An assessment of potential groundwater recharge zones in Bulgaria

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Abstract. Groundwater resources on the territory of Bulgaria are unevenly distributed in both spatial and temporal aspects. The effective usage of these valuable assets is of paramount importance, since any over-exploitation would eventually lead to their depletion. Remote sensing data and satellite images have increasingly been used in groundwater exploration and management. An integrated approach was applied in the present study in order to delineate potential groundwater recharge zones on the territory of Bulgaria. Data from various sources were used to prepare different thematic layers. These layers were then transformed into raster data of 1×1 km. Lineament and drainage density maps of the research area were made with the help of GIS technology. In addition, a map was made for the annual total precipitation for the period from 1931 to 1985. DEM (Digital Elevation Model) data on a global scale at 90 m horizontal resolution were used for the slope analysis. A groundwater potential map was produced, which integrates several thematic maps, such as annual rainfall, geology, lineament density, land use, slope, soils, and drainage density. The thematic maps were then converted into a raster graphic format in order to be easily integrated into a GIS platform. The raster maps of these factors were then allocated a fixed score and weight-computed. The weights of those factors contributing to the groundwater recharge were derived by using the following components: geological map, lineament-length density map, land cover data base, soil data base, drainage-length density map, and slope gradient map. Subjective weights were assigned to the respective thematic layers, and they were overlaid in a GIS platform for the identification of potential groundwater recharge zones within the study area. These potential recharge zones were then categorized as being very good, good, moderate, poor, and very poor.

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INTRODUCTION

Factors with major influence on potential zones for groundwater recharge can be divided into two main groups: climatic factors and land area factors. Among the climatic factors, the precipitation may be emphasized above all. The land area factors include the region's topography, hydrographic network, lithology, lineament patterns, type of soils, and land use/cover. Correct determination of the zones of potential groundwater recharge is of paramount importance since these are not only the areas where natural resources are replenished, but they are the areas where it is easier for pollutants to be infiltrated into aquifers of most active water exchange. In case of contamination of the surface and presence of recharge potential, this contami-

nation may penetrate through the vadose zone and reach the groundwater. The purpose of this study is to determine the boundaries of potential zones of groundwater recharge on the territory of Bulgaria based on the influence of morphometric parameters, such as slope gradient and horizontal fragmentation (or drainage-length density), lithological settings and lineament-length density, total sum of annual mean rainfall, soil texture, and land cover.

The elaboration of a methodology to delineate the potential groundwater recharge zones requires a thorough knowledge of the processes affecting recharge. The methodology described herein aims at clarifying the sequence until the final estimate of potential groundwater recharge zones can be reached. This is important, since the assessment generally involves a combination of several processes or a

succession of interconnected influencing factors of a certain feature of the area’s hydro-environment.

Delineating the potential recharge zones has been carried out in many countries, and various methods have been used so far (Krishnamurthy *et al.*, 1996; Saraf and Choudhury, 1998; Shahid *et al.*, 2000; Jaiswal *et al.*, 2003; Sener *et al.*, 2005; Shaban *et al.*, 2006; Yeh *et al.*, 2009; Chenini *et al.*, 2010; Kadam *et al.*, 2015). For the territory of Bulgaria, such an assessment has not been undertaken yet. Therefore, in the present study, a summary of all available free-access information on the subject of recharge potential zones has been attempted, and an up-to-date methodology for making such an assessment is presented.

A GIS-model was employed in order to delineate the potential groundwater recharge zones of Bulgaria. Identifying suitable sites for the recharge

was conducted through a knowledge-based factor analysis, making use of layers describing the precipitation, lithology, lineaments, slope gradient, land cover, soil types, and drainage features of the studied area.

STUDY AREA – TOPORGAPHY, GEOLOGY, SOIL COVER AND CLIMATE

The delineation of the zones of potential groundwater recharge on the territory of Bulgaria was carried out with respect to the relevant topographic features (Fig. 1), making use of GIS technology. Bulgaria is almost 111,000 km² in area, having a very complex geological structure, and widespread existence of varied rock formations with ages from the Quaternary to the Precambrian. Quaternary deposits (de-

Fig. 1. Location of the study area and a topographic map of Bulgaria.

luvial, eolian, and alluvial) occupy almost the entire northern part of the country, where loess cover is also widespread. The depth of loess deposits is about 40–50 m in close proximity to the Danube River and, south to the Fore-Balkan, its thickness is reduced to about 3–5 m (Minkov, 1968). According to their genesis, pre-Quaternary rocks in Bulgaria are magmatic (intrusive, effusive and pyroclastic), sedimentary, and metamorphic (Fig. 2). Their variable lithological compositions have led to the formation of porous, karst, fissured-karst, fissured and fissured-porous aquifers (Antonov *et al.*, 1960), which may be described as having very high, high, moderate, low, and poor water-holding capacity (Kamenov *et al.*, 1963b).

