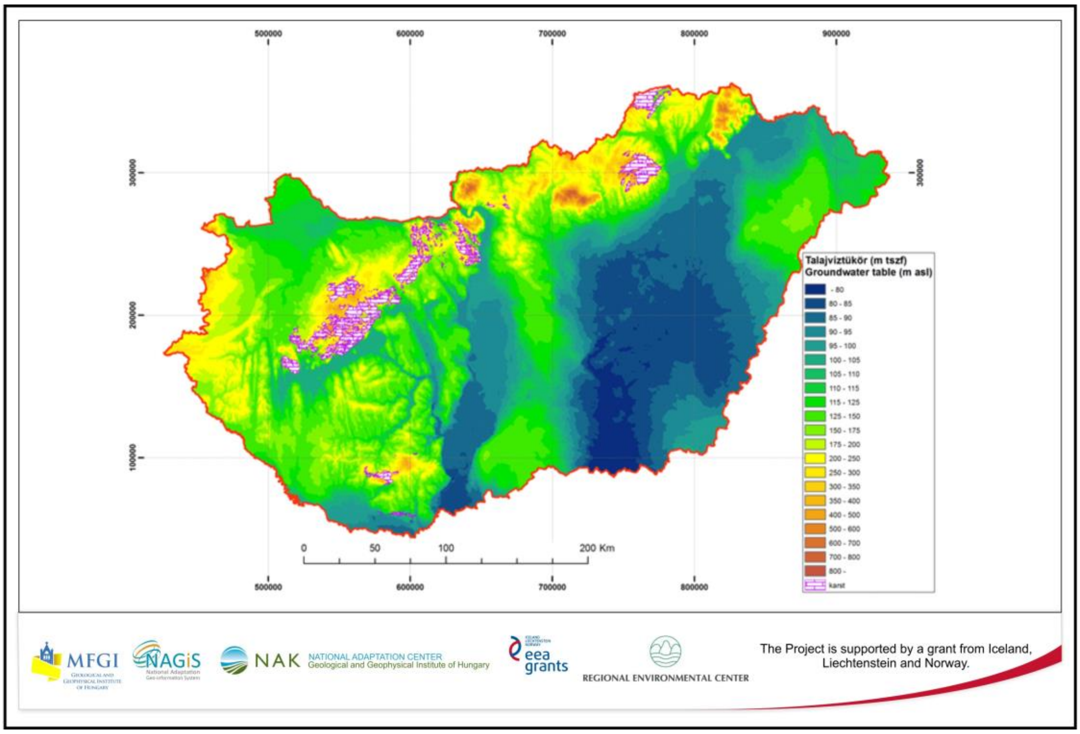

Figure 3633. Simulated water table distribution for the 1961–1965 stress period. Based on CarpatClim-Hu data

