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Climate impact on drinking water protected areas

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Abstract—Extreme weather conditions have caused difficulties in the Hungarian drinking water management many times in the past. High demand for drinking water in dry summer periods and the accompanying reduction in water resources lead to insufficiency in the availability of a number of water supplies, therefore causing limitations in water access. In some other cases, as a result of excessive precipitation, floods and flash floods evolved over karstic areas, and several water supplies had to be excluded from operation in order to avoid the risk of infections.

The expected increase in the number of extreme weather conditions and further possible changes in future climate necessitates the analysis of the vulnerability of drinking water resources to climate change. Since 95% of the total drinking water supply in Hungary originates from subsurface layers, significance of groundwater resources is outstanding.

Our work was carried out in the frames of the NAGiS (National Adaptation Geo-information System) project with the aim to devise a methodology for the study and determination of the vulnerability of drinking water supplies to climate. Methods have been chosen according to the CIVAS (Climate Impact and Vulnerability Assessment Scheme) model that has been developed in the frame of the international climate research project CLAVIER (Climate Change and Variability: Impact on Central and Eastern Europe). The CIVAS model, being based on the combined evaluation of exposure, sensitivity, impact, adaptability, and vulnerability provides a unified methodical scheme to quantitative climatic impact assessment.

The investigation involves the analyses of climatic parameters primarily influencing drinking water supplies and hydrogeological characteristics of the geological media that significantly determines vulnerability. Apart from the expected environmental changes, societal and economic processes have also been taken into account. Climate vulnerability has been determined on the basis of the distribution and categorization of the chosen indicators.

Further effects, independent of climate change and caused by anthropogenic activity, result in similar phenomena. It is often difficult to differentiate between natural and anthropogenic effects that occur simultaneously; therefore, anthropogenic activity is necessary to be taken into account.

In the analyses we used data of two different climate models covering two separate future time periods. Results on the basis of both climate model projections suggest that a considerable number of regions in the area under investigation appear to be vulnerable to climate change to a certain extent, and vulnerability intensifies to the end of the 21st century.

Key-words: climate change, vulnerability, exposure, sensitivity, adaptation capacity, drinking water

1. Introduction

In Hungary, 95% of drinking water is produced from subsurface layers, so in our drinking water supplies, the role of groundwater is crucial. Apart from the shallow groundwater primarily used for irrigation, a significant supply of the deep porous aquifer beneath the plains provides the majority of our drinking water. Karstic water of our various mountain ranges plays an important role as well, in some regions being the main drinking water resource. Bank filtered systems also provide a major contribution both as current and long-term future water supply.

Extreme weather conditions have caused problems concerning drinking water supplies in many cases in the past. During dry summer periods, reduced water resources and simultaneous increase of water demand caused water shortage in some areas and often led to water restrictions. In other cases, floods and karst-floods formed due to extreme rainy weather conditions, and consequently some water resources had to be suspended in order to avoid the risk of infection.

Anthropogenic activity, irrespective of climate change, can result in similar phenomena, and when these two are superimposed, distinction is difficult between them. The changing groundwater levels, due to groundwater withdrawal, together with groundwater quality changes caused by anthropogenic impacts are added to the impacts of climate change and amplified.

One part of the NAGiS (National Adaptation Geo-information System) project was to determine and characterize the climate vulnerability of drinking water supplies. The effect of climate change differs spatially, depending on local climate, geology, hydrology, and hydrogeology. Our task within the project was to characterize the most important climate elements of the expected climate change, geological environment, and hydrogeological conditions that mainly determine the vulnerability of drinking water resources. The effects of climate change on water supplies, together with the attenuation and elimination activities, have social and economic consequences as well. Therefore, our study was complemented with the characterization of adaptation possibilities to the changing environment. In the course of our work, a data system containing geospatial elements was built, aiming to improve our basis for planning and developing adaptation and mitigation techniques to any adverse effects.

2. Methods

In order to assess the climate vulnerability of drinking water protected areas, we used the CIVAS model (Climate Impact and Vulnerability Assessment Scheme) established in the CLAVIER (Climate Change and Variability: Impact on Central and Eastern Europe) international climate research project. The CIVAS model uses the approach proposed by the 4th Assessment Report of the Intergovernmental Platform for Climate Change (IPCC, 2007). The philosophy of the CIVAS model is similar to the DPSIR2 ('Driving Force – Pressure –State – Impact – Response') model, which is established and widely used in environmental status assessments in the European Union (*Pálvölgyi et al.*, 2010).

The effects of climate change in the CIVAS model are examined in the exposure → sensitivity → impact → adaptive capacity → vulnerability context. In our study, climate vulnerability assessment has been carried out for the drinking water protected areas and drinking water supply systems. In addition to the expected environmental changes, social and economic processes have been considered. Since anthropogenic activity may exacerbate the effects of climate change on drinking water resources, it is necessary to be addressed in the assessment of climate vulnerability. Therefore, in our work we applied the modified version of the CIVAS model with the following elements.

Exposure is related to climate and the expected climatic changes, for which data can be extracted from archived meteorological data series or climate models. It is characteristic to a geographical location.

Sensitivity is a specificity of the impacted system, a drinking water supply in this case. The sensitivity of the affected system is independent of climate change and primarily determined by the environmental and physical parameters of the system. In case of drinking water supplies, these features are related to the geological and hydrogeological characteristics.

Anthropogenic impacts on groundwater quantity and quality, which are independent of climate change, represent changes due to human activity.

Potential impact is a combined indicator of exposure, sensitivity, and other environmental impacts. It is peculiar to both the geographic location and the impacted system under investigation.

Adaptive capacity is a non-climatic factor, which represents the local social and economic answers to the mitigation of the unfavorable effects of climate change. In case of drinking water supplies, beside social and economic factors, technical factors are also important which maintain the quality and guarantee the security of drinking water services under the changing circumstances.

V*ulnerability* is a complex indicator, which integrates exposure (the expected climatic change at a geographic location), climate sensitivity (the physical characteristics of the natural environment affected by climate change at a given geographic location), and the adaptive capacity (the social and economic abilities to minimize the unfavorable changes).

For the investigation and definition of adaptive capacity indices, information was needed directly from the groundwater supply operator. We did not have the opportunity to consult all the presently accredited 34 regional waterworks, therefore we selected a pilot area, where the adaptive capacity and climate vulnerability assessment methodology could be worked out in detail. The selected area (*Fig. 1*) lies within the operational area of the Danube River Regional Waterworks Corporation (DMRV Zrt.)