The topography of Bulgaria is quite varied, consisting of high and low terrains that generally ex-

tend from the east to the west across the country. The average altitude is approximately 470 m, and the country's relief is characterized by the existence of lowlands in its northern part and heavily dissected mountainous and semi-mountainous areas in the south (Fig. 1). Most terrains on high elevations are located in the south-western part of the country, where Peak Musala, the highest point in the Rila Mountains and the Balkan Peninsula, rises to 2,925 m above sea level. The country is characterized by predominantly flattish and hilly areas, with altitude varying between 0 m and 600 m, and such areas cover about 72% of its territory.

As to the existing soil cover, the most widely spread types of soils in northern Bulgaria are the chernozems and luvisols. On the other hand, in the southern part of the country, a wide variety of soil

Fig. 2. Geological map of Bulgaria showing the main types of rocks (after Cheshitev and Kanchev, 1989). Legend: 1 – Quaternary sediments; 2 – Neozoic sedimentary rocks; 3 – Neozoic intrusive rocks; 4 – Neozoic volcanic and volcano-sedimentary rocks; 5 – Mesozoic sedimentary rocks; 6 – Mesozoic intrusive rocks; 7 – Mesozoic volcanic and volcano-sedimentary rocks; 8 – Mesozoic metamorphic rocks; 9 – Paleozoic sedimentary rocks; 10 – Paleozoic intrusive rocks; 11 – Paleozoic volcanic and volcano-sedimentary rocks; 12 – Paleozoic metamorphic rocks; 13 – Precambrian metamorphic rocks; 14 – water.

types can be found, such as cinnamonic soils, smol-nitza, leptosols, alisols (zheltozem podzolic soils), as well as soils having visible relict and identity with soils from areas in northern Bulgaria: chromic luvisols, nitisols, etc. Much of Bulgaria's territory is covered with shallow soil types (leptosols), which are widespread all over the country (Ninov, 1997, 2002).

The climate in Bulgaria is moderately continental, with maximum precipitation in May and June and minimum in February. In the southernmost part of the country, the climate is continentally Mediterranean, with maximum precipitation in the fall and winter seasons and extensive droughts in the summer. The yearly distribution of rainfalls can be described as uneven in time (Fig. 3). The average total sum varies in the range between 500 mm and 550 mm, and from 600–700 mm in the plains to 1,000–1,400 mm in the higher mountainous areas (Koleva and Peneva, 1990). The least amounts of

precipitation have been measured along the Black Sea coast – from 450 mm to 500 mm. During the winter months, it often snows at places of high altitudes. The average maximum yearly air temperature is +14 °C, and the minimal is –3 °C (Kyuchukova, 1983). The maximum temperatures have been recorded in July and August, and the minimum ones in January.

DATA AND METHODOLOGY

In order to assess the potential groundwater recharge zones of Bulgaria, a modern approach was attempted, making use of data integration and processing in GIS environment. The zones were delineated according to the influence of the following factors: precipitation, geological and hydrogeological settings, lineaments, land cover, slope gradient, drainage, and types of soil. GIS technology was also

Fig. 3. Annual mean precipitation in Bulgaria for the period 1931–1985 (data from Koleva and Peneva, 1990).

used in order to determine the horizontal fragmentation, lineament density, and areal-extent rainfall for the study area.

In the process, several subsequent steps were applied accordingly. Initially, the problem was reviewed in the relevant literature (Sener *et al.*, 2005; Shaban, *et al.*, 2006; Yeh *et al.*, 2009; Magesh *et al.*, 2012; Murasingh and Jha, 2013; Gumma and Pavelic, 2013; Venkateswaran *et al.*, 2014; Selvam *et al.*, 2016; Senanayake *et al.*, 2016; Yeh *et al.*, 2016; etc.). After that, data were collected, processed, and digitalized, when necessary. Finally, spatial analyses (*i.e.*, weighting of each factor pertaining to the potential recharge areas) were carried out, and the outputs were categorized.