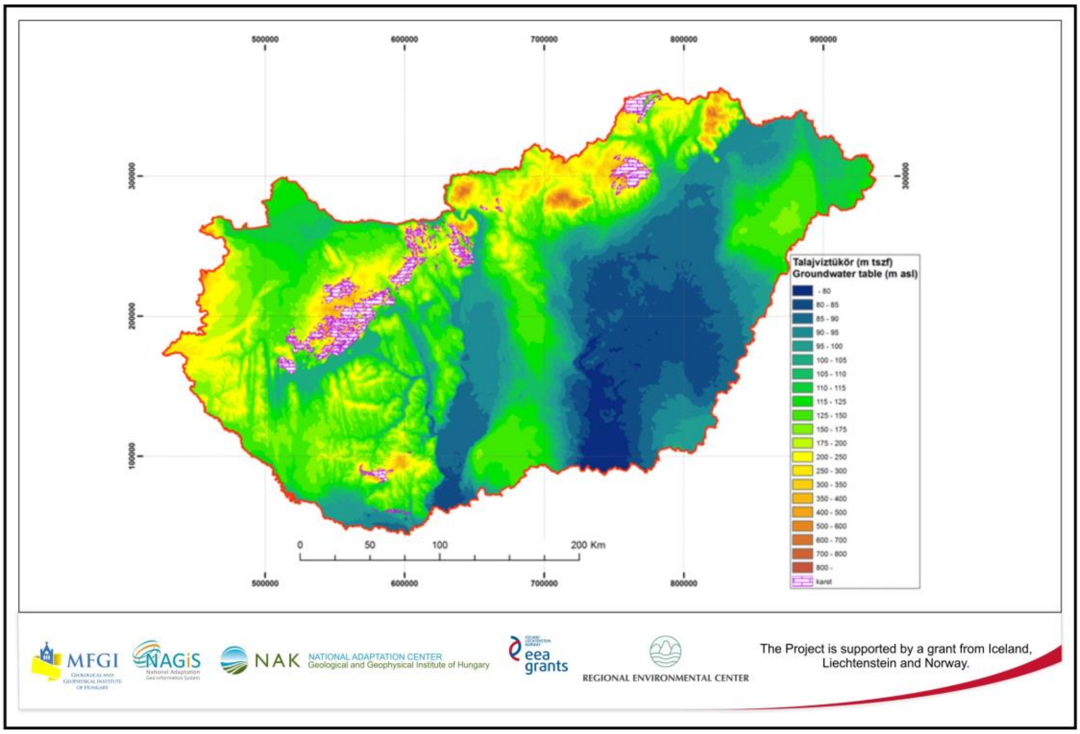

Figure 37. Simulated water table distribution for the 2005–2009 stress period. Based on CarpatClim-Hu data

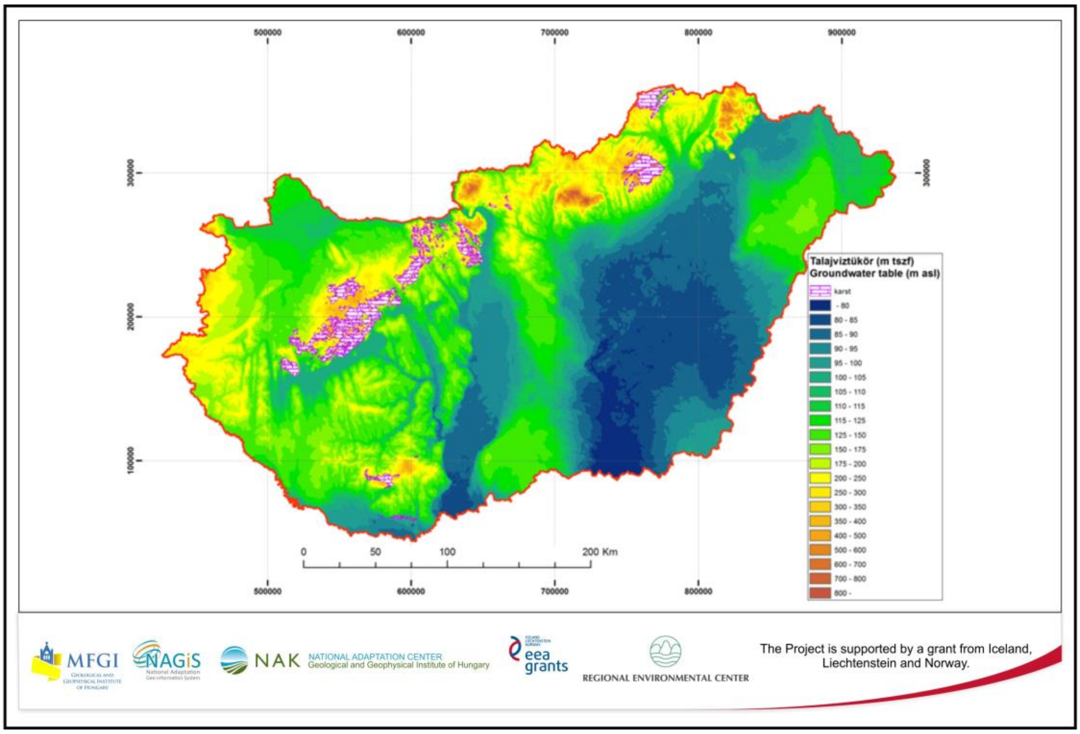

Figure 38. Simulated water table distribution for the 1961–1990 stress period.
Based on ALADIN model outputs

