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The utility of vulnerability maps and GIS in groundwater management: a case study

Muhterem DEMİROĞLU[1,*], **John DOWD**[2]
[1]Department of Geological Engineering, Mines Faculty, İstanbul Technical University, Ayazağa, İstanbul, Turkey
[2]Department of Geology, University of Georgia, Athens, GA, USA

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Abstract: Groundwater supplies are experiencing a critical shortage in arid and semiarid regions, as population growth, and hence demand, is not matched by the development of new water supplies. Groundwater is often the only water source in these areas, making the preservation of groundwater quality a critical issue. Powerful tools for groundwater protection are vulnerability maps, which can be used to identify protection zones. A number of factors influence aquifer vulnerability, including geology, geography, land use, and commercial and industrial development. These factors often display a complex spatial pattern easily addressed with GIS. Each factor is entered in the GIS as a layer, and these layers can be superimposed in various combinations to derive the vulnerability maps. The use of GIS is illustrated with vulnerability maps of Günyüzü basin, located in the semiarid region of northwest Turkey. The hydrogeologic parameters were identified and assigned weights depending on their potential to influence groundwater quality and quantity. The combined weights were mapped to identify critical protection areas. The vulnerability maps of the Günyüzü basin were reclassified into 5 class schemes, i.e. very high vulnerability rating area is 0.18%, high vulnerability rating area is 6.19%, moderate vulnerability rating area is 34.79%, low vulnerability rating area is 50.07%, and very low vulnerability rating area is 8.77%.

Key words: Semiarid, aquifer, groundwater management, GIS, vulnerability map, protection zones

1. Introduction

Groundwater is a major source of drinking water across the world and plays a vital role in maintaining the ecological value of many areas. However, the quantity and quality of groundwater is changing as a consequence of human activity (Dams *et al.* 2007) and climate variability (IPCC 2001; Dams *et al.* 2007). The demand for water is rising as population, economic activity, and agricultural irrigation grow. However, worldwide resources of accessible water are decreasing due to overuse or pollution. The balance between demand (consumption) and supply (resource) is becoming untenable. More than 30 countries suffer from serious chronic water shortage, and groundwater is increasingly being used to cover the demand (Struckmeier *et al.* 2005). Clearly groundwater management techniques that identify those areas vulnerable to contamination are needed so that protection measures can be implemented.

A principal objective of groundwater management is the identification of protection zones. A groundwater protection zone is an area around public groundwater sources such as wells, boreholes, and springs. Its size and extent is defined by the total catchment area. Within this area there are restrictions for land use and human activities. Generally, the closer the activity is, the greater the risk. In this paper we will describe an approach to defining a groundwater protection zone in a karstic terrane.

2. Protection zones

Most European countries divide the groundwater protection area into 3 zones (inner, outer, and total catchment), but their definition is not uniform (Table 1). The immediate area is often a 10-m radius around a spring or a well. The inner protection zone is often based on a water transit time of 10 to 100 days (DVGW 1995; VGW 1995; GSchV 1998; DoELG/EPA/GSI 1999; Goldscheider 2005). The outer protection area ranges from the rest of the catchment to at least 2 km or 400 days transit time (Doerfliger *et al.* 1999).

According to the water pollution regulation of the Ministry of Environment and Forestry in Turkey, groundwater is divided into first and second class quality. Total protection areas are defined in an area within 50 m of the groundwater source, such as a spring, well, or seepage galleries. All activities in this zone are prohibited. Protection areas can be reduced or increased by the authorities, taking into consideration the local conditions, and if necessary a second zone can be created for recreation activities (T.E.F. 1992). This regulation covers all kind of aquifers and does

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[*] Correspondence: demiroglum@itu.edu.tr

Table 1. European protection zones.

Country	Inner zone		Middle zone		Outer zone	
	Time of travel	Radius of zone	Time of travel	Radius of zone	Time of travel	Radius of zone
Denmark		10 m	60 days	300 m	10–20 years	
Netherlands	60 days	30 m	10 years		25 years	
United Kingdom	50 days	50 m	400 days		Whole catchment	
Switzerland		10 m	Individually defined		2* Middle zone	
Ireland	100 days	300 m			Whole catchment	
Germany	10–20 days		50 days		Whole catchment	
Austria		<10 m	60 days		Whole catchment	

not distinguish between consolidated/unconsolidated or confined/unconfined aquifers. Furthermore, the groundwater flow velocities can change from a few meters per day (Darcy flow) to kilometers per hour (karstic flow). Karst aquifers are particularly vulnerable to contamination due to thin soils and flow concentration in the epikarst (the uppermost, often intensively fractured and karstified layer of a carbonate aquifer). Point recharge via swallow holes can allow contaminants to quickly reach the groundwater, where they may be transported rapidly in karst conduits over large distances. The residence times of contaminants are often short, and contaminant attenuation is often inadequate in karst systems. For these reasons, karst aquifers need special protection. However, establishing protection zones for karst is more complicated than for granular aquifers because karst systems are highly heterogeneous and anisotropic. The catchments may cover large areas, and flow velocities may be as high as 500 m/h. If the same criterion were used for sources in karst aquifers, the protection zones would cover huge areas, often the entire catchment. For drinking water protection, it is most often not practical to demand the maximum protection of large areas, as the resulting land-use restrictions would be unacceptable in most cases. Therefore, the protection zones should be as large as necessary, but as small as reasonable to protect the resource (Alföldi 1986; Kaçaroğlu 1999). As a consequence, it is essential to protect at least those areas within a karst system where contaminants can most easily reach the groundwater.

This leads to the concept of groundwater vulnerability, which is defined by the International Association of Hydrogeologists (IAH): "Vulnerability is an intrinsic property of a groundwater system that depends on the sensitivity of that system to human and/or natural impact". Vulnerability maps are useful because they can clearly show the spatial distribution of complex systems (Vrba & Zaporozec 1994). The objective of vulnerability mapping is to identify and prioritize the most vulnerable areas. A vulnerability map can help the decision makers find a scientifically based balance between groundwater protection and socioeconomic demands. Aquifer protection zones cannot be defined unless the aquifer system is thoroughly understood. This includes defining the aquifers and any confining beds, the aquifer boundaries, the recharge areas, the aquifer properties, and the discharge points.