Data

Abundant data from various sources have been processed in the study, such as meteorology, soils, topography, land use, river drainage patterns, geological, hydrogeological, and lineament patterns.

The climatic data include mean annual total sum of the precipitation for the period of 1931–1985, measured at 284 stations unevenly distributed all across the territory of Bulgaria (see Koleva and Peneva, 1990). After the integration of all precipitation data into GIS, and using interpolation techniques, a map of the average annual rainfall was generated in a 1×1 km grid (Fig. 3).

As far as soils are concerned, data for their texture in the one-meter surface layer were used. When there is a difference between the top soil (0.3 m in depth) and the subsoil (0.7 m), the value less favorable for the recharge was used. Data was provided by the European Soil Data Centre (ESDB v2.0. 2004). They were prepared for usage by the Land Resource Management Unit of the Institute for Environment and Sustainability at the Joint Research Centre (JRC) of the European Commission, located in Ispra, Italy.

For the topographic analysis (Fig. 1), Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) data on a global scale at 90 m horizontal resolution (<http://srtm.csi.cgiar.org/>) were used in order to produce a slope gradient map. The slope of the terrain plays a major role in determining the recharge potential zones, *i.e.*, at steeper slopes more surface runoff is generated and on flatter terrains larger amounts of the precipitation are infiltrated into the ground. About 52% of the land area of Bulgaria is characterized by slopes of less than 4°, thus facilitating slow surface runoff, and only about 3% is characterized by slopes of >26°, which facilitates a more rapid surface runoff.

Both surface runoff and infiltration depend on the existence of forested areas on the terrain. The data utilized for the land cover were obtained from CORINE Land Cover 2006 Project (CLC 2006). The polygon data can be freely accessed at the website of the Executive Environment Agency of Bulgaria (<http://eea.government.bg/bg/projects/korine-14/osn-inform>). The basic information for the project comes from satellite images. Information for the land cover was interpretable from satellite images, as well as the land use maps. The CORINE Land Cover 2006 Project forms part of the pan-European CORINE Land Cover Project, developed by the European Environment Agency (<https://www.eea.europa.eu/data-and-maps/data/clc-2006-vector-data-version-2>).

The horizontal fragmentation map was compiled by using drainage features data. The river network was digitalized within the framework of JICA Project (2006–2008), with data collected from topographic maps of Bulgaria in scale 1:100 000.

The demarcation of geological formations was obtained from the geological map of Bulgaria, in which only the major geological formations are presented. The map was prepared by the Committee of Geology of Bulgaria in scale 1:500 000 (Cheshitev and Kanchev, 1989) and vectorized within the framework of JICA Project (2006–2008). The lineaments in the studied area were determined from the geological series maps of Bulgaria in scale 1:100 000. Subsequently, a lineament-length density map in a raster graphic format was prepared in GIS environment.

All data used in the present study can be seen in Table 1. This information was used in a digital format for the preparation of various thematic layers.

Methodology

The methodology developed below aims at determining the recharge potential and consists of four stages. Initially, the problem was investigated, the necessary data were collected, and a database was created. Thematic layers related to the recharge potential were identified. The second stage involved processing of the layers to ensure uniform projection in UTM (zone 35N, datum WGS84), assigning the relevant scores and weightages. During the third stage, the thematic layers were converted into raster images and integrated with their weightages in GIS environment. During the fourth (final) stage, the outputs were categorized into the following five classes: very good, good, moderate, poor, and very poor. The methodology followed in the process of research is shown in Fig. 4.

Table 1
Data layers used in this study

Layers	Data obtained from / Description	Source
Lineament patterns	–	Geological Series Maps 1:100 000
Land cover	Executive Environment Agency of Bulgaria, Land Cover 2006 Project	Database CORINE of the European Environment Agency
Geology (Lithology)	JICA Project (2006–2008)	Cheshitev, G., Kanchev, I. (1989) Geological map of Bulgaria 1:500 000
	Map of hydrogeological elements, important for construction work 1:500 000	Kamenov <i>et al.</i> (1963b)
	Engineering-geological map of Bulgaria 1:500 000	Kamenov <i>et al.</i> (1963a)
	Map of the hydrogeological division of Bulgaria 1:600 000 (1960)	Antonov <i>et al.</i> (1960)
Drainage network	JICA Project (2006–2008)	Topographic Series Maps 1:100 000
Slope	Digital Elevation Model (DEM) 90 m	http://srtm.csi.cgiar.org
Precipitation	Meteorological station / Precipitation Map was generated by employing interpolation techniques on a GIS platform	Koleva and Peneva (1990)
Soils	ESDB ver2.0. 2004. The European Soil Database distribution	Joint Research Center, European Commission

Fig. 4. Flowchart for groundwater potential assessment methodology using GIS techniques.