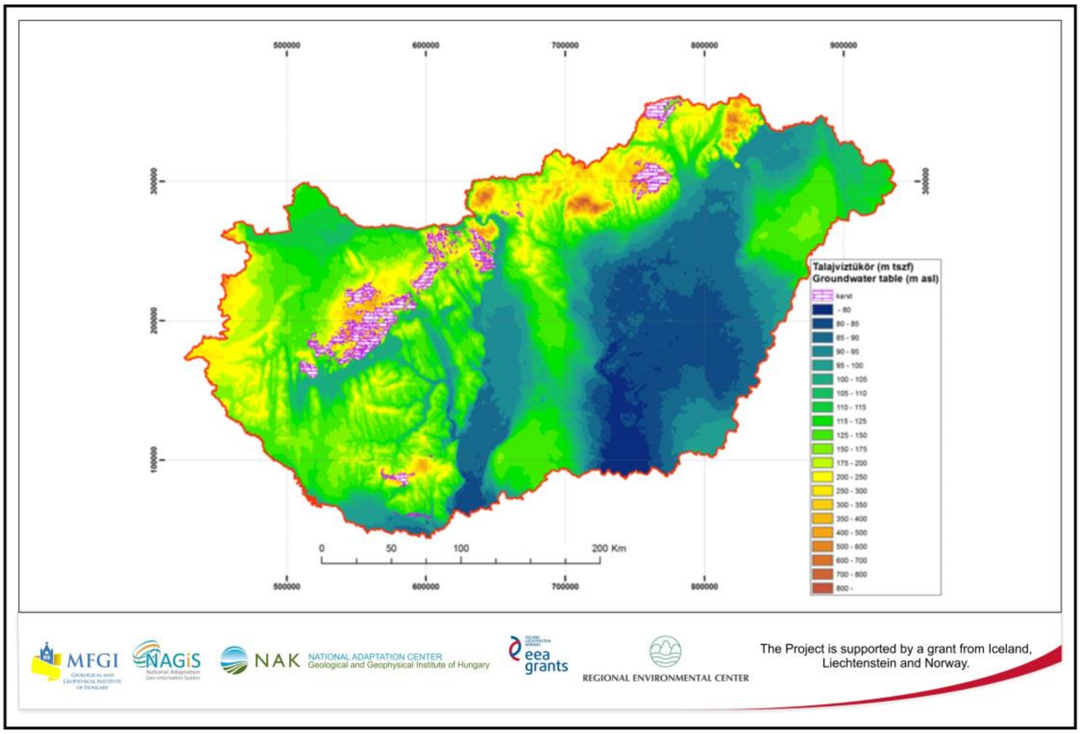

Figure 39. Simulated water table distribution for the 2021–2050 stress period. Based on ALADIN model outputs

