Vulnerability of groundwater resources under climate change in the Pannonian basin

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ABSTRACT

The impact of climate change on groundwater vulnerability has been assessed in the Pannonian basin over 1961–2070. High-resolution climate models, aquifers composition, land cover, and digital elevation model were the main factors which served to perform the spatial analysis using Geographical Information Systems. The analysis reported here is focused on the long-term period, including three temporal time sets: the past period of 1961–1990 (1990s), the present period of 2011–2040 (2020s), and the future period of 2041–2070 (2050s). During the 1990s, the high and very high areas of groundwater vulnerability were identified in all the central, western, eastern, southeastern, and northern sides of the Pannonian basin. In these areas, the water availability is lower and the pollution load index is high, due to the agricultural activities. The low and very low vulnerability class was depicted in the South-West part of the basin and in few locations from the peripheral areas, mainly in the North and West. The medium groundwater vulnerability spreads over the Pannonian basin, but it is more concentrated in the central, South, and South-West. The most affected territory is Hungary, while the territories of Slovenia, Croatia, and Bosnia and Herzegovina are less affected. In the present and future periods, the very high groundwater vulnerability increased in areas by 0.74% and 0.87%, respectively. The low class area decreased between the 1990s and the 2020s by 2.33% and it is expected to decrease up to 2.97% in the 2050s. Based on this analysis and the groundwater vulnerability maps, the Pannonian basin appears more vulnerable to climate change in the present and future. These findings demonstrate that the aquifers from Pannonian basin experience high negative effect under climate conditions. In addition, the land cover contributes to this negative status of groundwater resources. The original maps of groundwater vulnerability represent an instrument for water management planning and for research.

1. Introduction

The dynamics of the globe’s systems are rapidly changing and accordingly many changes occur at the Earth surfaces. The atmosphere composition, the air mass movements, and the anthropic activities might indicate the changes of the natural regions. Moreover, the biodiversity and the renewables resources such as water are often negatively affected by climate change (Klave et al. 2014). The most controversial global warming (Haeblerli et al. 1999) contributes to numerous environmental issues, mainly the negative problems in terms of water availability, cultivation pattern, glaciers melting and flooding, and sea level rise (Jiménez Cisneros et al. 2014). The related climate change problems regarding the water quantity and quality have been summarized by Jiménez Cisneros et al. (2014) in the “IPCC 2014 report”. Reduction of runoff and pollution of surface waters, depletion of the groundwater table, and decrease of the springs discharge are some aspects influenced by the recent climate change.

Considering the temperate zone of the Pannonian basin, the water resources and aquifers vulnerability are directly dependent by the climate regime and land cover. The recent studies indicate that evapotranspiration rate is expected to increase on the Pannonian basin (Nistor et al. 2017). At the specific latitude, in the Emilia-Romagna region from Italy, the large area with high climate change effect on the groundwater was observed (Nistor and Mindrescu 2019). In the Piedmont region, Galleani et al. (2011) also found the impact of climate on the spring’s vulnerability.

The water vulnerability and agricultural triggers may be understood in terms of quality and quantity indicators, while the evapotranspiration is a significant indicator for the water balance, runoff, and water surplus estimations. In the Mediterranean countries from Southern Europe, the climate conditions and land cover are the main drivers from the groundwater quality and quantity status. Čenčur Curk et al. (2014) signaled that the groundwater vulnerability is expected to increase in the next decades. Climate change and its contribution for the water availability together with the aquifers recharge are directly influenced by the precipitation regime. These parameters are controlled by evapotranspiration and infiltration processes. Nistor and Porumb-Ghiurco (2015) proposed an approach to determinate the crop evapotranspiration...
(ETc) at spatial scale of Emilia-Romagna region (Italy) using monthly potential evapotranspiration (ET₀) raster grids and seasonal crop coefficients (Kc) assigned for each land cover type. With an impressive applicability in climate, hydrogeology, and agriculture, their methods were rapidly used for other regions of Europe, such as South East Europe, Pannonian basin, and continental part of Europe. Thus, Nistor et al. (2016) carried out the ETc in the Carpathians region along 1961–2010. Güçlü, Subyani, and Şen (2017) carried out the evapotranspiration applying a regional fuzzy chain model in the Kingdom of Saudi Arabia. Using the REMO and ALADIN regional climate model simulations, Ladányi et al. (2015) evaluated the future drought hazard in the Kiskunság National Park from Hungary.