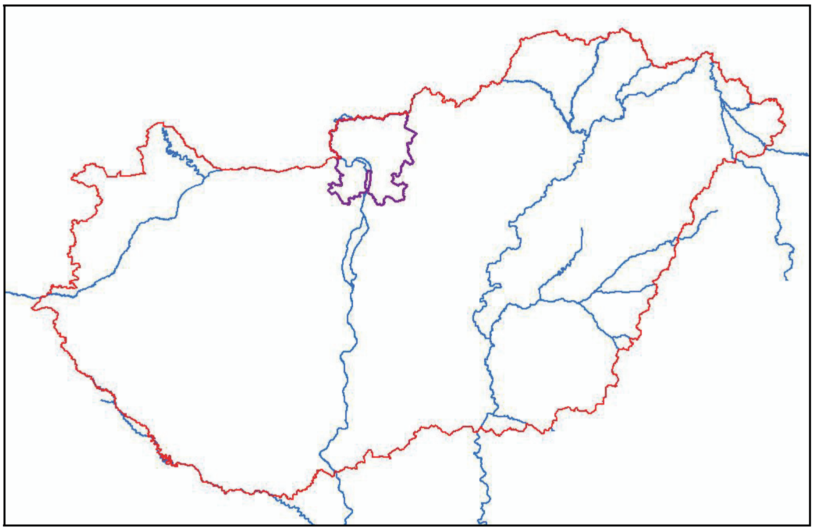

Fig. 1. Study area located in the operational area of the DMRV.

Climate vulnerability was characterized by the spatial distribution and categorization of all the used indicators. The final results have been uploaded into the NAGiS system.

3. Exposure

Climate change seldom has direct effect on drinking water protected areas. The subsurface reserves are mostly indirectly related to surface hydrological and meteorological processes which are subject to climate change. Therefore, climate change results in indirect changes in groundwater reserves and groundwater flow parameters. The factor influencing them is related to surface processes, infiltration, and discharge (including evapotranspiration).

Processes at the areas of infiltration are mainly regulated by the variability of precipitation and the extent of evapotranspiration of the given soil horizon, in the period prior to the precipitation event. The latter is basically the function of temperature change. At the discharge areas of groundwater, the effects of both precipitation and temperature and the closely related evapotranspiration processes are faster and more direct.

Based on the above considerations, the exposure of drinking water protected areas to climate change can be characterized by the investigation of the meteorological parameters influencing infiltration and discharge processes to the highest extent.

A unique groundwater system is the bank-filtration system, the exposure of which is regulated primarily by the meteorological conditions of the catchment area (in many cases having a transboundary character) of the recharging surface water system instead of the nearby area. The exposure of these groundwater systems are characterized mainly by the water level fluctuations of surface water systems. The issue of bank-filtration systems is outside of the frames of this work, however, for a comprehensive analysis, it is needed to be included in future investigations.

3.1. Exposure to climate change

The climate database for our analyses consisted of two types of data. CarpatClim-HU (*Szalai et al.*, 2013; *Bihari et al.*, 2017) data are climatological measurements interpolated to a regular grid, while modeled data comprise simulated data of the ALADIN-Climate and RegCM climate models based on the climate scenario A1B. Grid of the different datasets overlap, therefore the spatial resolution of roughly 10 km is consistent. CarpatClim-HU covers the time range 1961–2010, while data of the climate models are provided for the periods 1961–1990 (the reference period), 2021–2050, and 2071–2100. All datasets have been provided by the Hungarian Meteorological Service.

We used four climate indicators that have been chosen according to the aim of the analyses and the availability of the data necessary for the calculations.

The *aridity index* is defined as the ratio of precipitation and potential evapotranspiration. Potential evapotranspiration has been calculated using Thornthwaite's method (*Ács* and *Breuer,* 2013).

The Pálfai drought index (PDI) indicates the severity of droughts in the individual years and shows a strong correlation with the decrease of crop yield. PDI has a modified version called the *modified Pálfai drought index* (PaDI) that has been developed in the frames of the DMCSEE project. It shares the applicability of PDI, however, data necessity for the index is less and calculation is simpler (*Hungarian Meteorological Service*, 2012). Therefore, in our study we applied the modified PDI for our investigations.

The quantity of water filtrating under ground is strongly influenced by the annual distribution of precipitation. Precipitation of the winter hydrological half-year mainly determines annual infiltration (*Kessler*, 1954). In order to analyze precipitation trends over the consecutive hydrological half-years, we defined an indicator as the *ratio of precipitation sums of the winter and summer half-years*, where the summer half-year comprises the months from May to October, and the winter half-year is the period between November and the end of April.

For the further investigation into water budget, we determined the *climatic water balances* for the different areas of the country and their possible future changes. Climatic water balance in our analysis is defined as the difference between the annual sums of precipitation and potential evapotranspiration, where potential evapotranspiration has been calculated according to the method of Thornthwaite (*Ács* and *Breuer*, 2013).

As the majority of the chosen indicators yield one value for a year, we determined all the indices in annual resolution. From the annual values decadal and thirty-year means were then calculated.

Possible future changes in the precipitation and temperature conditions were estimated with the analysis of the climate model data available for the NAGiS project. We determined rates and signs of the changes for the 2021–2050 and 2071–2100 time periods compared to the reference period.

3.2. Past climate

Different indices for the consecutive decades show slightly different tendencies, however, the main characteristics in the results for the past climate are similar. In general, climate in the area of Hungary had gradually become dryer from 1961 until around the turn of the century, when a more humid period began. A significant decrease in aridity occurred in the first decade of the 21st century.

Fig. 2 shows the spatial distribution of the mean annual climatic water balance values for the reference period (1961–1990), based on CarpatClim-HU data. Analysis of the climatic water balance provides information on the water budget of various regions in the country.