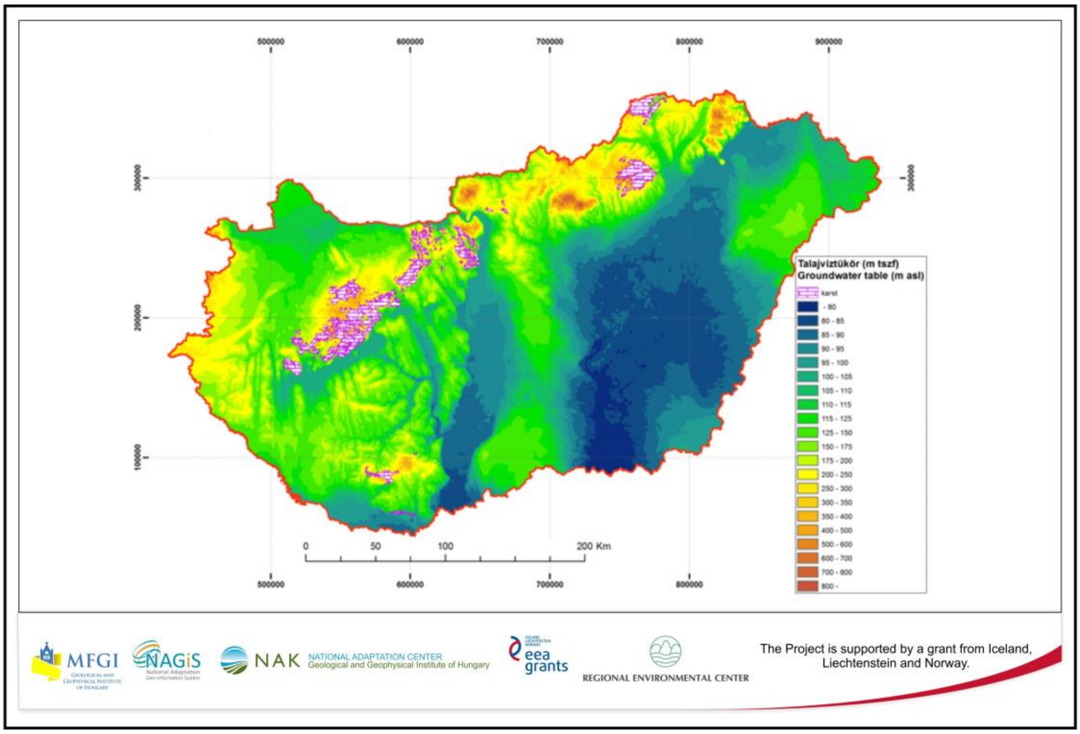

Figure 40. Simulated water table distribution for the 2071–2100 stress period. Based on ALADIN model outputs

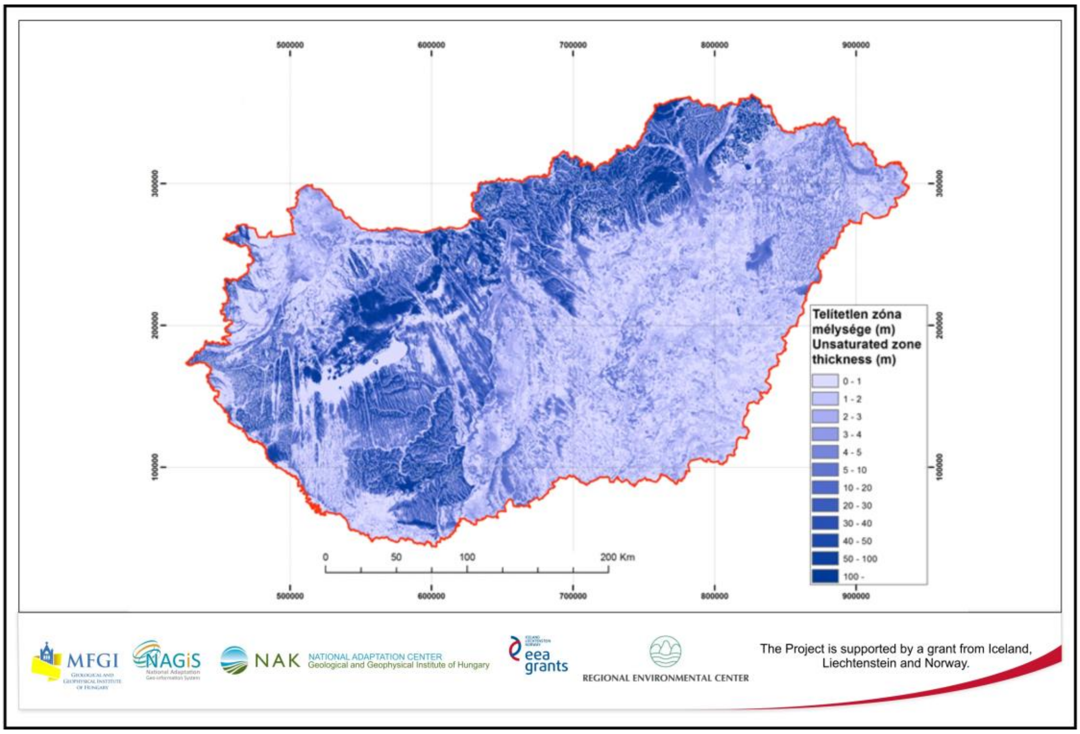

Figure 41. Simulated unsaturated zone thickness for the 1961–1965 stress period.
Based on CarpatClim-Hu data