The quality of the groundwater is closely related to the aquifers vulnerability factor, which is driven by the geological composition. In the same time, the land cover and land use compose different ecosystems that may influence the water quality through the pollution load index (PLI). Two kind of approaches, SINTACS and DRASTIC, are commonly used for the mapping the groundwater vulnerability. In Italy, Civita and De Maio M (1998) determined the groundwater vulnerability at spatial scale using SINTACS method. Civita and De Maio (2004) proposed a Geographical Information Systems (GIS) method to compute the groundwater vulnerability taking into consideration traditional Italian methods, such as GNDCI-CNR Basic method and PCSM SINTACS. The considered parameters for the groundwater vulnerability are the main factors which influence the vulnerability. Civita (2010) used eight parameters in which the most important ones include aquifers, land cover, slope, and hydraulic conductivity, to determine the groundwater vulnerability in the Alessandria district, from Northern Italy. Groundwater vulnerability in the central of Iran was mapped by Ghazavi and Ebrahimi (2015) using DRASTIC and GOD models. Almost all approaches were implemented into ArcGIS environment, which were applied using the most representative parameters for that study area. Here, we will develop a complex methodology, which includes also the climate data layers. No work on the groundwater vulnerability in the entire Pannonian basin was done at present.

The aim of this paper is to calculate the groundwater vulnerability at spatial scale of Pannonian basin by using the most sensitive factors, including climate variables. The analysis was completed on long-term of 30 years (1961–1990, 2011–2040, and 2041–2070) including actual crop evapotranspiration (AETc), water availability, aquifers, terrain, and land cover data. These maps represent useful tools for the strategies plan in the study area.

2. Study area

The Pannonian basin is an important lowland in the central part of Europe and extends over nine countries: Slovakia and Ukraine in the North, Hungary in the center, Romania in the East, Austria and Slovenia in the West, and Croatia, Bosnia and Herzegovina, and Serbia and Montenegro in the South. The geographic limits of the study area are: 43°50′ and 49°15′ latitude N and 15°06′ and 23°30′ longitude E (Figure 1). The orography of this region presents large plains areas, such as the Great Hungarian Plain, the Danube plain, the Sava and the Drava plains (European Environment Agency 2007). In the West, the Pannonian basin is bounded by the Alps, in the North and East by the Carpathians Mountains, and in the South by the Dinarics Mountains.

In base of the geology formations, the typology of aquifers was set (BGR & UNESCO 2013) and the productivity of each type of aquifer was established. The main types of aquifers are composed by sands, gravels, and dolomitic limestones. Near the borders of the Pannonian basin and limits of the mountains surroundings, there are the sandstones, conglomerates, schists, and gneiss formations (Figure 2). Thus, the porous aquifers are predominantly in the central part of the Pannonian basin, while in the peripheral areas the locally aquiferous and non-aquiferous rocks were depicted (BGR & UNESCO 2013).

The Pannonian basin is characterized by temperate climate with oceanic influence in major part of the territory and Mediterranean influence in the South and South-West. According to Köppen–Geiger climate classification, the study area has a fully humid (class Cfa) climate in the southeastern part and by a fully humid climate with warm summers (class Cfb) in most of the territory (Kottek et al. 2006). The Dfb climate class was depicted in the North-East side, close to the Carpathian Mountains and on in the West side near to the Alps (Kottek et al. 2006).