Intrinsic vulnerability of groundwater to contaminants takes into account the geological, hydrological, and hydrogeological characteristics of an area, but does not depend on the nature of the contaminants or the contamination scenario. Specific vulnerability adds the properties of a particular contaminant or group of contaminants to the intrinsic vulnerability of the area. Resource protection maps aim to protect the entire groundwater body, while source protection maps aim to protect a particular source, which may be a spring or well (Vrba & Zaporozec 1994; Goldscheider 2005). Although the first vulnerability map was produced by Margat in France at 1:100,000 scale about 40 years ago, it has become more practical with the introduction of geographic information systems (GIS), which integrate hardware, software, and data for capturing, managing, analyzing, and displaying all forms of geographically referenced information (esri.com/whatisGIS.cfm.2011). Examples of these GIS-based methods of intrinsic vulnerability mapping have been developed, and include DRASTIC (Aller *et al.* 1987), EPIK (Doerfliger & Zwahlen 1995), Aquifer Vulnerability Index (Van Stempuort *et al.* 1992), protective cover and the infiltration conditions (Goldscheider *et al.* 2000), and the transit time method (Brosig *et al.* 2007). However, standard methods have not been established.

3. Materials and methods

Günyüzü basin, located in the upper Sakarya basin in central Turkey, was used to illustrate an approach to producing an intrinsic vulnerability map (Figure 1). The

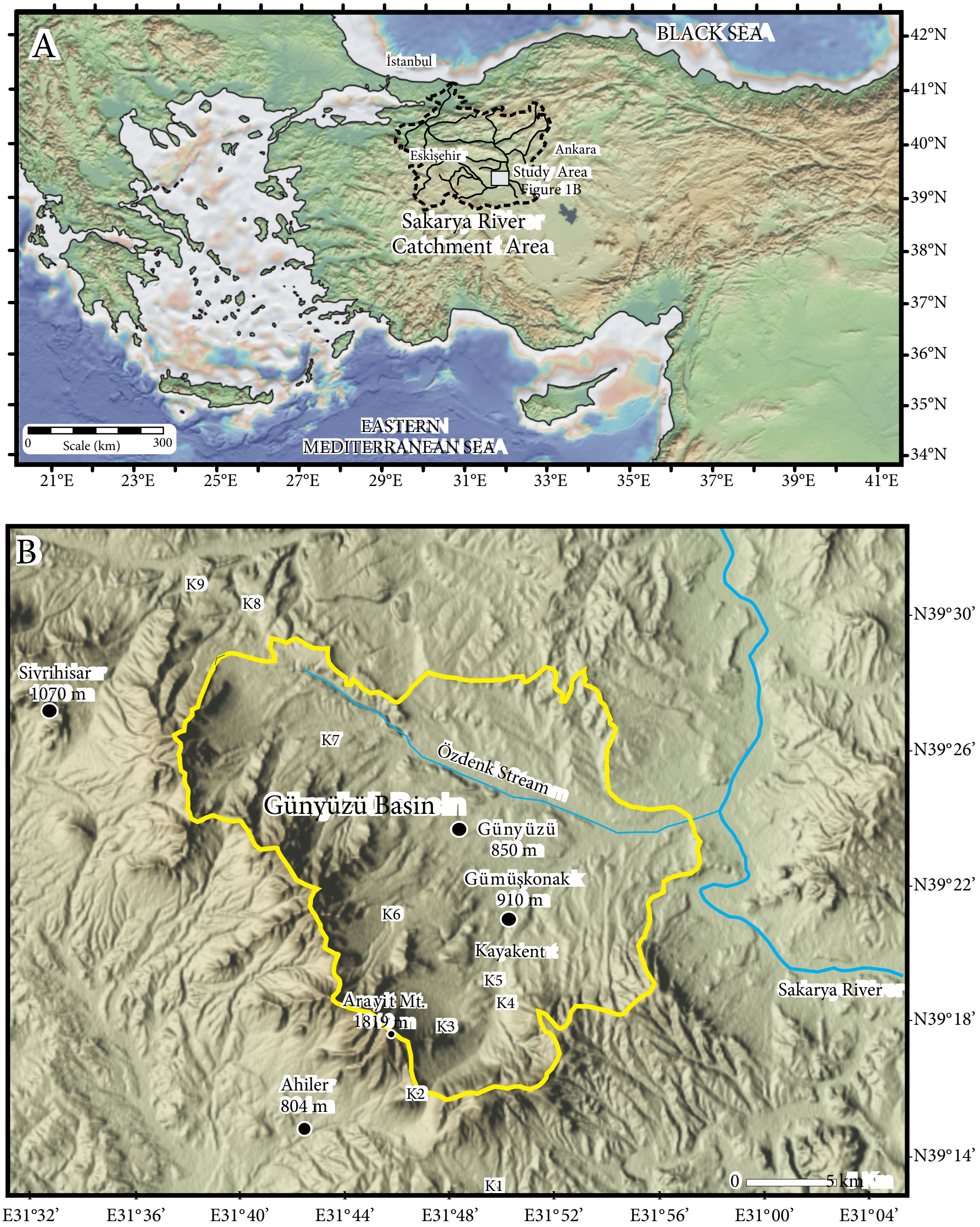

Figure 1. (a) The location map of the study area, (b) Günyüzü basin (Demiroglu *et al.* 2011).

area is semiarid, with an annual average precipitation of 393 mm (Demiroğlu *et al.* 2007). Five main lithostratigraphic units are recognized in the study area: Permo-Carboniferous Kertek metamorphic units represented mainly by schists and marbles (which form the basement of the Günyüzü basin), Eocene Sivrihisar granodiorite, Miocene sedimentary units, Pleistocene terrestrial clastics, and Holocene alluvium. The study area includes a variety of aquifers, including unconfined, confined, and semiconfined systems that may be karstic, fractured, or granular aquifers. Permo-Carboniferous marbles within the Kertek metamorphic unit represent the higher parts of the aquifer system. The thickness of the marbles is more than 100 m (Figure 2). The marbles, mapped as locally rich and medium aquifers, both contain and conduct considerable amounts of groundwater. Moreover, the marbles play a significant role in recharge of the basin. The K3 and K2 springs are recharged, circulate, and discharge through these marbles. This circulation happens at shallow depths and the uniform chemical properties of the springs