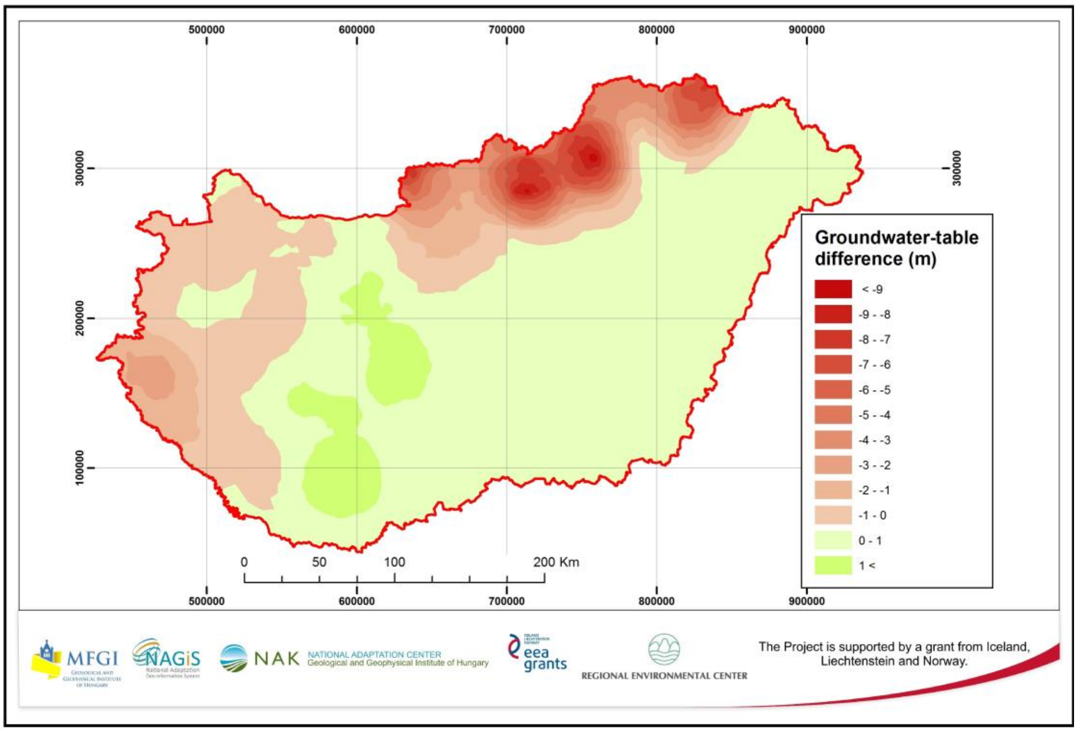

Figure 42. Groundwater table difference between the 2005–2009 and 1961–1965 simulation periods
based on CarpatClim-Hu data