For the 1990s, the climate models show mean annual temperature values between −3.9°C and 12.4°C (Figure 3(a)). During the 2020s, the temperature varies from 6.1°C to 14.4°C (Figure 3(b)) and from 7.1°C to 15.4°C in the 2050s period (Figure 3(c)). In the past period, the precipitation values ranges between 483 and 1607 mm per year (Figure 3(d)), with a slight decrease of the maximum value during the 2020s, from 1607 to 1549 mm (Figure 3(e)). For the 2050s period, the precipitation varies from 469 to 1542 mm (Figure 3(f)). The annual ET₀ varied from 399 to 563 mm (Figure 3(g)) during the 1990s, while in the 2020s the annual ET₀ varies from 450 to 710 mm (Figure 3(h)). In the far-future period of the 2050s, the ET₀ is expected to vary between 479 and 751 mm (Figure 3(i)).

In the Pannonian basin, chernozems and black soils are predominant (European Environment Agency 2007),
fact for that the region became an important agriculture land in this part of Europe. According to the orography, climate, and soils, the vegetation pattern includes pasture, natural grass, crops and agricultural areas, and forest with various species such as elm (*Ulmus*), oak (*Quercus*), beech (*Fagus*), and hornbeam (*Carpinus*) (European Environment Agency 2007). The artificial areas are very well developed, mainly around the large capital cities, e.g. Budapest, Vienna, Belgrade, Zagreb, etc.

### 3. Materials and methods

#### 3.1. Climate data

Climate data have a significant contribution for this study due to the evaluation of groundwater vulnerability on long-term period, including climate change. Climate models of mean monthly air temperature, monthly mean precipitation, and monthly $ET_o$ at high spatial resolution ($1 \text{ km}^2$) over 1961–1990, 2011–2040, and 2041–2070 were used to calculate the annual crop evapotranspiration ($ET_c$), actual crop evapotranspiration ($AET_c$), and water availability in the Pannonian basin. Andreas Hamann from Alberta University (Canada) has computed raster grid datasets of climate models for the whole Europe using the ClimateEU v4.63 software. These models are validated (Hamann et al. 2013) and are available on the website ([http://tinyurl.com/ClimateEU](http://tinyurl.com/ClimateEU)). For the precipitation models, the Parameter Regression of Independent Slopes Model was used. The Representative Concentration Pathway 4.5 for emission, which means a moderate climate changes projection,
gives a globally prediction of +1.4°C (±0.5°C) and the ANUSplin interpolation method were used to carry out the temperature models. The final products are an ensemble average of 15 Atmosphere Ocean Global Climate Models (AOGCMs). According to the CMIP5 multi-model, the climate models are in line with the IPCC Assessment Report 5 (2013) and the selection of these models was based on considering the high validation statistics in the CMIP3 equivalents. The summary of the models of AOGCMs is given in Table 1.

A bilinear interpolation correction was used for the artifacts in the locations with low-resolution AOGCM grid cells. For the bias correction, we used the Change Factor procedure in the raw results. Hamann and Wang (2005), Mbogga, Hamann, and Wang (2009), and Wang et al. (2016) described in details the whole procedure of the climate models computation, which is in line with Daly (2006). Recently, the mean monthly ET<sub>0</sub> and water availability for the 1990s, 2020s, and 2050s were performed for Europe (Dezsi et al. 2018).

### 3.2. Aquifers data

The International Hydrogeological Map of Europe (IHME), released in 2013 at 1:1,500,000 scale (BGR & UNESCO 2013), has been used as reference of the aquifers delineation and typology. Based on the lithology and geological composition of the aquifers, six categories of aquifers productivity were defined: highly productive fissured aquifers, highly productive porous aquifers, low and moderately productive fissured aquifers, low and moderately productive porous aquifers, locally aquiferous rocks — porous or fissured, practically non-aquiferous — porous or fissured. Moreover, considering the typology of the aquifers and geology composition, the vulnerability factors (Figure 4) of each aquifer were set according to the hydrogeological studies (Civita 2005). Table 2 reports the aquifers types and the vulnerability factor related to the Pannonian basin.