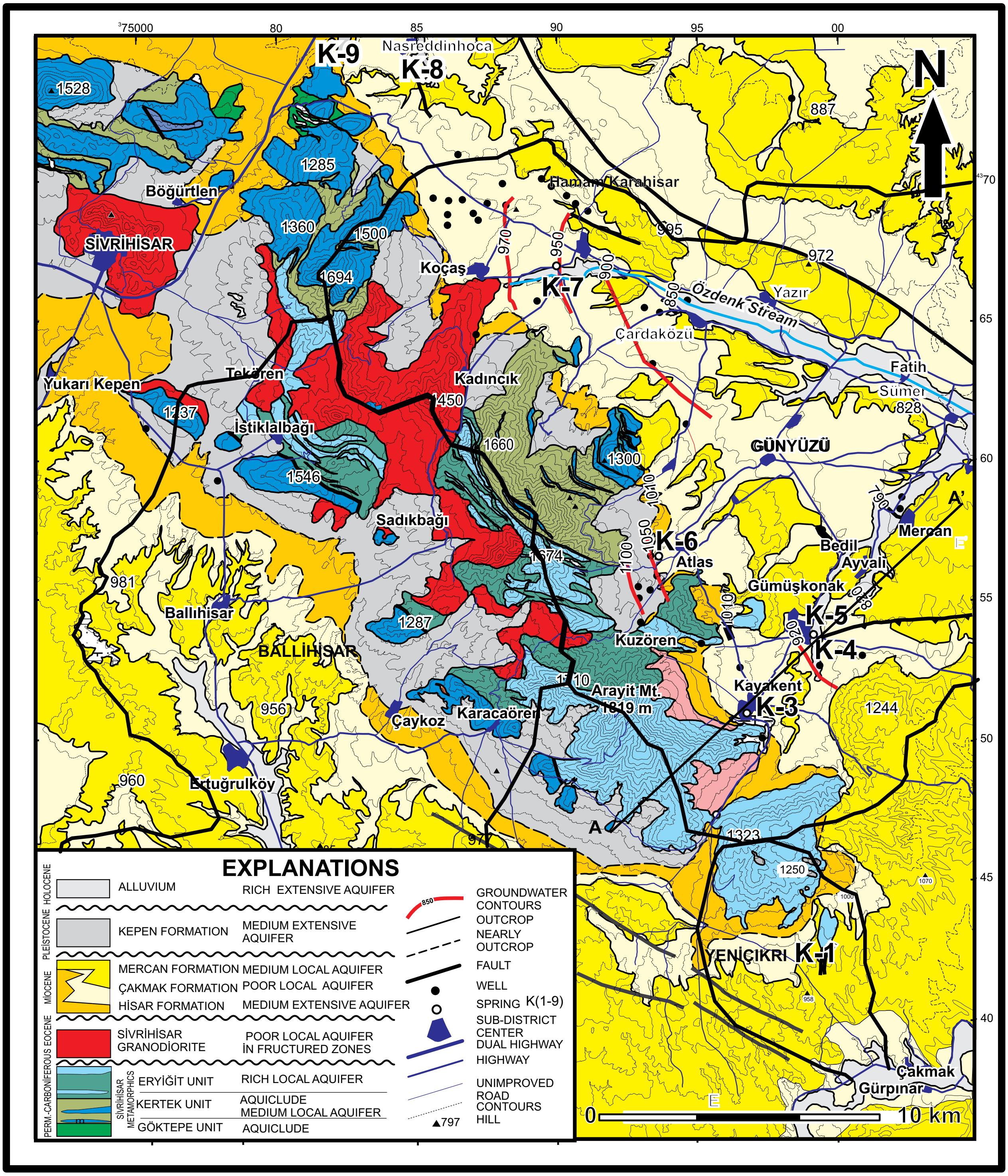

Figure 2. Hydrogeological map of the study area (Demiroglu *et al.* 2011).

imply laminar flow conditions. Karstic springs and aquifer systems are illustrated in a conceptual model (Figure 3). Pump tests in the marbles yielded hydraulic conductivities from 1.19 to 98.9 m/day and specific capacity ranges from 0.64 to 75 L/s/m. The highest hydraulic conductivity and specific capacity were associated with karstic structures. Additionally, some aquifers contain waters with elevated temperatures. These systems are characterized by a heterogeneous permeability distribution that includes rapid karstic channels. This heterogeneity produces a wide range of water recharge zones, transfer mechanisms, and residence times (Figure 3) (Demiroğlu *et al.* 2011). First the physical properties of the system are defined in a GIS, including rainfall, soils, lithology, depth to groundwater, and hydraulic conductivity. Then the DRASTIC (US EPA 1993) methodology was employed to define appropriate weights for the parameters. Finally, GIS layers were prepared for these properties and then combined to produce a composite weight for each cell of approximately 36 m^2. The high risk areas were identified by this final composite score. The primary physical parameters that must be defined are listed in Table 2, with their resulting weighting for this example.

The aquifer type is a principal parameter in vulnerability, and it can be defined as local or extensive, and good, medium, or poor. The formations are classified on a scale of 1–5 depending on their features such as developed karstic structures and fractured, granular, and unpermeable units, and scaled to integrate with other maps. Protective cover or soil thickness of the upper unconsolidated zone, which includes both the soil and other geological overburden such as saprolite, epikarst, and other Quaternary deposits, is commonly regarded as one of the most important attributes in the assessment of groundwater vulnerability (Doerfliger *et al.* 1999). Protective cover is not a barrier to infiltrating contaminants, but it can supply time for the contaminants to degrade. Microbial contamination, for example, is assumed to survive not longer than 60 days in a subsurface environment (Ekmekçi & Günay 1997). Long infiltration times generally mean low aquifer vulnerability. The infiltration time depends on the thickness and hydraulic conductivity of the vadose zone. The soil type and the likely overburden thickness of the Günyüzü basin area was defined using satellite imagery, borehole records, and field observations. Unfortunately, a detailed soil map is not available for this area.