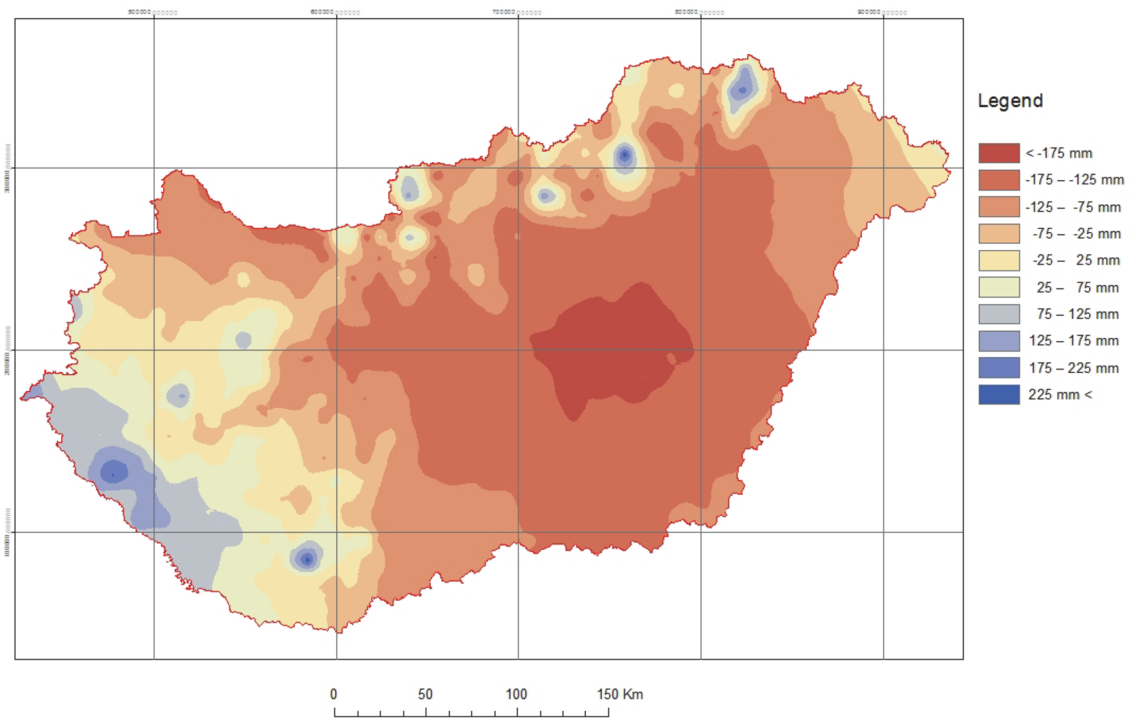

Fig. 2. Spatial distribution of the annual mean climatic water balance in the reference period based on CarpatClim-HU data.

Fig. 2 indicates the areas of Hungary which abounded in precipitation in the reference period, and where water shortage was more general. On the basis of water balance analysis, lowland areas appear to be the most arid regions. Annual water balance is negative for the largest part of the country, meaning that the amount of water, that the area is capable of evaporating under the specific climate conditions, exceeds average precipitation. The largest extent of water shortage is present in the middle areas of Alföld. Along with the increase in altitude, water balance gradually increases and turns into positive, reaching a maximum in hilly areas and the southwestern part of Transdanubia.

3.3. Future climate

It is necessary to note that climate model simulations naturally contain a set of uncertainties that often lead to differences or even contradictions in data calculated by different models (*Szépszó et al.*, 2015). The purpose of climate models is to describe the behavior of the climate system, as a whole, that is only possible in an approximate way, due to the complexity of physical processes. The reason behind the uncertainties lies within the differences in approximations, calculation methods, and parametrizations. When investigating future climate, analyses are therefore suggested to be carried out with data of several climate models or simulations.

Projected future changes in the aridity index based on ALADIN-Climate data show a continuous decrease from the western parts of Hungary towards the eastern areas, suggesting the climate to get dryer in the whole country but to a different extent regionally. The drying process is likely to intensify by the end of the 21st century. We can draw a similar conclusion from the calculations using the data of RegCM. Aridity is expected to intensify generally in the future, although the spatial distribution of the changes differ from the one based on ALADIN data.

The two models estimate mainly similar future changes concerning the modified Pálfai drought index. According to the results, intensification of aridity is most probable in the middle and southern parts of the country and less affected are the northern, northwestern, and northeastern regions.

The models yield different estimations for the changes in the rate of precipitation sums of the winter and summer hydrological half-years for the 2021–2050 period. ALADIN data suggest slight changes being negative in most areas and positive in the southern and eastern parts. RegCM indicates negative changes for the whole country, with the largest extent relating to the eastern regions. However, an unambiguous increase in the values of precipitation rates is expected for the end of the 21st century on the basis of both model projections, which means an increase in winter and a decrease in summer precipitation. Based on these results we draw the conclusion that projections of climate models suggest a shift in precipitation amounts toward the winter half-years for most parts of Hungary, which tendency means that the summer half-years are probable to get more arid in the future.

The projected changes in the mean annual climatic water balance are summarized in *Fig. 3*. Both of the climate models estimate the water balance to shift to the negative side of the spectrum throughout the whole area of Hungary. ALADIN places the largest decrease in the water budget to the eastern parts of Alföld, while RegCM estimates it to occur in the southwest regions. Less affected areas are expected to be the western, northern, and northwestern regions. Drying tendencies are likely to intensify with time till the end of the 21st century.

The research carried out in the frame of the CLAVIER project provided results in accordance with our conclusions. Analyses based on data provided by the REMO climate model indicate a widespread decrease in summer precipitation for the middle areas of Europe, while winter precipitation is expected to increase.

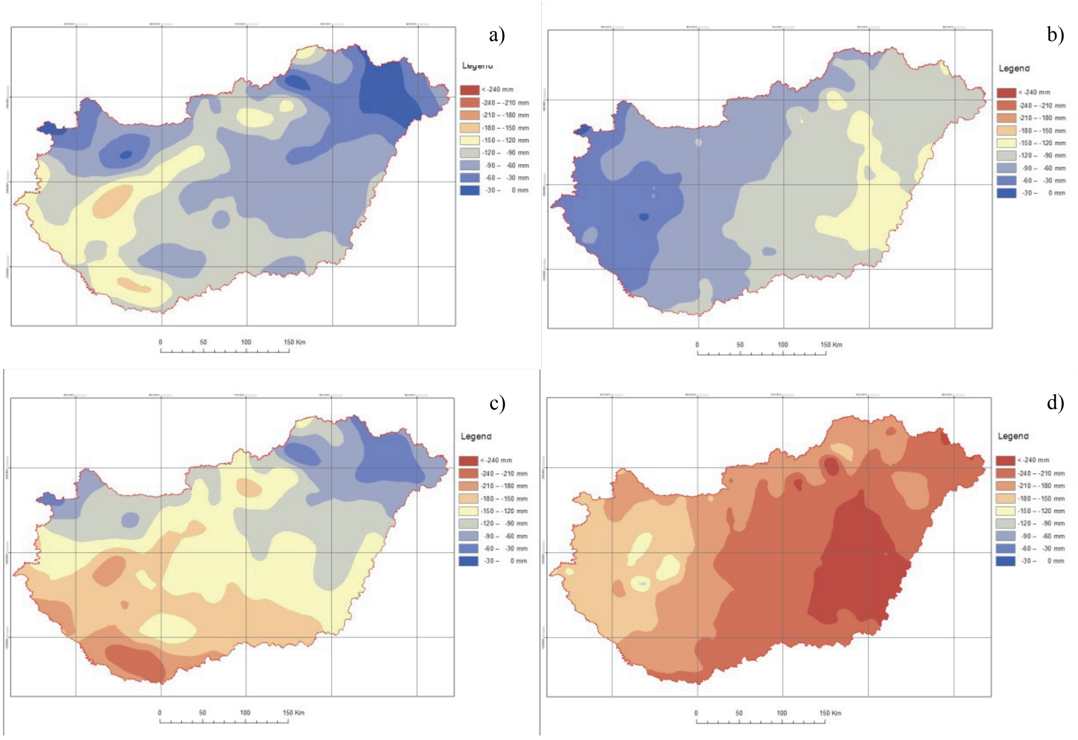

Fig. 3. Spatial distribution of the changes in the climatic water balance for the 2021–2050 (a, b) and 2071–2100 (c, d) periods on the basis of RegCM (a, c) and ALADIN-Climate (b, d) data.