In order to delineate the potential groundwater recharge zones of Bulgaria, GIS technology was employed in the study. The identification of suitable sites for groundwater recharge was conducted through a knowledge-based factor analysis, making use of precipitation, lineament-length density, slope gradient, horizontal fragmentation, land cover, lithology, and type of soil layers. For each factor, a thematic map was created. The thematic maps were then converted into a raster graphic format (1×1 km), which can easily be integrated into a GIS platform. To each of these thematic maps, a suitable weightage factor was assigned, and the factors' influence on the groundwater recharge and the interaction between them was examined.

INTERRELATIONSHIP AND WEIGHTAGE CALCULATION FOR THE FACTORS AFFECTING THE POTENTIAL RECHARGE ZONES

Multi-influencing factors – interrelationship

The outlining of potential recharge areas is based on analysis of the most influential factors. In this study, the weights of different factors for the assessment

of the potential groundwater recharge and the scoring of various features were assessed based on the characteristics of the study area. The factors influencing the groundwater recharge, and their relative importance, were compiled from the available literature (Yeh *et al.*, 2009; Magesh *et al.*, 2012; Murasingh and Jha, 2013; Gumma and Pavelić, 2013; Venkateswaran *et al.*, 2014; Selvam *et al.*, 2016; Senanayake *et al.*, 2016; Yeh *et al.*, 2016).

Data for all the factors were integrated into a single final map, showing the overall recharge potential of the studied area. An integrated recharge potential map was then produced, showing the areas (actual or potential) with different levels of groundwater recharge. The recharge potential for a given area can be represented as a sum of the specific values for the individual processes, as shown in Fig. 5. It is necessary to take into account the intensity of these processes.

The integration of hydrogeological processes into a single map is an easy process when GIS technology is being used. A more problematic issue can be the weightages that should be assigned to the factors related to the groundwater recharge. Such a task requires some expert assessment to be performed, which can have a significant impact on the resulting integrated potential recharge values.

Fig. 5. Calculation processes for the groundwater recharge potential.

Table 2
Factors influencing the groundwater recharge classified criteria (after Yeh *et al.*, 2009)

Factor	Basis of categorization
Geology	Rock type, terrain permeability
Land cover	Type, areal extent
Slope	Slope gradient
Lineaments	Lineament-length density value
Drainage	Drainage-length density value
Rainfall	Average value, areal extent
Soil	Texture, areal extent

The various factors affecting the recharge and their relative importance have already been described in many of the previous studies conducted abroad. The present study analyzed the main factors influencing the process of recharge on the territory of Bulgaria. The basis of their categorization is given in Table 2. The interrelationships between these factors, as well as their effects, are shown in Fig. 6. Each aspect of these relationships has been weighted according to the strength of its impact and described as either primary (major effect) or secondary (minor effect).

Weightage calculation

The multi-influencing factors for groundwater potential zones, namely the lineament density, horizontal fragmentation, lithology (rock permeability), slope gradient, land cover/use, annual precipitation, and soil texture, were examined and an appropriate weightage was assigned (Table 3). The effect of each influencing factor may contribute to delineating the groundwater potential zones. Moreover, these factors were found to be interdependent. The effect of each major and minor factor (Fig. 6) was assigned a weightage of 1.0 and 0.5 (cf. Yeh *et al.*, 2009). The cumulative weightage of both major and minor effects were considered when calculating the relative rates (Table 3). These rates were further used to calculate the score for each one of the influencing factors. The proposed score for each influencing factor has been calculated by using the following equation:

$$\text{Score} = 100 \times \left(\frac{A+B}{\sum_{i=1}^7 (A+B)} \right) \quad (1)$$

where: 'A' is a major interrelationship between two factors, and 'B' is a minor interrelationship between two factors.

The concerned score for each influencing factor was divided equally and assigned to each reclassified

Fig. 6. Interrelationship between the multi-influencing factors concerning the groundwater potential zone.