Wells in Kayakent district discharge the semiconfined aquifer. Potentiometric level is between 891.7 and 891.6 m (Figure 4) Well 56968-A and well 56968-B have the same geological units but depth to water level changes their vulnerability. Depth to water table influences the infiltration time. Its interaction with the vadose zone properties is illustrated in Figure 4. Greater depth to water table results in a lower vulnerability rating. Groundwater

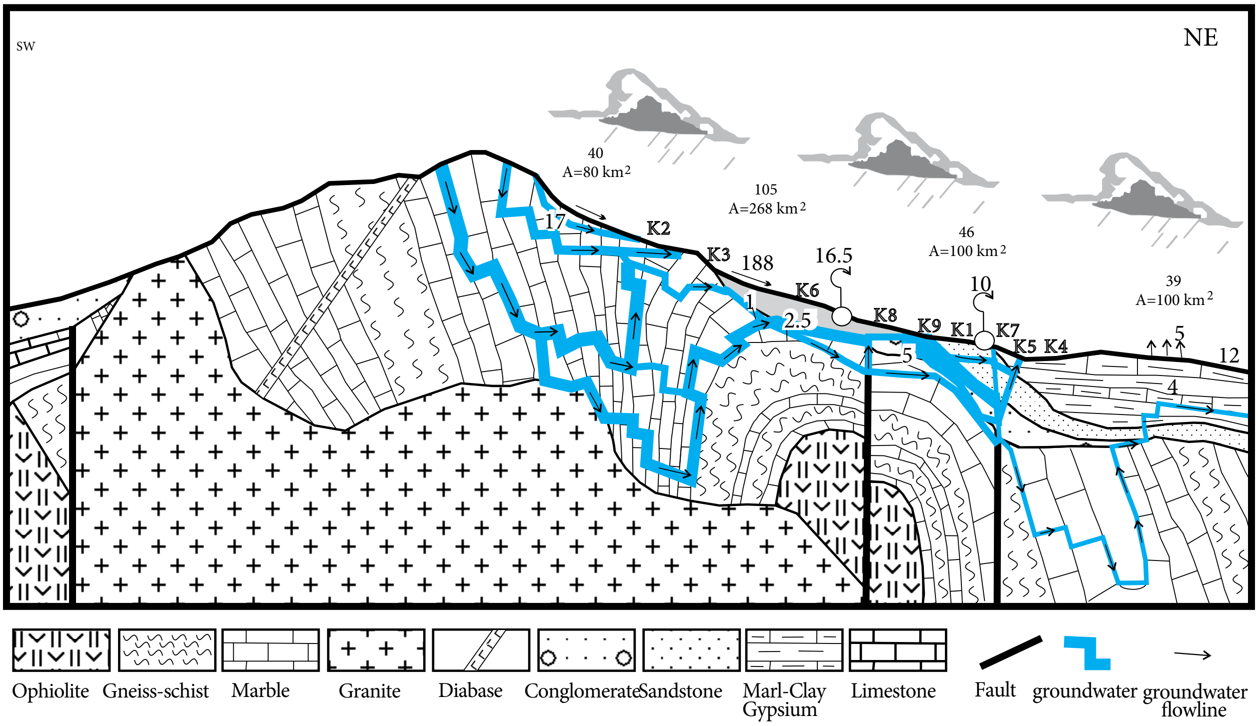

Figure 3. Schematic illustration the hydrogeological conceptual model of the Günyüzü basin and recharge area of springs (box) (Demiroglu *et al.* 2011).

Table 2. Primary physical parameters.

Theme	Weight	Class	Range	Result
Hydrogeology	3	Karst	5	15
		Mixed	4	12
		Fructured	3	9
		Matrix	2	6
		impermeable	1	3
Lithology of vadose zone	4	Clay, impermeable	1	4
		Sandy clay	2	8
		Sand, fractured	3	12
		Sand	4	16
		Absent, fractured	5	20
		Absent, massive	1	4
Hydraulic conductivity (m/day)	3	0.02–0.36	1	3
		0.36–0.71	2	6
		0.71–1.06	3	9
		1.06–1.40	4	12
		1.40–1.75	5	15
Hydraulic conductivity (m/day)	3	1.19–2.70	1	3
		20.70–40.21	2	6
		40.21–59.72	3	9
		59.72–79.22	4	12
		79.22–98.7	5	15
Depth to groundwater	5	0–2	5	25
		2–5 m	4	20
		5–10 m	3	12
		10–20 m	2	10
		>20 m	1	5

depth and hydraulic conductivity overlays were prepared using an inverse distance weighted interpolation scheme.

Hydraulic conductivity is a critical component in vulnerability assessment. High hydraulic conductivity results in rapid contaminant movement. The aquifers in Günyüzü basin are characterized by heterogeneous hydraulic conductivities, which vary widely from 1.19 to 98.9 m/day, with a specific capacity that varies from 0.64 to 75 L/s/m. The hydraulic conductivity of the Neogene limestones varies between 1.39 and 4.1 m/day (specific capacity 1.8–2.9 L/s/m), the hydraulic conductivity of the Neogene conglomerates and Quaternary alluvium is 0.27 to 0.39 m/day (specific capacity 0.38–0.55 L/s/m), and the ophiolite and schists of the metamorphic complex, Eocene granites, Neogene marl, clays, and diabases are considered impermeable in the basin (Demiroglu 2008). Two hydraulic conductivity maps were prepared in this study, one of the marbles and the other of the younger units.

Additional parameters that affect vulnerability include hydromorphology, slope, drainage density, recharge, land use, lineaments, and distance to wells and springs. These features are assigned different weights depending on their importance with respect to vulnerability. The different classes are assigned weights ranging from 1 to 5 (Israil *et al.* 2006) depending on their influence on the groundwater vulnerability. These 2 weights are combined to yield the net weight (Table 3).