4. *Climate sensitivity of drinking water protection areas*

The effect of climate change on groundwater is not so direct and intense as in case of the surface water system. Often, what we observe is the result of changes that have been happening over several years. As the change has been continuous for a long time in most cases, upon termination of the unfavorable effect, the original status can be achieved slowly.

The infiltrating water is transported either through the available subsurface pore space or fissure network of the karst system. Due to the subsurface conditions, the movement of groundwater is significantly slowed down, and processes are acting on a longer time scale. The degree of porosity is regulated by geological processes, therefore, the climate sensitivity of drinking water supplies is determined by the geological and hydrogeological properties of the recharge and drinking water protected areas.

Based on the different climate sensitivity of the groundwater systems and on the hydrological constraints, climate sensitivity categories can be established (*Table 1*).

Table 1. Climate sensitivity categories of drinking water systems

Type of aquifer	Climate sensitivity category	Intensity of climate sensitivity
porous aquifer	porous aquifer < 30 m	very sensitive
	porous aquifer 30–100 m	moderately sensitive
	porous aquifer >100 m	no direct effect
karst system	karstic aquifer with well developed channel network	very sensitive
	open karst system	sensitive
	confined karst system connected to recharge area	moderately sensitive
	deep karst system, part of regional groundwater flow system	no direct effect
bank filtration system	bank-filtration system	sensitive
	alluvial aquifer affected by watercourse	sensitive
fractured aquifer	fractured aquifer	moderately sensitive
surface water	surface water	very sensitive

Based on the drinking water database (available in the frames of cooperation of General Directorate of Water Management and Geological and Geophysical Institute of Hungary), categorization has been carried out on all the 2018 drinking water protected areas of Hungary into the climate sensitivity categories listed in *Table 1*.

The categorization of drinking water protected areas regarding climate sensitivity is not clear in all cases. If the aquifer can not be categorized unambiguously into one of the categories, first the dominant character is considered as a basis, and indication is made to the secondary aquifer type. An example for this is the discrimination among the confined karstic aquifers, as these are hydraulically connected to the unconfined karstic aquifers, and in case of the confined karstic aquifers, climate sensitivity is determined by the travel-time of water particles. There are no sharp boundaries among the bank-filtration water system and the alluvial aquifer affected by the watercourse, and the transitions are related to the similarity of the environments. In our consideration, a drinking water protected area is considered as a bank-filtration system, where the contribution of the surface water component is more than 50%. In order to define the percentage of the contributing sources, we used the values determined by numerical flow modeling of the diagnostic measurements in the „National Groundwater Protection Program”. In porous aquifers, it is frequently the case that wells are penetrating to different depths. In this case, according to a „worst-case-scenario”, the depth of the shallowest well gives the basis of the climate sensitivity qualification. Due to this reason, in the dominantly shallow porous aquifers, there are wells often taping deeper aquifer horizons (30 to 100 m, rarely greater than 100 m), and based on their secondary character, they belong to the less climate-sensitive category.

Fig. 4 shows the climate sensitivity of the drinking water protected areas using centroid coordinates of each drinking water protected area.

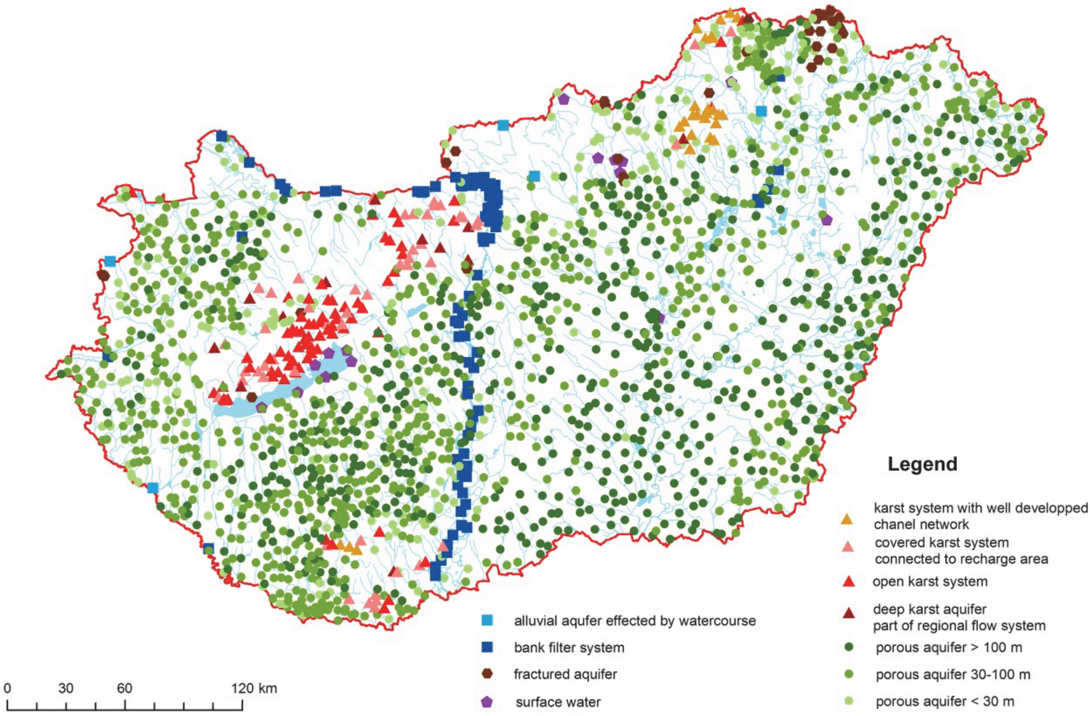

Fig. 4. Climate sensitivity of the drinking water protected areas

Applying the sensitivity categories we also determined the intensity of the climate sensitivity of drinking water protected areas (*Fig. 5*).