Table 3
Effect of influencing factors, their relative rates, and score for each potential factor

Factors	Major effect (A)	Minor effect (B)	Proposed relative rates (A+B)	Proposed score for each factor
Lineaments	1+1	0	2.0	10
Land cover	1+1	0.5+0.5+0.5	3.5	18
Lithology	1+1+1+1+1	0	5.0	25
Drainage	1	0.5+0.5	2.0	10
Slope	1+1+1	0.5	3.5	18
Precipitation	1+1	0.5	2.5	13
Soils	1	0.5	1.5	8

factor (Table 4). All factors were classified into five categories (domains of effect) along with their weightages, which were assigned according to very good, good, moderate, poor, and very poor recharge zones, *i.e.*, the higher weightages correspond to better recharge, and the lower weightages to worse recharge (Table 4).

Finally, a number of raster maps with the proposed weightages for the individual factors relevant to the recharge potential were created. Then, all raster maps were integrated in order to obtain the groundwater recharge potential index of each pixel in the studied area (Fig. 4). The equation of the groundwater recharge potential model can be presented as follows:

$$RP = \sum_{i=1}^7 w_i \quad (2)$$

$$w_i = \frac{\text{Score}_i}{n} \quad (3)$$

where: RP is the recharge potential; ' w_i ' is the proposed weight of effect defined in Table 4; ' Score_i ' is the proposed score for each influencing factor, defined by equation (1) and Table 3; the subscripts ' i ' refer to the individual features of a theme; ' n ' is domain of effect (in our case, $n = 5$ classes according to Table 4).

RESULTS AND DISCUSSION

Groundwater recharge potential factors and spatial assessment – weightage calculation

Geological settings

The geological and hydrogeological settings, as well as the bedrock composition, are very important for the formation of the recharge zones. Shaban *et al.* (2006) pointed out that the type of rock exposed on the surface significantly affects the groundwater re-

Table 4
Classification of weighted factors influencing the groundwater potential zones

Factors	Domain of effect	Weight of effect (weightage)
Lineament-length density, km/km ²	0–0.5	2.0
	0.5–1	4.0
	1–2	6.0
	2–3	8.0
	>3	10.0
Land cover	Artificial surfaces	3.6
	Water bodies	7.2
	Forest and semi-natural areas	10.8
	Agricultural areas	14.4
	Wetlands	18.0
Lithology (terrain permeability)	Very high	25.0
	High	20.0
	Moderate	15.0
	Low	10.0
	Very low	5.0
Drainage-length density, km/km ²	0–0.5	10.0
	0.5–1	8.0
	1–2	6.0
	2–3	4.0
	>3	2.0
Slope gradient, degree	0–4	18.0
	4–10	14.4
	10–17	10.8
	17–26	7.2
	>26	3.6
Precipitation, mm	423–500	2.6
	500–600	5.2
	600–700	7.8
	700–900	10.4
	>900	13.0
Soil texture	Very fine	1.6
	Fine	3.2
	Medium fine	4.8
	Medium	6.4
	Coarse	8.0

charge. Lithology affects the groundwater recharge by controlling the percolation of water flow (El-Baz and Himida, 1995, seen in Yeh *et al.*, 2009). Although some researchers have ignored this factor by regarding the lineaments and drainage characters as a function of primary and secondary porosity, this study has included lithology in order to reduce the uncertainty when determining the lineaments and drainage.

Despite being a small country not very large in area, Bulgaria is characterized by a complex geological structure. On its territory, rocks of Proterozoic, Paleozoic, Mesozoic, Paleogene, Neogene, and Quaternary ages occur. According to the conditions of their formation, they are magmatic (intrusive, effusive and pyroclastic), sedimentary, and metamorphic (Fig. 2). Alluvium Quaternary sediments cover almost the entire northern part of the country and can be located mostly in the central southern part of the studied area (Fig. 2). Around 25% of the total area is covered by Mesozoic sedimentary rocks (primarily in the northern part of the country), followed by alluvium and Quaternary sediments (23%), Neozoic sedimentary rocks (19%), and Precambrian metamorphic rocks (13%) (Table 5).