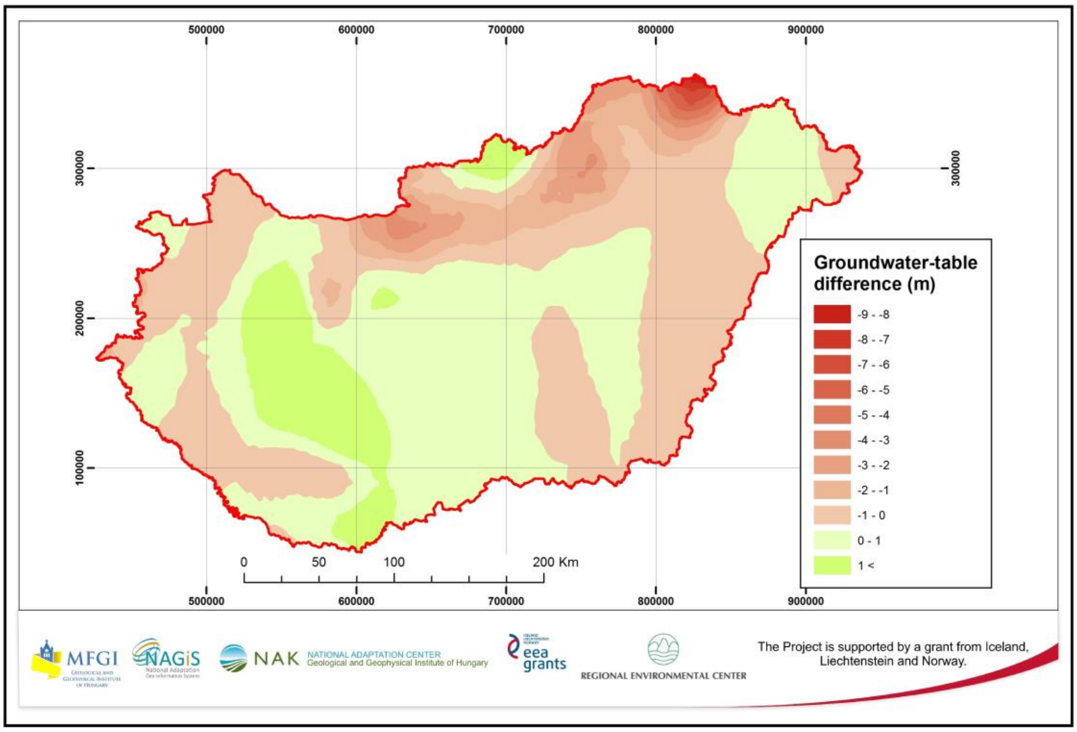

Figure 43. Groundwater table difference between the 2021–2050 and 1961–1990 simulation periods based on ALADIN model outputs

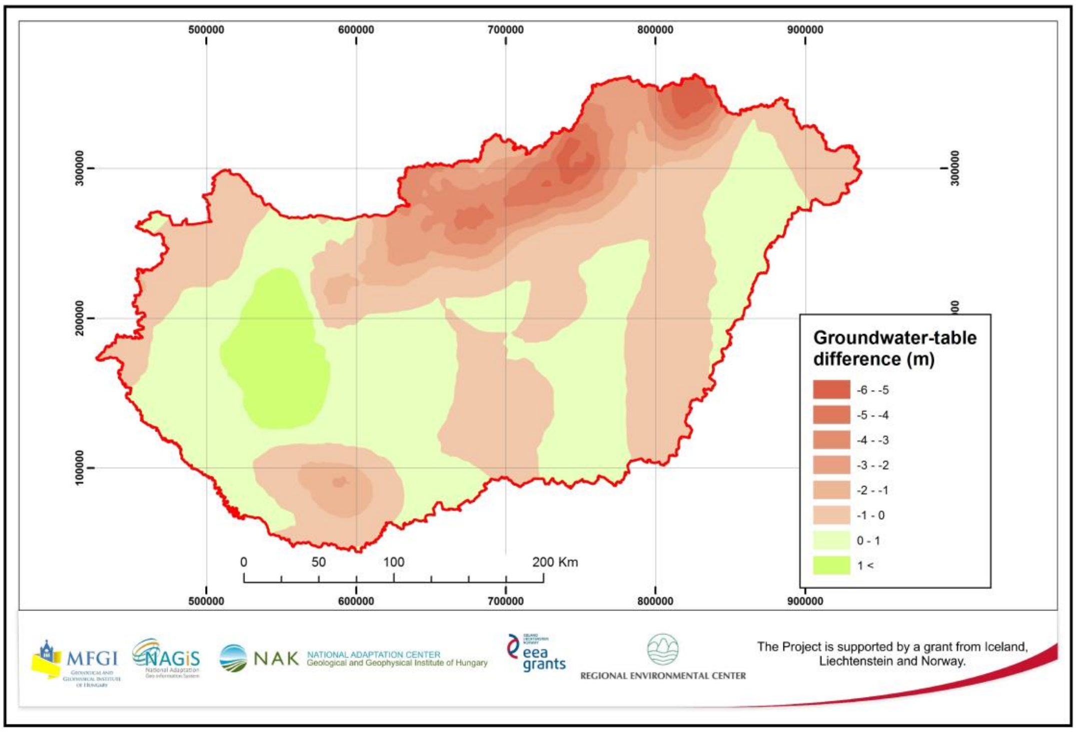

Figure 34. Groundwater table difference between the 2071–2100 and 2021–2050 simulation periods based on ALADIN model outputs