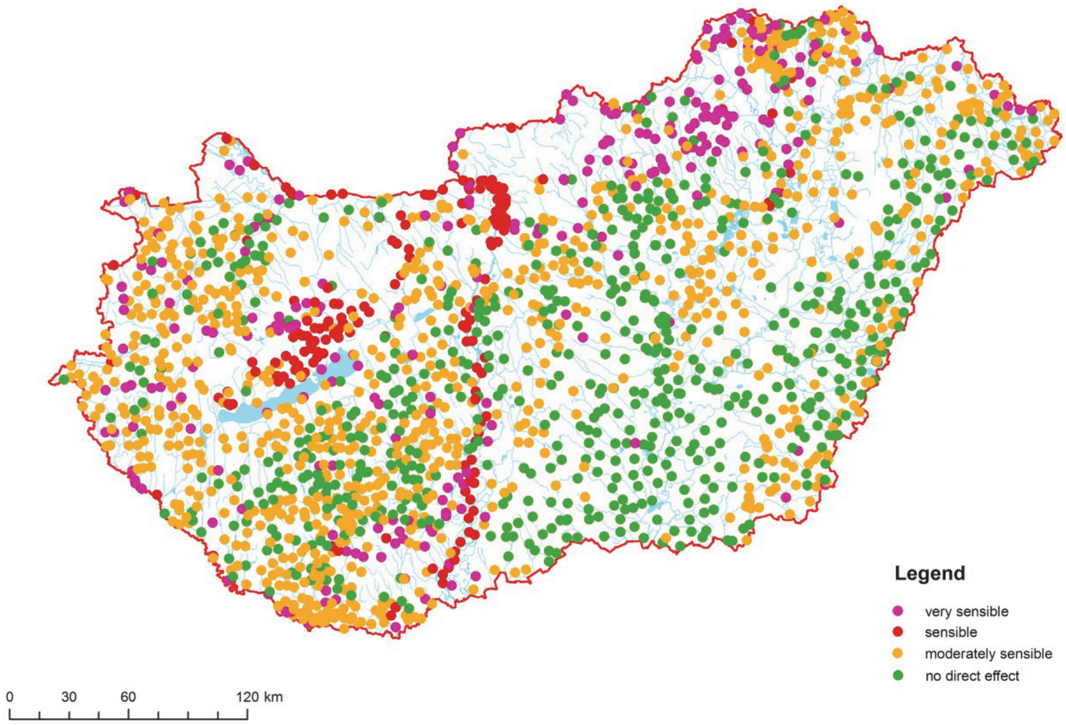

Fig. 5. Intensity of the climate sensitivity of drinking water protected areas.

4.1. Current demand on groundwater resources

It is difficult in all aspects to differentiate between the effects of climate change and other anthropogenic activities. In groundwater systems these are superimposed and amplify each other. For this reason, it is essential to consider the water production data of the past decades for the investigation of climate change. The effect of overexploitation of water resources is now a global pressure on water resources (*Green et al.*, 2011). The production of groundwater, primarily for drinking water purposes, has increased significantly in Hungary since the 50s. The increased water exploitation can result in further significant water level decline, and in specific regions, it can even reach the limits of the exploitable quantities.

We carried out the investigation of groundwater level decline due to exploitations so far, using monitoring data of our groundwater monitoring network and by the interpretation of simulation results of numerical groundwater flow models. Based on the results, we determined the intensity of overexploitation.

5. *Results regarding the pilot area*

A pilot area was selected to characterize the adaptation capability and vulnerability to climate change. This pilot area (the operation territory of DMRV), situated at the Danube Bend, is mainly of mountainous character.

5.1. Climate sensitivity of the pilot area

Due to the geological settings, the drinking water resources are located in a concentrated way. There are only a few drinking water protected areas situated in the distribution area of volcanic formations with limited groundwater potential. The bank-filtration systems of greater volume drinking water potential and prognostic supply potential are located alongside the river Danube.

In addition to the display of drinking water protected area centroids on the thematic climate sensitivity category map, we also assigned these to the settlements, in order to provide a basis for the climate vulnerability assessment, which can be determined in relation to settlements. For the assignment, we identified the settlements directly supplied by the respective drinking water protected areas. However, for emergency cases, DMRV has the technological capacity within its operational area which enables any regional water supply to be governed to secure water supply of another region. As the drinking water supply of a settlement is often provided by more than one drinking water protected area, the climate sensitivity categorization is implemented on the basis of the least sensitive drinking water protected area (*Figs. 6* and *7*).

5.2. Climate adaptation of settlements regarding water supply

As a result of climate change, the extent and frequency of summer heat wave periods are expected to increase significantly and also changes in the distribution of precipitation are expected to take place. In the winter semester, precipitation is expected to increase, while in the summer semester, which is the vegetation growing season, it is expected to decrease. As a result, water demand of the population is anticipated to increase, partly due to domestic water use, as well as water used for irrigation in the private sector. Therefore, regarding climate adaptation, the current status and upgradeability of the infrastructure and the water demand of the population are the main factors.

In addition to climate exposure and climate sensitivity, we need to define climate adaptation for the climate vulnerability assessment of the settlements regarding drinking water supplies. For the investigation of adaptation we used the social-economic indices of the National Settlement Development and Planning Information System (TeIR) of the KSH-T-STAR and NAV SZJA databases, and data relevant to the status of the water supply system infrastructure in the pilot area provided by DMRV.

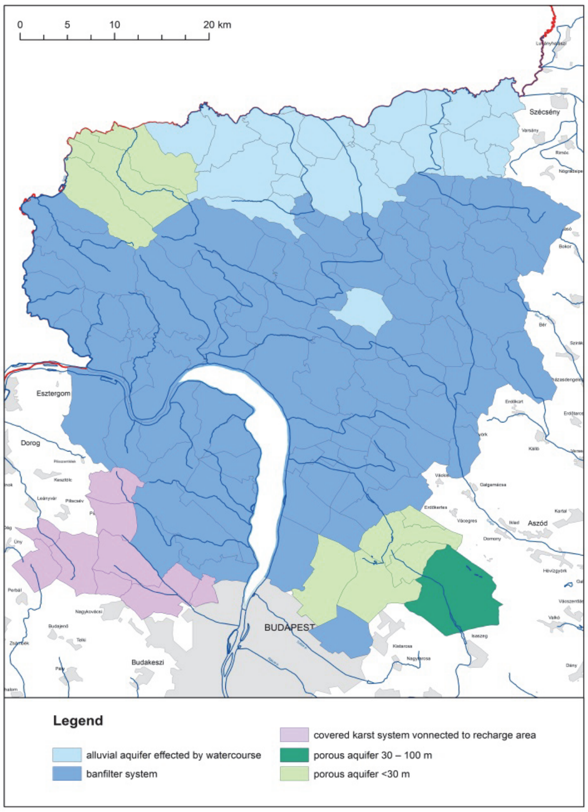

Fig. 6. Climate sensitivity of drinking water protected areas of the settlements based on the least sensitive direct water supply type, within the operational area of the DMRV.

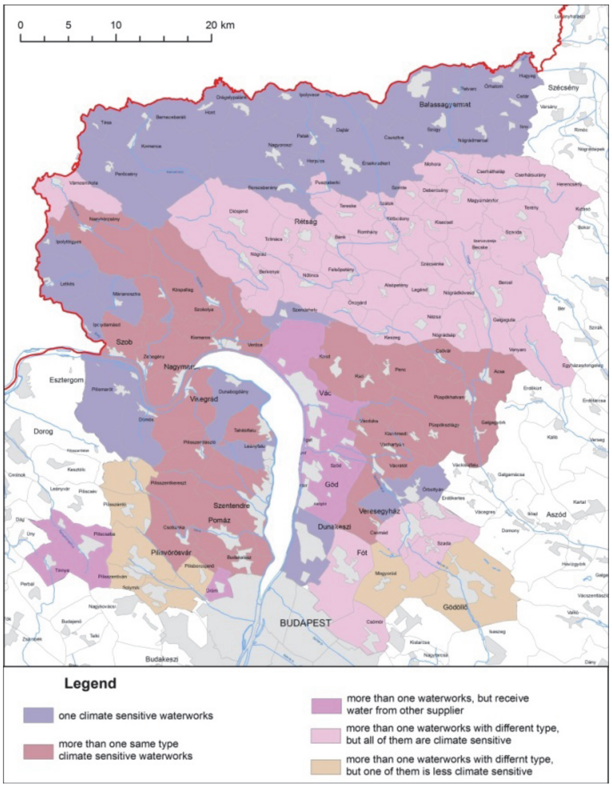

Fig. 7. Climate sensitivity of drinking water protected areas of the settlements based on the number and climate sensitivity of the direct water supply, within the operational area of the DMRV.