Table 5
Types of rocks on the territory of Bulgaria

System	Bedrocks lithology	Area, km ²	(%) of the entire territory
Quaternary	Quaternary deposits	25,998	23.4
Neozoic	Sedimentary rocks	21,301	19.2
Neozoic	Intrusive rocks	440	0.4
Neozoic	Volcanic and volcano-sedimentary rocks	3,669	3.3
Mesozoic	Sedimentary rocks	27,958	25.2
Mesozoic	Intrusive rocks	2,053	1.8
Mesozoic	Volcanic and volcano-sedimentary rocks	3,588	3.2
Mesozoic	Metamorphic rocks	1,157	1.0
Paleozoic	Sedimentary rocks	1,383	1.2
Paleozoic	Intrusive rocks	7,373	6.6
Paleozoic	Volcanic and volcano-sedimentary rocks	334	0.3
Paleozoic	Metamorphic rocks	807	0.7
Pre-Paleozoic	Metamorphic rocks	14,176	12.8

In order to accomplish its goals, the study makes use of data for establishing the approximate permeability of geological formations (Fig. 7). These data were prepared on the basis of the following sources: 1) geological map of Bulgaria 1:500 000 (Cheshitev

and Kanchev, 1989); 2) map of hydrogeological elements, important for construction work 1:500 000 (Kamenov *et al.*, 1963b); 3) engineering-geological map of Bulgaria 1:500 000 (Kamenov *et al.*, 1963a); and 4) map of the hydrogeological division of Bulgaria 1:600 000 (Antonov *et al.*, 1960). These maps were used in order to compile the geology layer and to determine the respective weightage. It was found that the lower-laying regions around the downstream are mainly composed of sands, clay sands, gravels, and gravel sands, *i.e.*, sediments displaying inter-granular porosity and high water permeability. Gravels and sands in the lowlands/plains, and open karst areas in the mountainous are excellent regions for water percolation (rainfall infiltration). The suitable weightages for terrain permeability are shown in Table 4. Weightages 5 and 10 were assigned to the fissured, fissured-karst, and fissured-porous types of groundwater collectors. Weightage 15 (the moderate value) was set for the fissured, fissured-karst, fissured-karst-porous, and porous media. Areas of high permeability (weightage 20) refer to highly weathered rocks, fissured-karst, karst-porous, fissured-karst-porous, and porous environments. The very high permeability areas (weightage 25) were reserved for karst, porous, and karst-porous environments.

Lineament patterns

O'Leary *et al.* (1976) defined lineaments as simple and complex linear geological structures, such as faults, cleavages, fractures, and various surfaces of discontinuity, that are arranged in a straight line or forming a slight curve. According to Subba Rao *et al.* (2001), lineaments give a clue to movement and storage of groundwater, and therefore can serve as important guides for groundwater exploration.

A high lineament density value infers high secondary porosity, thus indicating a zone with high levels of potential groundwater recharge. The lineaments were obtained from the geological series maps of Bulgaria in scale 1:100 000. From these maps, a raster layer was prepared, showing the lineament-length density (Fig. 8). A lineament-length density map shows, in quantitative terms, the linear features expressed in the form of a grid. The lineament-length density of an area can reveal the groundwater potential areas indirectly, since the presence of lineaments usually denotes a permeable zone and permeability increases as the fracture density increases (Bisson and Lehr, 2004). For the purpose of the present analysis, a lineament map was made and subsequently categorized into five classes. Therefore, the weightage was assigned as high

Fig. 7. Adapted map of approximate permeability of the studied terrain showing the assigned weight of effect.

for the higher densities and low for the lower ones (Fig. 8). Suitable weightages for lineament density are shown in Table 4. The average frequency values fall into the range of 0–6.6 km/km² (Fig. 8).

Drainage patterns

Drainage density is one of the most important characteristics describing the landscape, and it depends on the permeability of the terrain. According to Edet *et al.* (1998), the drainage pattern is an important indicator of hydrogeological features since, along with texture and density, it is controlled in a fundamental way by the underlying lithology. In addition, the creek pattern is a reflection of the rate with which precipitation infiltrates in comparison with the surface runoff. The relationship between infiltration and runoff is controlled to a large extent by the permeability, which is in turn a function of the rock type and fracturing of the underlying rock

or bedrock surface. A drainage-length density map was prepared from drainage-length per square km (Fig. 9). In addition, a table of suitable weightages for the drainage density was also prepared in due course (Table 4). Hydrographical settings influencing the formation and regime of the discharge affect indirectly the potential groundwater recharge zones.