The topographical digital data were obtained from the Mineral Research and Exploration General Directorate (MTA). The digital elevation model (DEM) was prepared with ArcGIS 3D analyst, and the Triangular Irregular Network (TIN) and slope map were formed from the DEM. Slope gradation was estimated in degrees and reclassified into 4 groups: 0–1, 1–5, 5–10, and >10 degrees. Slopes are important because they are linked to recharge rates. Low slopes allow more time for infiltration. Very steep slopes, coupled with high drainage density, result in low infiltration and high runoff volumes. Therefore, high drainage density, which indicates a high runoff component, was assigned a value of 1.

Lineaments were used to predict fracture orientation and karstic channels. In general, these linear features are underlain by zones of localized weathering that increased permeability and porosity. In the analysis, all lineaments

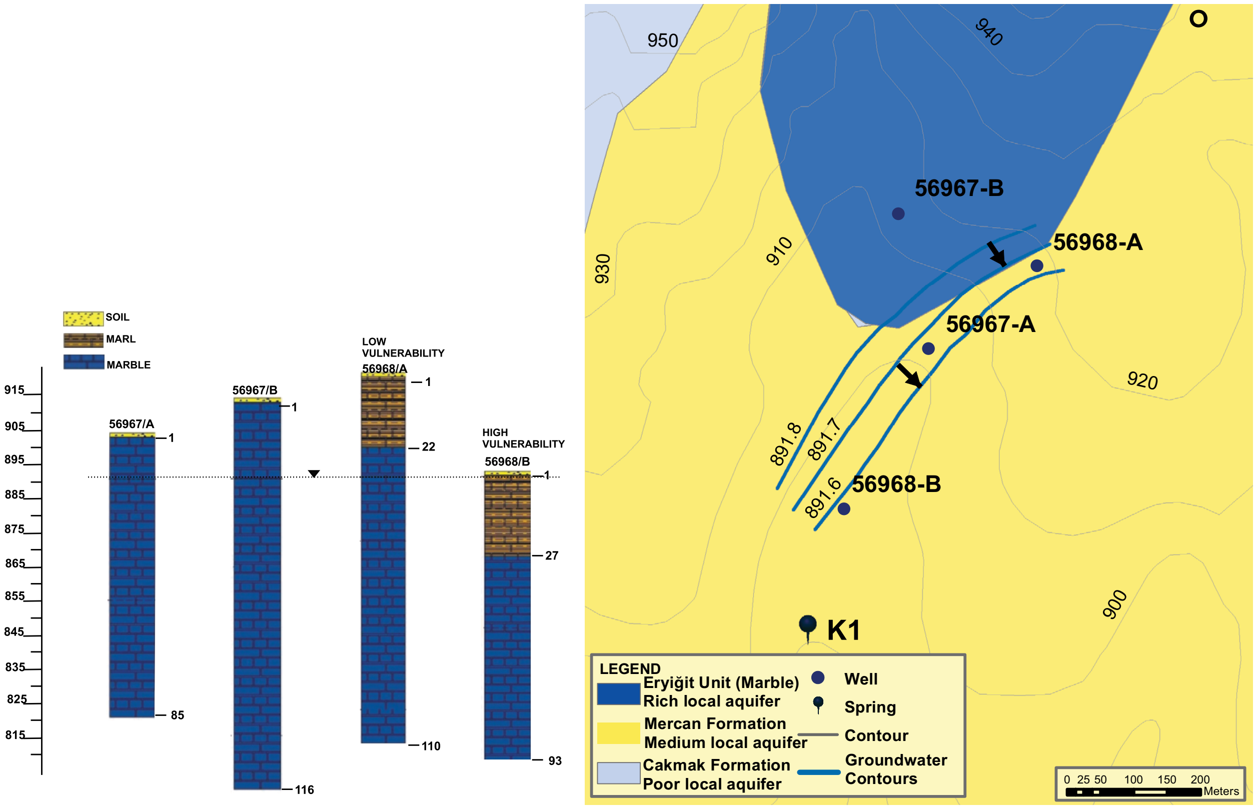

Figure 4. Wells in Kayakent region have the same geological units but depth to water level changes their vulnerability.

were buffered by a distance 200 m, and each buffer zone was assigned a value of 5.

A land use map, with a resolution of 5.8 m, was prepared using IRS–IC satellite images. Land use such as agriculture carried out over long periods in the same area can result in potential changes to the soil that can impact the vadose zone and hydraulic conductivity. A map was prepared differentiating dryland agriculture from irrigated agriculture. Nitrate concentrations in ground water in irrigated agriculture and urban areas were significantly higher than in rangeland, dryland agriculture, and forest areas. For this reason, irrigated agricultural areas were assigned an intermediate probability rating of 3, while range land, dryland agriculture, and forest areas were combined and assigned a value of 1. Gypseous areas were assigned a grade of 3 because of their contamination potential.

Maps were prepared with distance calculated using the rasters. Maps of each parameter were reclassified at each step to generate a composite map of the study area (Figure 5). These maps were assigned the appropriate weights, giving each a relative influence. The higher the resulting value, the greater the vulnerability, with the final map prepared by adding the scores of various parameters for each pixel (Figure 6).

4. Discussion

There is a general lack of awareness of the importance of groundwater protection, and the establishment of a national strategy is an important step for the protection of natural resources and the prevention of environmental pollution. A GIS and remote sensing approach for the identification of vulnerable recharge areas provides a valuable tool for studies of large regions due to its ability to manage large volumes of spatial data from a variety of sources. This is especially useful in karstic regions, such as the Günyüzü basin, because the flow paths are difficult to discern and the potential for contamination traveling quickly over great distances is large. The utility of the approach, however, is limited by the available data, and how amenable these data are to interpolation. Some data will be readily available at a sufficient resolution, while other data will have to be inferred. If the data are limited for a critical parameter, the results derived from this approach will not be satisfactory.