In the first stage of the investigation, we delineated data needs and classified data specificities, in cooperation with the DMRV. The important tasks of this stage were the screening of data for errors, checking and correction of outlying values.

It was an important aspect in the assessment, that data should possibly represent a single, specific year; however, this could be satisfied only partially. Data related to the status of the infrastructure is up-to-date, that is representative of the present conditions, while the social-economic indices are available uniformly for the year 2013.

With regard to the above, we used the following specific indices for the determination of climate adaptation:

1) The infrastructural factors of climate adaptation:
   a) the number of drinking water protected areas directly supplying a given settlement,
   b) the expandability of the drinking water protected area (category),
   c) the potential to increase drinking water supply capacity (category).
2) The social-economic factors of climate adaptation:
   a) drinking water consumption per inhabitant, 2013 (m^3/per capita),
   b) all domestic income per inhabitant, 2013 (HUF/per capita/year).

In the further stages of the investigation, we related category values to each indices, then by summing up the category values, we determined the intensity of climate adaptation for each settlement.

5.3. The infrastructural factors of climate adaptation

Regarding water supplies, the intensity of climate adaptation is fundamentally influenced by the number of drinking water protected areas directly supplying a settlement, as well as the upgradeability of the water supply system infrastructure. Using data obtained from the DMRV, we could define the number of operating drinking water protected areas supplying each settlement (*Fig. 8*). We also investigated whether drinking water protected areas can be extended or water supply system infrastructure supplying a settlement can be increased. Meanwhile, it is important to emphasize that as a result of water supply network establishment, the drinking water supply can always be secured by appropriate water governance. We defined three categories regarding water supply security in climate adaptation (*Fig. 8*). We considered conditions the least favorable, when a settlement is supplied solely by a single drinking water protected area. Consequently, the most favorable case is when more than two drinking water protected areas supply the given settlement. In this respect, there are significant differences throughout the operational area of DMRV. Along the river Ipoly, settlements are usually supplied only by a single drinking water protected area, but in the Budapest area, most of the settlements are supplied by more than one drinking water protected areas.

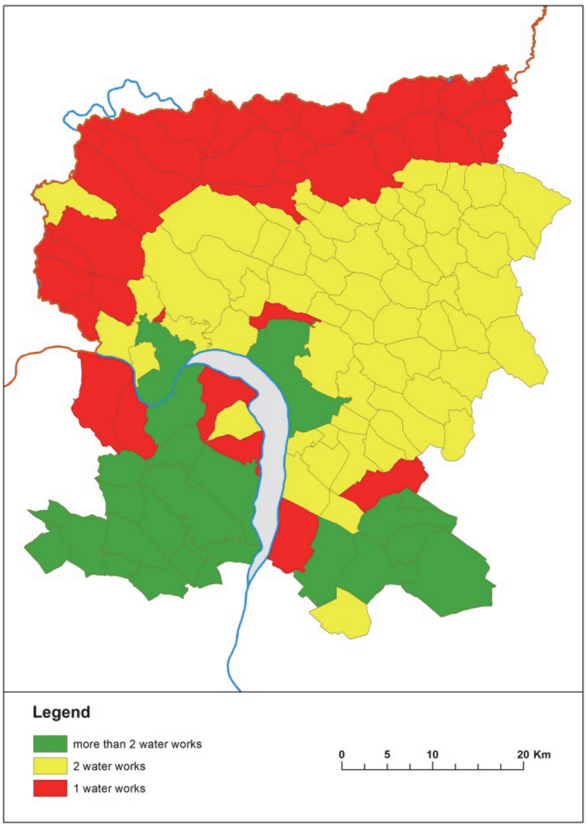

Fig. 8. Number of drinking water protected areas supplying settlements in the operational area of DMRV, 2015 (Source of data: DMRV).

Regarding the upgradeability of the drinking water protected areas, the situation is more uniform. Within the pilot area, for the majority of the settlements, there are drinking water protected areas where both the extension and the capacity increases are possible, according to the data provided by DMRV. Extension of a drinking water protected area involves the possibility to establish a new production well. While the increase of capacity means the increase of existing production capacities, exchange, or modernization of existing production wells. Development of drinking water protected areas can be hindered mainly by the built-up of the area or the contamination of the water resources; however, it requires great financial investment, in general. There are two significant connected areas in the southern section along the river Ipoly and the Danube Bend, where related problems arise.

5.4. Social–economic factors of climate adaptation

The fundamental objective of climate adaptation investigation is to determine the capability of society to respond to challenges caused by climate change. In case of drinking water supplies, the most important socio-economic questions are the water demand of the population and the ability of the individuals and communities to tackle the problems. The public water demand can be defined simply based on the water consumption per person indices, the situation is, however, more complex. The main issue in this context is whether the individual or the local community has the capability to take necessary measures in tackling the problems. To answer this question, the figure of all domestic income per person, which is representative of the public income ratio, is well suited, since development of a region is primarily determined by the income of the population (*Faluvégi*, 2000). With the investigation of population income we gain information on the differences in the state of development. Based on the research carried out by *Bíró* and *Molnár* (2004) it can be stated, that there is a strong, direct relationship between the economic and infrastructural developments, therefore it is justified to investigate income ratio in the study of climate adaptation.

This relationship is well indicated by the strong correlation of public income ratio and water consumption figures as well. There is a clear positive, linear correlation between population income ratio and water consumption with the exception of certain outlying values. These outlying values are related to unique impacts. The highest amount of water consumption per person was observed for Visegrád in 2013, primarily due to tourism.

Regarding the territorial differences in water consumption (*Fig. 9*), there is a significant duality in the region. Settlements of the Budapest agglomeration, the area of the Danube Bend, and the Lower-Ipoly Valley are characterized by higher water consumption, while the settlements of Nógrád County have mostly lower (30 m^3/per capita) consumption figures.

There are also significant regional differences in the income ratios of the area. The income ratio is the highest in the area of Budapest, in the settlements of the agglomeration. There are average values in the area of the Danube Bend, of Vác, and Balassagyarmat. In the remaining part of the pilot area, the income ratio per inhabitant is low.