The river network density in Bulgaria is considerable, and it alternates in the range of 0 km/km² to 5.1 km/km² (Fig. 9). It is influenced by the variability of terrain, its geologic and tectonic structure, the lithology of rock formations, the land cover, as well as the climatic conditions. The river network density is greater in the mountainous areas, where there is more surface runoff. On the other hand, the density is at its lowest in the Danube Plain, and particularly in the Dobrudzha Region, in the northeast of the country. It is a well-known fact that the denser the drainage network, the smaller the recharge rate, and vice versa. The drainage density map re-

Fig. 8. Lineament-length density map of Bulgaria showing the assigned weight of effect.

veals that density values are regrouped into five categories and range from 3–5.1 km/km² (very high), 2–3 km/km² (high), 1–2 km/km² (moderate), 0.5–1 km/km² (low) to 0–0.5 km/km² (very low) (Fig. 9). Considered from a recharge point of view, more weightage was assigned to regions of very low drainage-length density, whereas less weightage was assigned to very high densities – areas unsuitable for groundwater development because of the greater surface runoff. The most appropriate weightages for drainage density are shown in Table 4 and Fig. 9.

Land Cover

The land cover and its usage in the studied area can be characterized as a mixture of forests, pastures, agricultural land, urban areas, and water bodies. Out of 44 classes described in Level 3 of the CORINE Land Cover 2006, in Bulgaria can be observed 36

land features (classes) (Executive Environment Agency of Bulgaria, <http://eea.government.bg/bg/projects/korine-14/osn-inform>). For the territory of Bulgaria, most land falls in the following classes: arable lands (51.40%); forests and semi-natural areas (42.44%); and anthropogenic objects (4.70%). For the current task, the classes of land cover from Level 1 were used (Fig. 10). The suitable weightages for the particular type of land cover are shown in Table 4.

Slope Gradient

The slope of the terrain has a significant role when assessing the potential recharge zones. The steepness of the slope affects the generation of surface runoff, and the infiltration of precipitation. The slope gradient is very important for the formation of soil cover, as well as the land use for any given territory. The various regions in Bulgaria range in their

Fig. 9. Drainage-length density map of Bulgaria showing the assigned weight of effect.

steepness from 0–4 degrees in the plains and valleys, to above 25 degrees in the mountainous areas (Fig. 11). According to data from DEM90, 52% of the territory of Bulgaria has a slope of 0–4 degrees, and only 3% are with a slope above 26 degrees (Table 6).

Slope has been classified into five categories (plain, slight, moderate, steep, or very steep), along

Table 6

Steepness of the studied area

Slope, deg.	Area, km ²	(%) of the entire territory
0–4	57,663	52
4–10	26,041	24
10–17	15,229	14
17–26	9,009	8
>26	2,786	3

with their weightages; the weights were assigned according to the slope influence on recharge potential (Fig. 11). A slope of <4° is regarded as plain region because low level of the surface runoff usually translates into a very good recharge zone. The areas having a 4°–10° slope are considered as good for groundwater storage due to slightly undulating topography with little overland flow. The areas having a slope of 10°–17° cause relatively moderate runoff, and hence they can be categorized as moderate. Slopes having 17°–26° are mostly considered as poor recharge zones, and areas having a slope >26° are considered very poor recharge zones due to their steeper slope and rapid surface runoff. In the process of preparing a map of the potential groundwater recharge zones, the least amount of weightage was assigned to steeper terrains, whereas more weightage was given to gentler slopes, as the slope gradient plays a significant role in infiltration versus runoff.

Fig. 10. Land cover map of Bulgaria (CLC 2006) showing the assigned weight of effect.

The suitable weightages for different slope gradients were prepared according to SRTM_90 (<http://srtm.csi.cgiar.org>), and the results are shown in Fig. 11 and Table 4.

Precipitation

One of the main climatic factors affecting the formation of river discharge and recharge potential zones is precipitation, which is unevenly distributed on the territory of Bulgaria. The annual precipitation increases from the northern parts towards the southern parts of the studied area (Fig. 3). The total sum of rainfalls is higher: approximately 1,100–1,400 mm in the mountainous areas and lower in the middle and low mountain regions (from 800–900 mm to 1,000–1,200 mm); in the hilly regions the precipitation is 700 mm on average, and in the lowlands, where the main portion of the precipitation evaporates or infiltrates, it is about 600 mm.

An annual precipitation map of the research area (Fig. 12) was prepared using the annual precipitation measured at the meteorology stations for the period 1931–1985 (Koleva and Peneva, 1990) and the surrounding area. Grid cells (1×1 km) were created on this map. Suitable weightages for annual mean areal extent precipitation is shown in Table 4.