Even if the data are insufficient for a satisfactory set of parameter overlays, the approach is useful because it helps the practitioner identify critical data gaps. Efforts can then be made to resolve the missing data. Furthermore, the approach is well suited to an iterative approach. Additional data can be added easily to the analysis to refine the results as future needs arrive.

Table 3. Additional parameters considered in the analysis.

Theme	Weight	Class	Range	Result
Hydromorphology	2	Hill	1	2
		Hillslope	3	6
		Plain	2	4
Distance to well and springs (m)	2	0–50	5	10
		50–100	4	8
		100–200	3	6
		200–300	2	4
		>300	1	2
Slope	3	0–1	4	12
		1–5	3	9
		5–10	2	6
		>10	1	3
Drainage density	1	0.0–0.35	4	4
		0.35–0.9	3	3
		0.9–1.1	2	2
		1.1–1.9	1	1
Land use	1	Irrigated	3	3
		Dry land	1	1
		Green area	2	2
		Bare area	1	1
		Bare (gypseous)	3	3
Rainfall	4	286–318	1	4
		318–336	2	8
		336–353	3	12
		353–373	4	16
		373–405	5	20
Lineaments	3	0–200 m	5	15
		>200 m	1	3

5. Conclusions

Given the growing population, land use changing demands are inevitable and protected areas should be defined as narrowly as possible but as large as necessary. In this sense, the most important approach for establishing ground water protection areas is to determine different criteria for different aquifers. Preparing vulnerability maps is the first step and a useful basis for groundwater management.

It allows the decision makers to make preliminary assessments such as ranking, thus identifying the most vulnerable areas within a karst system where contaminants can most easily reach the groundwater. An experienced hydrogeologist, however, should perform more detailed studies after the vulnerable areas are identified.

In the present study, a methodology for assessing vulnerability of the Günyüzü basin was developed using GIS and remote sensing techniques. Based on the results of this study, the most vulnerable areas were determined for groundwater protection and land use. For this aim, 11 criteria, namely vadose zone lithology, lineament, aquifer, groundwater depth, hydraulic conductivity, rainfall, slope, distance to wells and spring, land use, drainage density, and hydromorphology, were determined depending on region properties. The criteria were weighted according to the DRASTIC method developed by EPA (Aller *et al.* 1987).

At the end of the analyses, a suitability map was created using the 11 criteria layers in the GIS environment. The expanded view of the final vulnerability map revealed the recharge area of karstic aquifers took place in the very high and high vulnerability rating areas. The box located near the center of the map marks the recharge area for the Sivrihisar, Kayakent springs. A garbage dump is located in this area, as can be seen in the photograph in Figure 7. This is an example of the necessity for this type of approach for aquifer management.

Contamination from this dump has serious implications for the long-term water quality of the springs and illustrates the merit of the approach presented in this paper from a planning perspective.

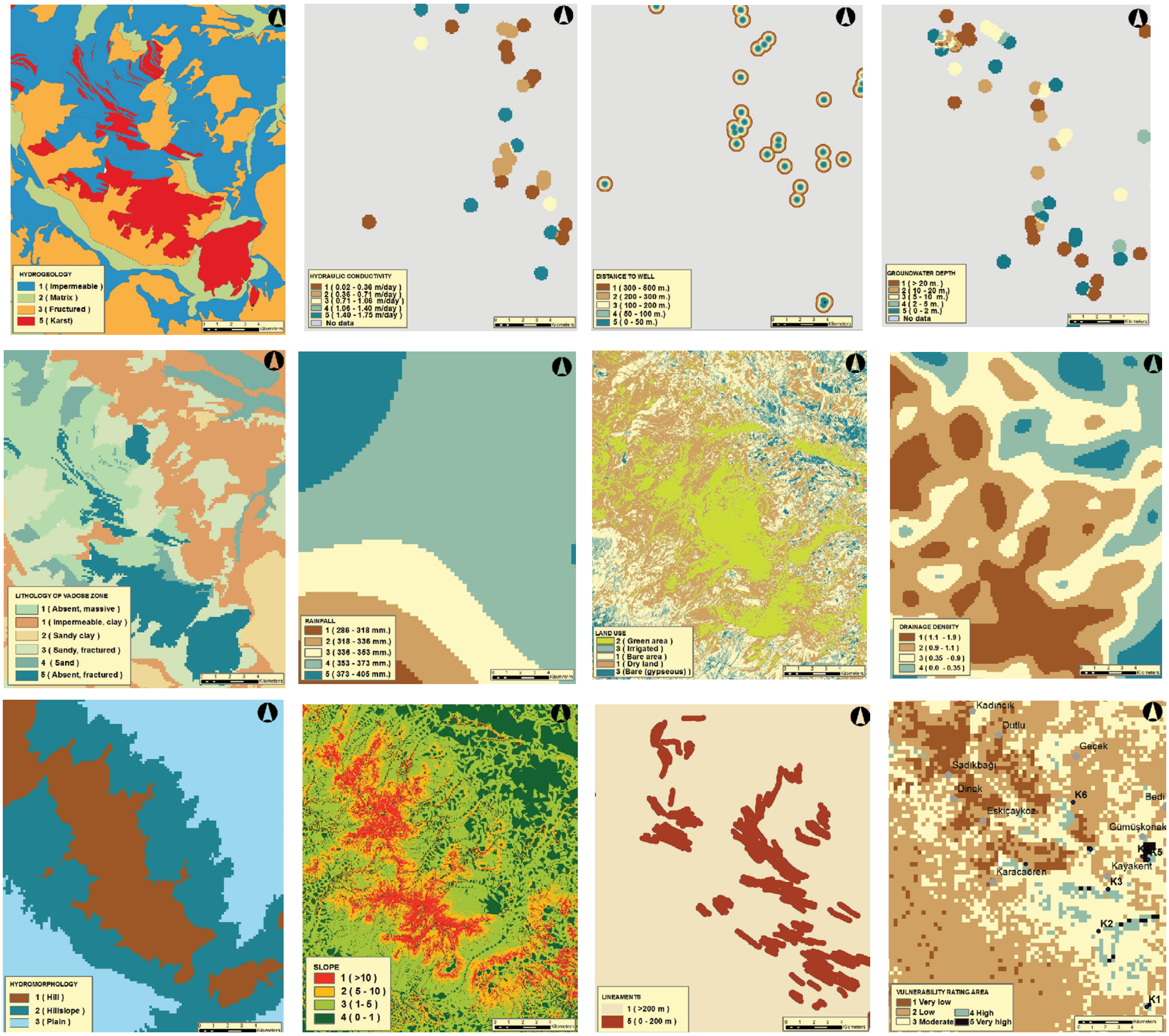

Figure 5. Illustration of weighting combination maps.