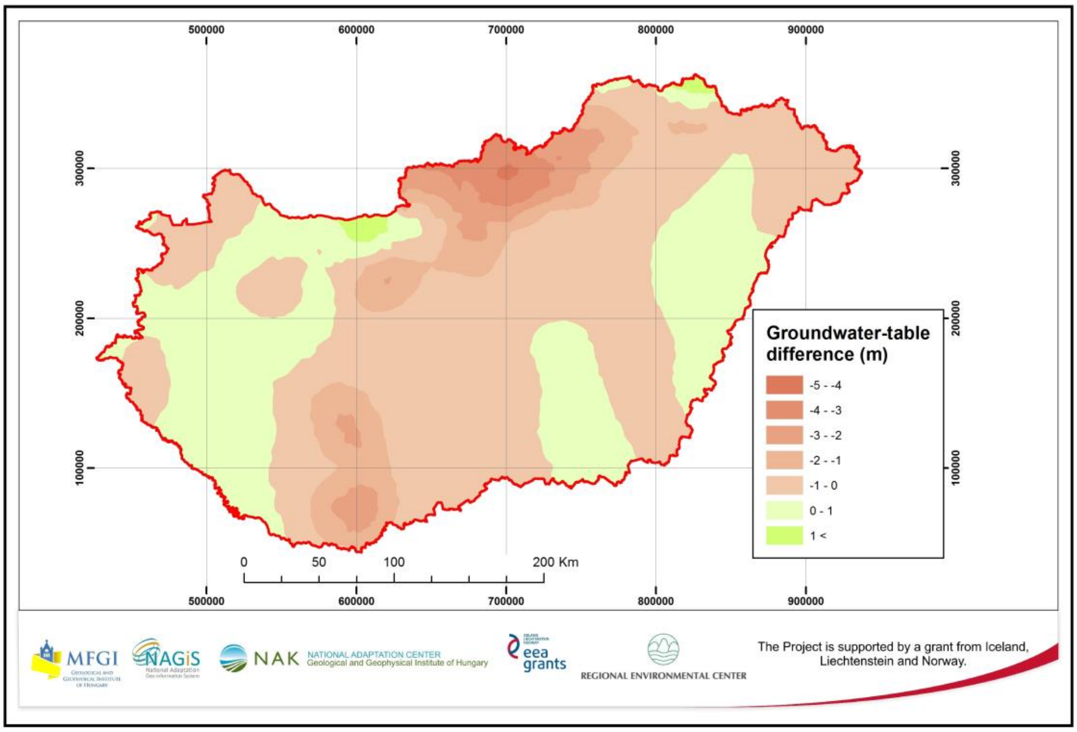

Figure 45. Groundwater table difference between the 2071–2100 and 1961–1990 simulation periods based on ALADIN model outputs