The potential infiltration coefficient (PIC) of each aquifer was assigned at spatial scale. This coefficient reflects the water quality sensitivity (Čenčur Curk et al. 2014). The spatial distribution of PIC in the Pannonian basin is depicted in Figure 5.

### 3.3. Terrain data and infiltration index

The infiltration processes are mainly controlled by the lithology characteristics and morphology of the
terrain. The slope angle (radian degrees) map of the region was generated from the digital elevation model and in base of PIC, the infiltration index of the Pannonian basin was carried out. The procedure follows the Nistor, Dezsi, and Cheval’s (2015) approach and it considers that where higher the PIC and lower the slope angle, higher will be the infiltration values. Using the normalized values from 0 to 1, we have divided the PIC to the slope angle to calculate the infiltration index. The mathematical operations were done at spatial scale, using ArcGIS environment.

### 3.4. Land cover data

Regarding the groundwater vulnerability, the land cover pattern has double implication due to the vegetation evapotranspiration and pollution phosphorous transfer through the soils. Thus, the quantitative effect should be assessed by the evapotranspiration variation at spatial-temporal scale and its contribution for the water availability in a certain area. Regarding the qualitative impact, each type of land cover composes different ecosystems. These ecosystems may support the high quality of the water (e.g. forest, natural parks) or may influence negatively the water quality, due to the load pollution released, especially in the agricultural areas, dump sites, and mineral extraction sites.
The classes of land cover are detailed up to the fourth level, which indicates 32 types of land cover in the Pannonian basin. Due to the lack of data for the Ukraine territory, we have incorporated the Global Land Cover, dating from 2010, 30 m spatial resolution, elaborated by China and United Nations. This layer depicts 10 classes of land cover and were well extracted and merged with the Corine Land Cover 2006 database. Figure 6 illustrates the land cover variation in the Pannonian basin.

For each type of land cover, the specific PLI (Table 3) and evapotranspiration coefficient (Table 4) were assigned. The operations were performed on vector data and further, the raster grids 1 km × 1 km were obtained. This resolution was set to be in line with the climate data models and infiltration index.

### 3.5. Potential evapotranspiration (ET₀)

Thornthwaite (1948) method was used to perform the monthly and annual ET₀ for the 1990s, 2020s, and 2050s. The Thornthwaite formula (Equation (1)) requires monthly temperature data and it is widely applied at regional scale for long-term periods. Due to its significance and applicability also for the future periods (Nistor and Mindrescu 2019), this approach was engaged in many agricultural, climatological, and hydrological studies (Čenčur Curk et al. 2014; Cheval, Dumitrescu, and Barsan 2017; Zhao et al. 2013; Nistor 2019). In this paper, the annual ET₀ was used to carry out the annual ETᵣ, AETr, and water availability at the spatial scale of Pannonian basin. Monthly and annual ET₀ related to the past, present, and future for whole Europe have been calculated by Dezsi et al. (2018) and raster data could be accessed via website (https://doi.org/10.5281/zenodo.1044306).

$$ET₀ = 16 \left( \frac{10Tᵢ}{I} \right)^α$$

where ET₀ is the monthly potential evapotranspiration (mm), and ET₀ = 0 if mean temperature <0, Tᵢ is the average monthly temperature (°C), I is the heat index (see Equation (2)), and α is the complex function of heat index (see Equation (3)).
3. ETc, AETc, and water availability

Based on land cover $K_c$ (Table 4) and annual $ET_0$, the annual $ET_c$ was determined for Pannonian basin during three analyzed periods. The vegetation capacity for evapotranspiration (Allen 2000) was assessed through the standard $K_c$ values, which were set by Allen et al. (1998) in different climate zones. One of the outcomes is that in the urban areas the buildings, streets, and trees form the micro-climates (Grimmond and Oke 1999). The $K_c$ related to the urban areas was adapted to Pannonian basin area according to the latitude factor using Grimmond and Oke’s (1999) findings, while for the bare soils, open water areas, glaciers etc., the values used in the study (Nistor 2019) have been taken into consideration.