5.5. Determination of climate adaptation of the settlements

As a result of the detailed investigation on the individual impact factors, we determined the climate adaptation of the settlements rearing water supply (*Fig. 10*). In the investigation, we considered the number of drinking water protected areas responsible directly for water supply, the potential to develop water supply, the public water demand, and the indices related to the income ratio of the population with equal weights. With respect to climate adaptation, it can be judged positively if there are more than one drinking water protected areas which supply a settlement, or there is a potential to extend the drinking water protected area and develop its capacity, and if the population has low water demand and favorable income ratio.

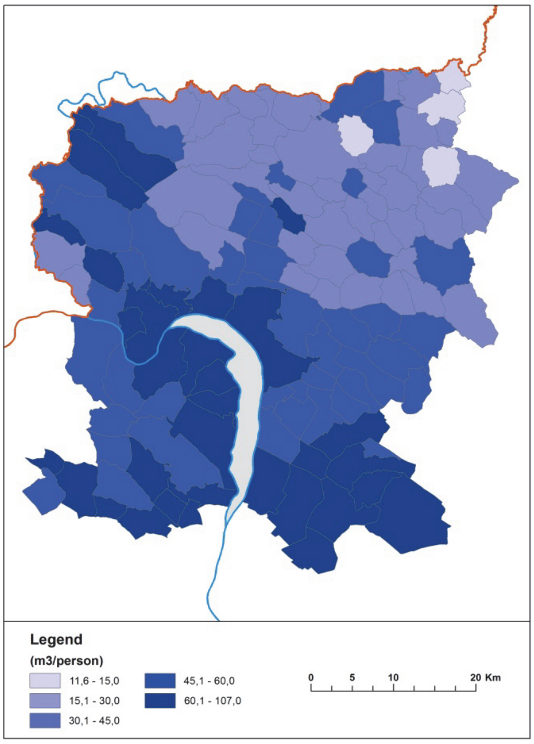

Fig. 9. The specific water consumption of settlements in the operational area of the DMRV, 2013 (Source of data: DMRV, KSH T-STAR).

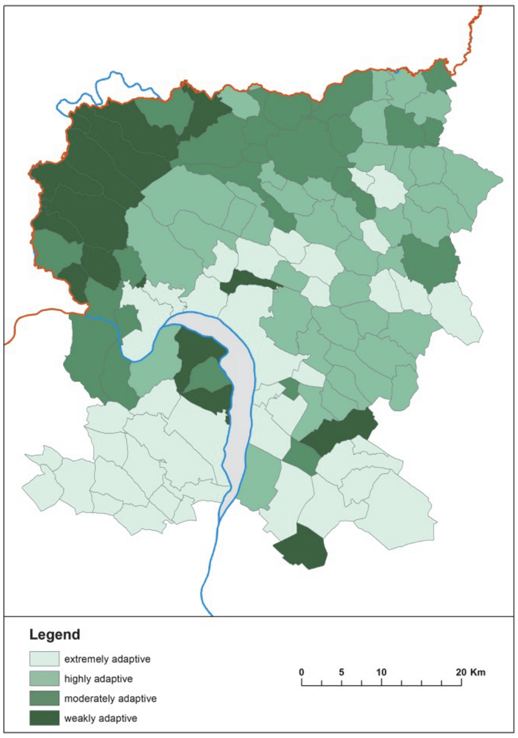

Fig. 10. Climate adaptation of the settlements regarding water supply.

We classified climate adaptation into four categories on the following basis: extreme, high, moderate, and weak adaptations. Regarding climate adaptation, the least favorable region is proved to be the Lower-Ipoly Valley area. In this area all of the investigated indices are poor. The majority of the settlements are supplied by only one drinking water protected area, and the potential to develop the water supply system is limited, but the water consumption is high and the income ratio of the population is low.

The settlements in the right bank of the Danube River Bend are also in poor conditions, regarding climate adaptation. Problems are mainly due to deficiencies in the infrastructure and high water consumption of the population.

5.6. Climate vulnerability assessment of drinking water protected areas

The climate-vulnerability of drinking water protected areas is derived from the combined assessment of exposure, climate sensitivity, and adaptation according to the introduced methodology.

We identified categories in order to characterize the intensity of climate vulnerability. In deriving the categories, exposure, climate sensitivity, pressure, and adaptation factors are considered with uniform weights for the derivation of the combined indicator. Indicator values and climate vulnerability categories are defined in a way that they could be applicable country-wide, following the same methodology.

The combined exposure indicator is thus calculated on the basis of UNEP aridity index and the meteorological water balance value.

The climate vulnerability of drinking water protected areas was determined based on the data of both of the two climate models for the two future time periods. Figs. *11* and *12* well indicate areas with different intensities of climate-vulnerability, already present in the period 2021–2050, according to both models. As time progresses, the intensity of climate vulnerability is expected to increase for the period between 2071 and 2100.

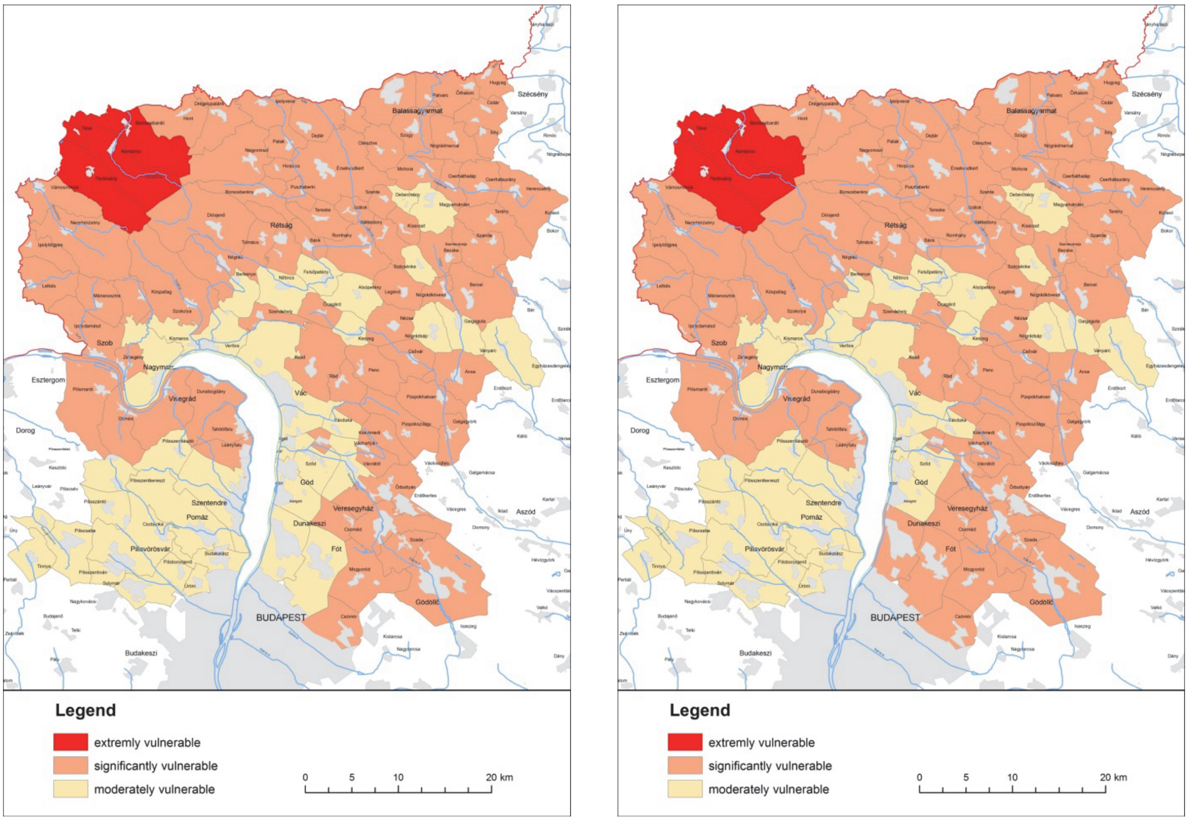

Fig. 11. Climate vulnerability of drinking water protected areas using the ALADIN (left) and RegCM (right) models for the period 2021–2050.