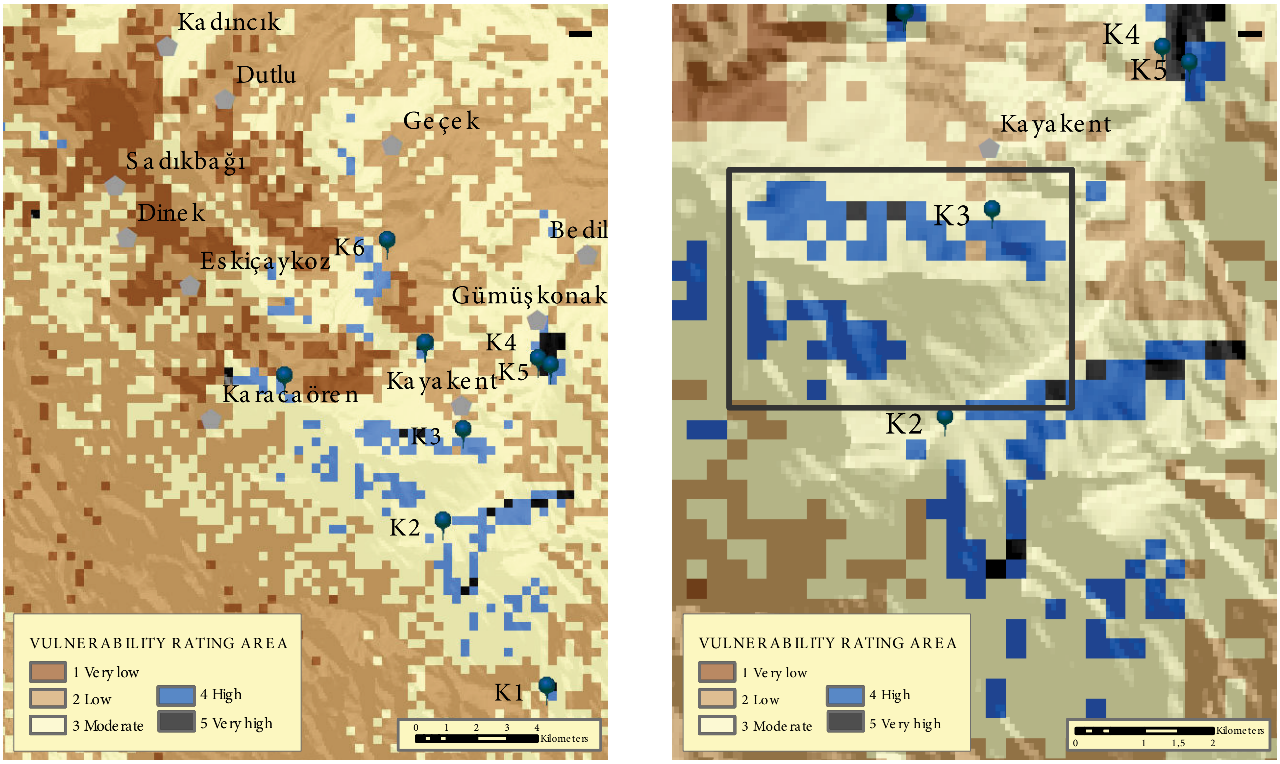

Figure 6. Final vulnerability map and enlarged view of final vulnerability map showing critical recharge region (box).