The annual $ET_c$ calculation was performed making the product between the annual $ET_0$ and annual $K_c$ (Equation (4)). Thus, in the evapotranspiration parameter we have incorporated the land cover contribution to obtain more realistic situation for the phenomena. Based on the annual $ET_c$ calculation, the annual $AET_c$ and water availability were carried out. Using these findings, the precipitation models contribute to generate the annual $AET_c$ using the Budyko approach (Budyko 1974).

$$\text{Annual } ET_c(\text{mm}) = \text{annual } ET_0(\text{mm}) \times \text{annual } K_c(\text{mm})$$ (4)

Budyko equation (Equation (5)) is an important tool for hydrological studies because it estimates the water balance and through this method it is possible to know if the heat energy could produce the evaporation from precipitation (Gerrits et al. 2009). In this work, we applied Nistor and Mîndrescu’s (2019) and Nistor’s (2019) methodology to obtain the annual $AET_c$ from the annual $ET_c$ using climate and land cover data. For the water availability (Equation (7)) determination, we have subtracted the annual $AET_c$ from annual precipitation. All mathematical operations, related to the 1990s, 2020s, and 2050s, were completed using raster grids, 1 km² cell-size resolution, in ArcGIS environment.

$$\text{ETc} \text{ (mm)} = \left[ \left( \frac{\tan(\varphi)}{\varphi} \right)^{0.5} \right] (1 - e^{-\varphi})^{0.5}$$ (5) 

where $AET_c$ is the actual land cover evapotranspiration (mm), $PP$ is the total annual precipitation (mm), and $\varphi$ is the aridity index (Equation (6))

$$\varphi = \frac{ET_c}{PP}$$ (6)

$$\text{Annual water availability (mm)} = \text{annual precipitation (mm)} - \text{annual } AET_c(\text{mm})$$ (7)

3.7. Groundwater vulnerability mapping using GIS spatial analysis

Multi-layers analysis by weights in GIS was used to map the groundwater vulnerability in the Pannonian basin. Sensitive factors of aquifers,
climate, land cover, and terrain were defined and normalized to perform the spatial analysis. Thus, the climate change effect on the groundwater vulnerability was assessed through the water availability in three time shifts. The groundwater quality was evaluated by two main factors at spatial scale: (1) PLI in conformity with the land cover distribution and (2) aquifers vulnerability factor in base of the aquifer media productivity and hydraulic conductivity. The morphology of the Pannonian land and the related PIC for lithology were combined to carry out the infiltration index, which suggests the areas with high infiltration rate. This parameter is important while it contributes to both the quantity evaluation (aquifers recharge) and the quality assessment (pollutants that infiltrate in the media).

The spatial analysis applied in this study follows the appropriate methodology proposed by Nistor, Dezsi, and Cheval (2015). They have generated the groundwater vulnerability in a mountain district from Western Carpathians using GIS and weights. The annual AET and water availability were calculated following the Nistor and Mindrescu’s (2019) and Nistor’s (2019) procedures. In these studies, they have mapped these parameters at regional scale of Emilia-Romagna region, respective South East Europe.

According to the GIS spatial analysis standards (McCoy and Johnston 2002), the considered layers for the analysis are weighted, but the sum of weights should be 100%. Related studies (Stempvoort, Ewert, and Wassenaar 1993; Daly et al. 2002; Dixon 2005) to groundwater vulnerability mapping indicate that the assigned weights to each factor are mainly determined by the most important driver parameter for the groundwater vulnerability in the respective area. Thus, our study is focused on the climate effect and we set 30% weight for the water availability. Due to dual importance for the groundwater vulnerability, the land cover pattern, hele as PLI, was weighted by the same value with the water availability, 30%. The aquifers vulnerability factor and the infiltration index factor were ranked with 20% each (Equation (8)). In the equation, the weights indicate the relative importance of the respective parameter in the cluster. Through the balancing factors, applied to the water availability and PLI, the significance related to the maximal deviations of the respective parameter and the limitation of that parameter to substitute another one were implemented into the formula. Using this methodology and the proposed spatial analysis equation, the groundwater vulnerability maps were generated for the past, present, and future periods. The final product maps were divided in equal classes of the final raster.