Soils

Soils in Bulgaria are very diverse in origin and composition, and soil cover has a complex spatial structure (Ninov, 2002). In the lowlands, plains and hills of the country, most widely spread are the chernozems (CH), luvisols (LV), followed by vertisols (VR), phaeozems (PH), planosols (PL), and leptosols (LP). In this belt, solonetz (SN) and solonchaks (SC), some fluvisols (FL), and other type of soils can also be found. Most limited in this zone are the cinnamonic soils, alisols (AL), and regosols (RG).

Fig. 11. Slope-gradient map of the study area showing the assigned weight of effect.

The mountainous areas of Bulgaria are characterized by the widespread occurrence of cambisols (CM).

Diffuse groundwater recharge is the amount of water that infiltrates through the soil cover and reaches its level. Therefore, when determining the potential groundwater recharge zones, it is important to have data on the soil texture on which both the field capacity and infiltration of rainwater depend. Water content of soils depends on their grain-size composition. Soils with coarse texture have higher water permeability, whereas soils with fine and very fine texture have the lowest permeability. Most of the country is covered by soils with medium-fine texture. Soils with fine texture can be found in north-eastern Bulgaria, and soils with medium texture in the south-western parts and some areas in northern Bulgaria. Soils having very fine texture are characteristic of the south-eastern regions (Fig. 13). Clayish soils have greater water-holding

capacity than sandy soils. Soils with greater available water capacity (AWC) have higher water-holding capacity, and they were assigned lower weightages accordingly. These soil types are located in the south-eastern and western regions of the studied area. Soils with poor water-holding capacity were given higher weightages. Such soil types are located in small regions in the western, some central, northern and south-western parts of the study area. The suitable weightages for the various types of soils are shown in Table 4.

Demarcation of the groundwater recharge zones

At the final stage, a map was drawn up, showing the potential groundwater recharge zones (Fig. 14) within the study area. The indicators of groundwater occurrence and recharge are related to rainfall distribution, land cover, geology, slope, soil, and

Fig. 12. A long-term mean annual precipitation map of Bulgaria showing the assigned weight of effect.

Fig. 13. Soil texture map of Bulgaria showing the assigned weight of effect.

Fig. 14. Groundwater recharge potential zones of Bulgaria.

Table 7
Reclassification of potential recharge zones generated during the integration of thematic layers

Recharge Potential	Area, km ²	(%) of the entire territory
Very poor	13,414	12
Poor	23,341	21
Moderate	27,726	25
Good	25,772	23
Very good	20,495	19

drainage features of the area. In order to predict the groundwater recharge potential zones, different thematic maps were prepared. These include annual mean precipitation distribution, land cover, geology (rocks' permeability), lineament-length density, soil texture, slope gradient, and drainage-length density (see Figs 7–13). Integrated assessment of thematic maps, using a model based on GIS techniques, was a suitable method for predicting groundwater potential. The compiled map (Fig. 14) shows that, in large areas of the territory of Bulgaria (33%), the re-

charge potential is poor to very poor (Table 7), 23% of the area has good recharge potential, 25% of the area has moderate groundwater recharge potentiality, and the remaining area (19%) has a very good groundwater recharge potential.

CONCLUSION

The delineation of the groundwater recharge potential zones in the Bulgarian countryside was conducted making use of GIS technology that provided an effective methodology in the context of time, labor and cost. Seven parameters, such as the annual precipitation, lineament density, slope gradient, drainage density, land cover, lithology, and soil texture layers, were integrated on a GIS-platform employing the weighted linear combination method. The data presented in the article were analyzed and processed in GIS environment, and for each factor a raster map with 1×1 km grid was generated. Also, for each of the factors, influencing the groundwater recharge, the weightage was assigned in a spatial domain.

In this study, seven thematic layers have been generated for the analysis and integration into a groundwater recharge prospect map.

The resulting final map shows that 67% of the area has very good to moderate recharge potential, mainly confined to agricultural land use and river terraces (where a considerable amount of precipitated water percolates into the subsurface), 21% of the area has a poor groundwater recharge potential, and the remaining area (12%) has a very poor recharge potential. The residual hills and linear ridges with steep slopes have been found to be unsuitable for recharge sites.

An integrated map showing the potential groundwater recharge zones has been prepared on the basis of available free data (resources). The main concept of the present research might be used for a more elaborate investigation of the problem. From the final map, it can be concluded that, for large areas of Bulgarian territory, the recharge can be described as insignificant, *i.e.*, very poor to poor (33%). The resultant suitability map and the methodology employed in the study can serve as guiding principles for future water management projects.

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