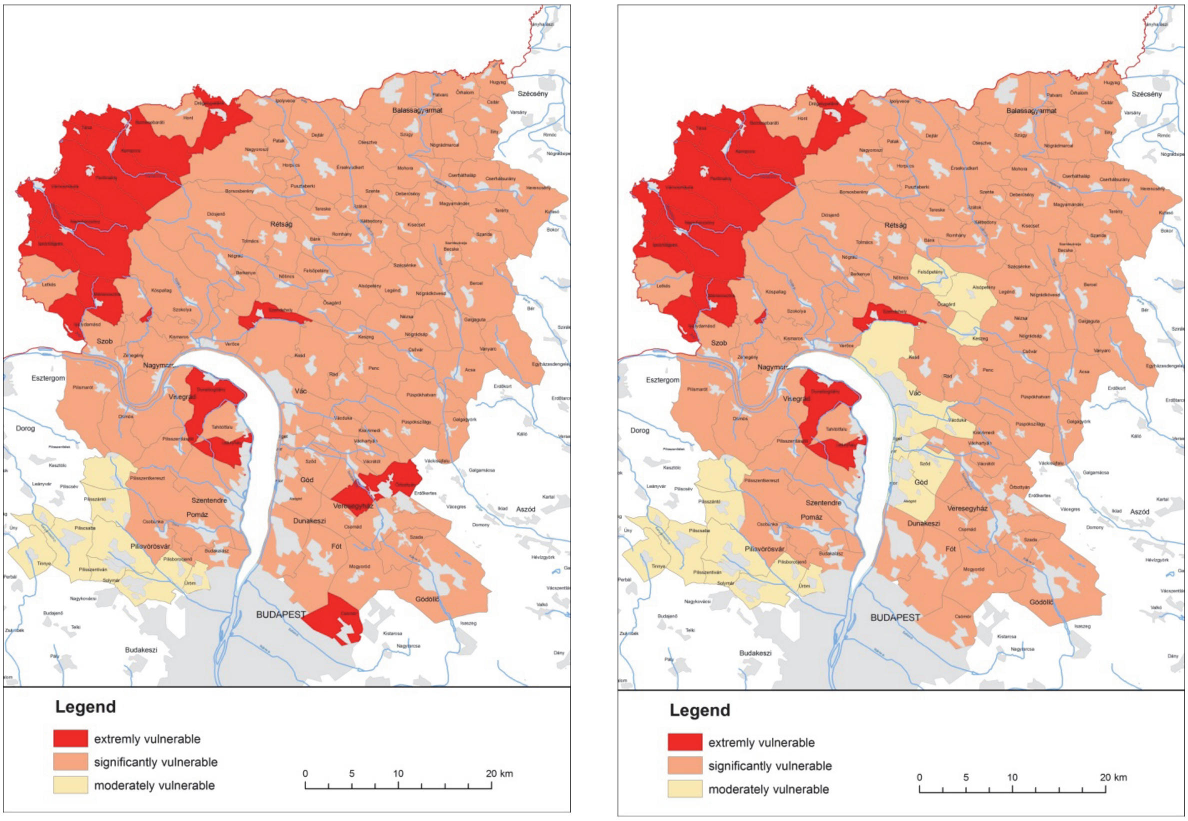

Fig. 12. Climate vulnerability of drinking water protected areas using the ALADIN (left) and RegCM (right) models for the period 2071–2100.

6. Conclusions, recommendations

We can conclude from the results of our investigation that the climate exposure of the drinking water protected areas is not uniform in the different regions of the country. However, regarding the European scale, it is within a relative narrow range. As a result of climate change, the amount of infiltration responsible for groundwater recharge is expected to decrease. This process is somewhat balanced by changes in the annual distribution of precipitation, that is expected to increase in the winter half-year.

Climate model projections naturally involve uncertainties, therefore in future research, it is important to reduce this uncertainty with the use of new, high-resolution climate model data. In addition to the clarification of climate-exposure, further investigation is needed for the characterization of the exposure of bank-filtration systems.

The drinking water protected areas have different climate sensitivity depending on their geological and hydrogeological settings. In supplying drinking water, drinking water protected areas of less climate sensitivity need to be assigned a greater role. Despite their sensitivity to climate change, bank-filtration systems are of major importance and can be the basis of perspective water supplies, as they have great reservoir capacities and constantly renewable reserves. It is advisable to replace the karstic and shallow-porous drinking water protected areas of increased climate vulnerability by new drinking water protected areas of greater security.

The status of groundwater, the effects of climate change and groundwater pressures need to be monitored on a regular basis. Similarly, it is necessary to register water consumption, typical consumer habits, and underlying social and economic factors. By the regular periodic evaluation of these observations, the identification and characterization of changes, it is possible to develop the appropriate climate adaptation measures.

In order to reduce the effects of climate change, we need to put greater emphasis on adaptation. Regarding the supply of water, regional supply systems can provide greater security, due to the importance of groundwater governance and the trans-regional redirection of water, as applied successfully already, nowadays.

In the regional developments, besides the climate vulnerability of the drinking water protected areas, we need to take into consideration the underlying social and economic factors. A constant drinking water supply can be guaranteed by the utilization of the drinking water reserves exclusively for drinking purposes, and the supply for other uses from different reserves, thus by the separation of the two systems.

As a part of the climate adaptation strategy, water consumption habits are necessary to be changed, towards a conscious and economic water use.

The investigation of the climate vulnerability of drinking water protected areas needs further research. It is necessary to extend the methodology of climate vulnerability assessment to a nation-wide scale, with the detailed assessment of climate exposure, climate sensitivity, water demand, and climate adaptation, accompanied by the participation of the other regional public waterworks.

As a result of climate change, there might be changes in the chemical composition of groundwater as well. It is of the utmost importance to consider these changes in the bank-filtration systems and the changes in the processes determining pollution propagation. These processes are expected to change according to the different climate scenarios and their detailed examination is needed, for preventive purposes.

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