\[
GWV = (1 - WA)^{1.5} + AV \times 0.2 + II \\
\times 0.2 + PLI^{1.5} \times 0.3
\]

(8)

where GWV is the groundwater vulnerability, WA is the water availability, AV is the vulnerability factor of aquifer, II is the infiltration index, and PLI is the pollution load index.

4. Results

Overall, our findings under climate change and additional analyzed factors indicate high and very high groundwater vulnerability in the Pannonian basin. Water availability oscillation during three long periods at spatial was assessed taken into account the evapotranspiration from land cover. Thus, based on the annual ETc and annual precipitation, the annual AETc during the 1990s, 2020s, and 2050s was found. In the past period, 1990s, the AETc varied from 91 to 672 mm. The higher values (over 500 mm) of the AETc were depicted in the southwestern, southern, and northeastern sides of the Pannonian basin. Low values (below 200 mm) of the AETc are located mainly in the artificial areas, while the rest of the territory appears as medium values (between 200 and 500 mm). During the 2020s period, the AETc values vary from 109 to 767 mm and the higher values were depicted in the southwestern and northeastern sides. The AETc ranges from 91 to 787 mm for the 2050s period. The future periods indicate a larger area with high values of AETc (over 500 mm) is expected. This meaning that the aridity increase trend in the Pannonian basin over 1961–2070 is expected. Spatial distribution of the annual AETc in the Pannonian basin, over the three periods, is depicted in Figure 7.

Water availability pattern varied from 81 to 1237 mm during the 1990s period. The higher values (over 1000 mm) were depicted in the southwestern extremity of the Pannonian basin, mainly in the Croatia and Slovenian lands. The lower values (below 200 mm) were identified in the central part of the region. In the 2020s period, the water availability ranges from 57 to 1165 mm, while in the 2050s period the water availability ranges from 45 to 1144 mm. Interestingly, the negative trend of the water availability has major impact on the extended area during the 2020s and 2050s, in comparison with the 1990s. The most affected territories are in the central part of Hungary, West of Romania, North of Serbia and Montenegro. Figure 8 shows the variation of the water availability in the Pannonian basin during the 1990s, 2020s, and 2050s.

The aquifer’s vulnerability factor has high values in the South-West of the region, in the lands of Slovenia and Croatia, where the fractured media composed by limestones and sandstones are located. In the central
part of Hungary, East of Austria, and West of Slovakia, some aquifers with high vulnerability factor could be found as well as in the West of Romania.

The infiltration index of the Pannonian basin shows high values (over 0.8) in the central, East, North, West, South, and South-West sides of the area. The major part of the Pannonian basin has very low infiltration values, due to the impermeable lithology layer. Figure 9 shows the infiltration index of the Pannonian basin.

The PLI map of the Pannonian basin indicates a high variation over whole territory. Thus, in the irrigated agricultural areas and in the dump sites, PLI has the maximum values (0.90 and 0.93) after normalization. In the non irrigated arable land, the PLI values reaches 0.80 after normalization and in the lands with permanent crops and the complex cultivation patterns, the PLI values reaches 0.60 after normalization. The forest lands, such as agro-forestry areas, broad-leaved forest, coniferous forest, and mixed forest, have the low PLI values (below 0.23). The natural grass and the wetlands (e.g. inland marshes, peat bogs, salt marshes, intertidal flats, water bodies, water courses) have a values of PLI below 0.2 after normalization. In terms of PLI impact on the groundwater vulnerability, the forest and water ecosystems offer the proper environment for the high water quality and for the water supply.
Figure 10 depicts the PLI variation at spatial scale of the Pannonian basin.