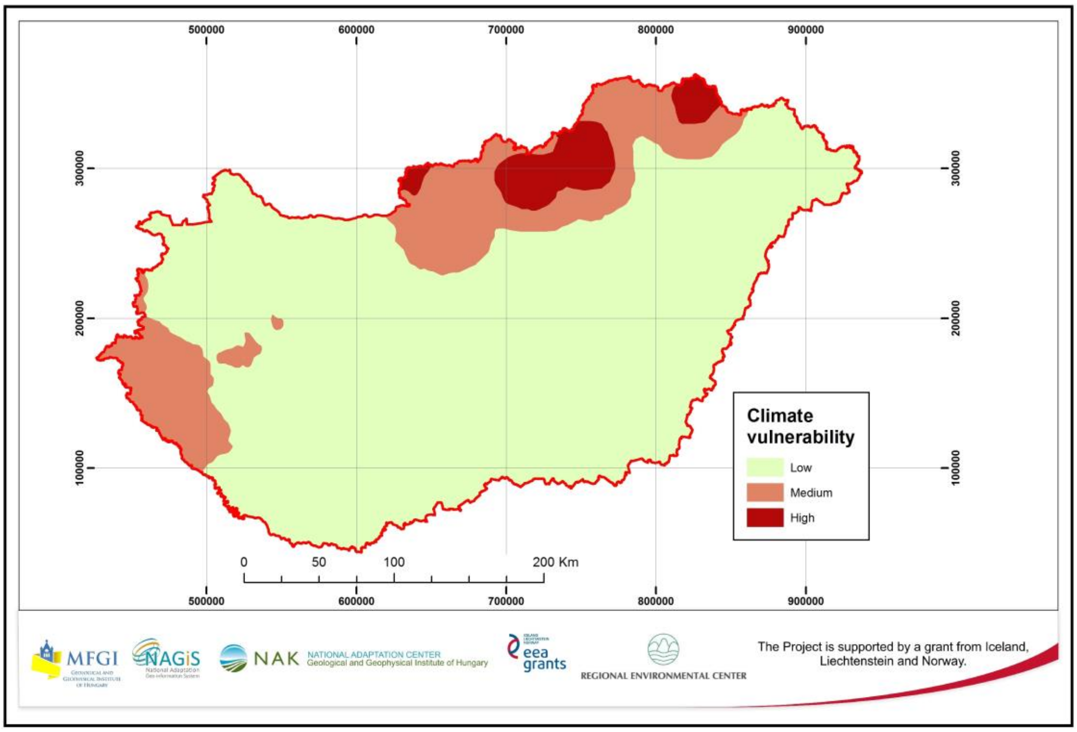

Figure 46. Simulated sensitivity map based on measured climate data

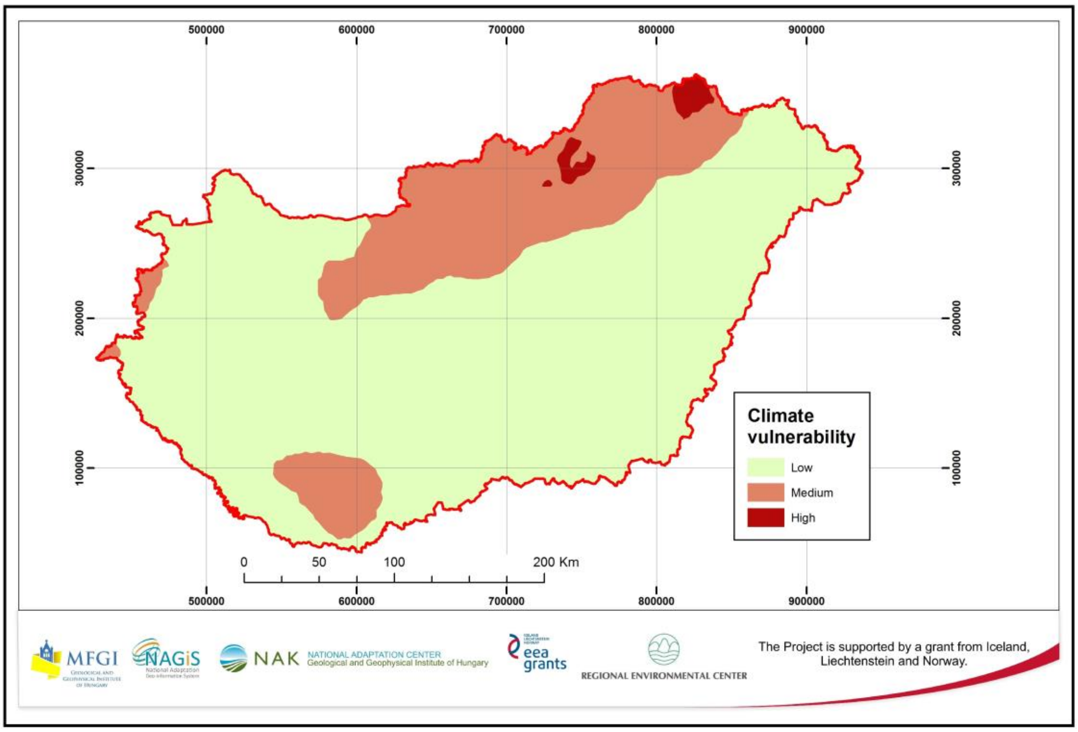

Figure 47. Simulated sensitivity map based on modelled climate data

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