Groundwater vulnerability in the Pannonian basin area was determined using spatial analysis by weights in the ArcGIS software. Figure 11 shows the groundwater vulnerability during the past, present, and future periods. The very high vulnerability class during the 1990s was found in the central, South-East, West, and North-East of the Pannonian region. The high groundwater vulnerability class spreads over central, northern, eastern, southeastern, and western sides. Hungary territory experiences the largest areas with high and very high groundwater vulnerability. The medium class was depicted more in the South, East, North, and central parts of the Pannonian basin, while the low class extends more in the South, South-West, North, and North-West areas. Very low groundwater vulnerability was depicted in the South-West part of the Pannonian basin, especially in the Croatian and Slovenian territories.

Present and future scenarios of the groundwater vulnerability indicate appropriate pattern of the vulnerability classes’ distribution, slightly with increases of the high class area from 36.54% (1990s) to 36.69% (2020s), and to 36.7% (2050s). The very high groundwater vulnerability class increased between the 1990s and the 2020s by 0.74% and between the 1990s and the 2050s by 0.87%. These results would seem that the positive trend of the high and very high groundwater vulnerability classes might have negative implications for the groundwater resources, human water consumption, and related activities. The medium vulnerability class increased in area from 28.64% (1990s) to 30.33% (2020s), and to 30.89% (2050s). Drastic decrease was found for the low groundwater vulnerability class by 2.33% between the 1990s and the 2020s, and by 2.97% between the 1990s and the 2050s. Consistent decrease was obtained for the very low vulnerability class, from 1.34% to 1.09% between the 1990s and the 2020s, and from 1.34% to 1.03% between the 1990s and the 2050s.
between the 1990s and the 2050s. Table 5 reports the vulnerability class areas in the Pannonian basin during 1961–2070.

5. Discussion

The objective of this study is to evaluate the groundwater vulnerability under climate change in the Pannonian basin. Spatial analysis by weights was applied including climate models, aquifers data, land cover, and terrain morphology data. The high vulnerability factor of aquifers coincides with the dolomitic and karstified limestone formations in the Pannonian basin. These types of media represent highly productive fissured aquifers, with high permeability and PIC values. In the Pannonian basin, the dolomitic and karstified limestone aquifers extend mainly in the South-West part and in few locations from North-West and West-central sides of the region. However, the climate impact is not major in South-West of the Pannonian basin, while the mean annual precipitation registers higher amount (over 1400 mm) in respective areas and the water availability is still higher (over 1000 mm) than in other sides of the region. Our spatial analysis indicates high and very high groundwater vulnerability in the central, North, North-West, North-East, and East of the region because of the low water availability (below 200 mm) amount in those territories, but also due to the large extension of agricultural areas. In the permanent irrigated land and nonirrigated arable land, in the dump sites, and in the rice field cultivation areas, the PLI is higher and the groundwater vulnerability is negatively influenced from qualitative point of view. The high infiltration values in the central, East-central, North-West, and North-West contribute to higher amount of infiltrated water and together with the pollution discharge of the agricultural lands, and the groundwater vulnerability is higher.

Figure 9. Infiltration index of the Pannonian basin.

Figure 10. Pollution load index calculated in base of land cover in the Pannonian basin related to CLC2006 and Global Land Cover 2010. The maps show the unique values used in Table 2.
The low vulnerability class, mainly in the South, South-West, North, and North-West areas, is highly depending by the lower PLI (below 0.25). In those areas, the land cover is composed by forest and natural landscapes, which provide good quality of ecosystems. In addition, the South-West part of the Pannonia basin records high values of water availability (above 1000 mm) in all three periods. The very low groundwater vulnerability extends in areas with "non-aquiferous rocks", where the hydraulic conductivity is very low and the infiltration index is also low. Due to this fact, the potential pollutants are not prone to infiltrate in such kind of aquitards.

The influence of the nonirrigated arable land, mainly in the central, eastern, northern, and northwestern parts, is reflected in the high PLI (above 0.8) and in the final groundwater vulnerability maps. Thus, in these areas, the high and very high groundwater vulnerability was depicted. In opposite, the areas covered by forest, water bodies, moors and heathland, and sclerophyllous vegetation have lower PLI values (below 0.2) and the groundwater vulnerability resulted as low and very low.

Overall, during 1961–2070, the climate change indicates negative impact on the groundwater resources in the Pannonian region. The GIS spatial analysis by weights represents one of the existing approaches, which could fit with the regional groundwater vulnerability assessment. However, the field measurements and continuous monitoring of the water table and spring discharge would contribute to the in situ groundwater vulnerability. Chemical analyses of the principal minerals of the water in different land cover types may contribute to the quality status of groundwater and to improve the coefficients of the PLI used at present. These procedures are very realistic and offer the possibility to assess the groundwater vulnerability at present time. In this work, the long-term analysis may give a general view at spatial scale of Pannonian basin over three main periods of 30 years. This perspective that we followed in the past, present, and future periods has a key role in the policy maker strategies and environmental planning. Moreover, the proposed method and our original maps contribute to the research on the Pannonian basin.

The findings of this paper are in line with the findings obtained by Čenčur Curk et al. (2014) in South East Europe. In their study, the spatial analysis by weights was carried out and the southern part of the Pannonian basin resulted as high vulnerable. Only the southwestern side of the Pannonian region appears medium and low vulnerable, which is in perfect agreement with our maps. The difference between the applied method in this study and the Čenčur Curk et al.'s (2014) approach is related to the different input data. They analyzed the water demand and included also the gross domestic product for each administrative unit. In our study, the water demand was replaced by the $AET_c$, so the climate parameter for each

| Class          | 1990s (%) | 2020s (%) | 2050s (%) |
|----------------|-----------|-----------|-----------|
| Very low       | 1.34      | 1.09      | 1.03      |
| Low            | 29.28     | 26.95     | 26.31     |
| Medium         | 28.64     | 30.33     | 30.89     |
| High           | 36.54     | 36.69     | 36.70     |
| Very high      | 4.20      | 4.94      | 5.07      |

Figure 11. Groundwater vulnerability map of the Pannonian basin during the past period (1990s) (a), the present period (2020s) (b), and the future period (2050s) (c).
land cover is more representative for a proper location while the water demand could have various origins and exchanges between regions. Regarding the Pannonian basin region, the output of this study has finer resolution than the previous studies, which is much more useful for the water resources investigations.

6. Conclusions

Climate change effect on the groundwater vulnerability was determined using spatial analysis by weights in the Pannonian basin. The improved procedure of Nistor, Dezsi, and Cheval (2015) contributes to a high spatial resolution layer analysis and it was focused on three periods of 30 years. Climate models, aquifers hydrological characteristics, terrain data, and the land cover parameters were included in the groundwater vulnerability calculation.

The findings indicate that during the past, present, and future periods, the groundwater vulnerability is exposed to increase. Central parts of the Pannonian basin, mainly the Hungary territory, the North-West side in the West of the Slovakia and East of Austria, North-East of Croatia and Bosnia and Herzegovina, North of Serbia and Montenegro, West of Romania, and West of Ukraine, are the areas with high and very high groundwater vulnerability during the 1990s, 2020s, and 2050s. These territories with high and very high vulnerability represent about 40% from the entire Pannonian basin area. In comparison with the 30% of the low and very low vulnerability class area, during the present, and about 27% in the future, we can affirm that the groundwater resources are under high pressure of climate change and land cover in the Pannonian basin.

Overall, the study of groundwater vulnerability by GIS technology and multi-layers analysis contributes to regional strategies for water resources management between transboundary territories. In addition, the original maps represent significant tools for future planning, protection areas, or limitation in water extraction.

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Notes on contributor

Mărgărit-Mirea Nistor is a researcher in hydrogeology, GIS, and climate fields. His research interests include spatial analyses of water resources, glaciers, landslides risk mapping, and climate data variables with respect to climate change.

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