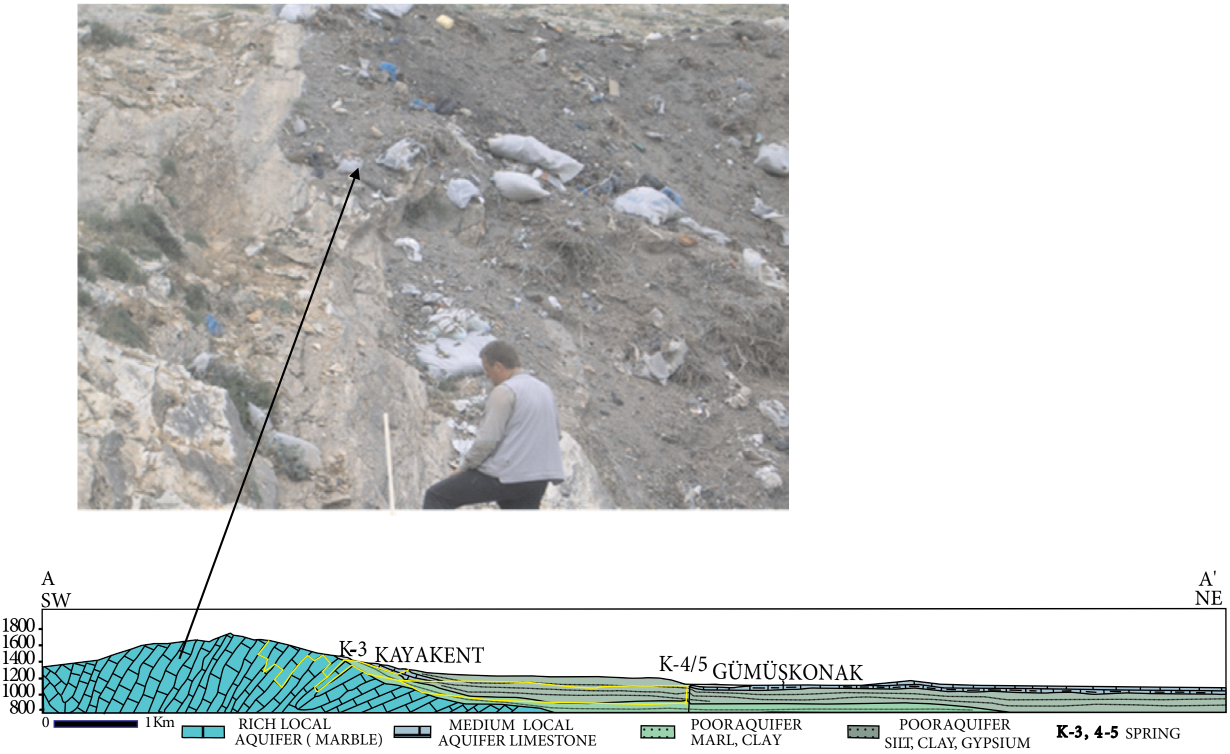

Figure 7. Cross-section from Figure 2 (A-A') showing the K3 spring and recharge area.

References

Alföldi, L. 1986. Groundwater protection in porous, fractured and karstic aquifer systems (General report)', *in Symposium on Groundwater Protection Areas* (19th Congress of IAH), Proceedings, Novinar Publ. House, Czechoslavakia, **19/2**, 89–103.

Aller, L., Bennett, T., Lehr, J.H., Petty, R.J. & Hackett, G. 1987. *DRASTIC: a standardized system for evaluating groundwater pollution potential using hydrogeologic settings*. US-EPA 600 2-87-035, Washington DC, USA.

Brosig, K., Geyer T., Subah, A. & Sauter, M. 2007. Travel time based approach for the assessment of vulnerability of karst groundwater: the transit time method. *Environmental Geology* **54** (5), 905–911.

Dams, J., Woldeamlak, S T. & Batelaan, O. 2007. Forecasting land-use change and its impact on the groundwater system of the Kleine Nete catchment, Belgium. *Hydrol. Earth Syst. Sci. Discuss*, **4,** 4265–4295.

Demiroglu, M., Örgün, Y. & Yaltırak, C. 2011. Hydrogeology and hydrogeochemistry of Gunyuzu semi-arid basin. *Environmental Earth Sciences*, **64/ 5**, 1433–1443.

Demiroglu, M. 2008. *Hydrogeology and Hydrochemistry of Eskişehir-Sivrihisar-Günyüzü Basin*. PhD Thesis, Institute of Science and Technology, İstanbul Technical University, İstanbul-Turkey [unpublished].

Doerfliger, N. & Zwahlen, F. 1995. Groundwater vulnerability mapping in karstic regions (EPIK), Practical Guide. *Swiss Agency for the Environment. Forests and Landscape (SAEFL).* Berne, 56.

Doerfliger, N., Jeannin, P.Y. & Zwahlen, F. 1999. Water vulnerability assessment in karst environments: a new method of defining protection areas using a multi-attribute approach and GIS tools (EPIK method). *Environmental Geology*, **39/2,** 165–176.

DOELG/EPA/GSI, 1999. Groundwater protection schemes. *Department of the Environment and Local Government, Environment Protection Agency and Geological Survey of Ireland.*

DVGW, 1995. Richtlinien für Trinkwasserschutzgebiete, I. Teil: Schutzgebiete für Grundwasser [Guidelines for drinking water protection zones, part I: protection zones for groundwater]. Deutscher Verein des Gas und Wasserfaches e.V., DVGW-Regelwerk, Arbeitsblatt W101/23.

Ekmekçi, M. & Günay, G. 1997. Role of public awareness in groundwater protection, *Environmental Geology.* **30**(1/2), 81–87.

Esri, 2011. What is GIS. Esri GIS Education Community. http://edcommunity.esri.com/aboutGIS/whatisGIS.cfm.

Goldscheider, N., Klute, M., Sturm, S. & Hotzl, H. 2000. The PI-method—a GIS based approach to mapping groundwater vulnerability with special consideration of karst aquifers. *Zeitschrift Angewandte Geologie*, Hannover, **46** (3), 157–166.

Goldscheider, N. 2005. Karst groundwater vulnerability mapping - application of a new method in the Swabian Alb, Germany. *Hydrogeology Journal.* **13**, 555–564.

GSCHV, 1998. Gewesserschutzverordnung vom 28. Oktober 1998 (GSchV, SR 814.201) [Swiss Water Protection Ordinance]. *Swiss Federal Law*, Bern.

Israil, M., Al-hadithi, M., Singhal, D.C., Kumar, B., Someshwar, R.M. & Verma, S.K. 2006. Groundwater resources evaluation in the Piedmont zone of Himalaya, India, using Isotope and GIS techniques. *Journal of Spatial Hydrology* **6/1,** 105–119.

IPCC. Climate Change 2001. The Scientific Basis. Contribution of Working Group I to the Third *Assessment Report of the Intergovernmental Panel on Climate Change*, edited by Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., Johnson, C.A., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881.

Kaçaroğlu, F. 1999. Review of groundwater pollution and protection in karst areas. *Water Air and Soil Pollution.* **113,** 337–356.

Struckmeier, W., Yoram, R. & Jones, J.A.A. 2005. Groundwater—reservoir for a thirsty planet? *Earth Sciences for Society Foundation*, Leiden, the Netherlands.

U.S. EPA, 1993. *Ground Water Resource Assessment*. EPA 813-R-93–003, USEPA Office of Ground Water and Drinking Water, Washington, DC.

T.E.F. 1992. *Turkish Environmental Laws*. Publication of the Turkish Environment Foundation (T.E.F.) Ankara -Turkey, p.1276, (in Turkish).

Van Stempvoort, D., Ewert, L. & Wassenaar, L. 1992. *Aquifer vulnerability index: a GIS-compatible method for groundwater vulnerability mapping.* – Canadian Water Resources Journal **18**, 25–37.

VGW. 1995. *Richtlinie W72. Schutz- und Schongebiete* (Guideline W72: protection zones). sterreichische Vereinigung frdas Gas- und Wasserfach. Wien. p. 45.

Vrba, J. & Zaporozec, A. 1994. *Guidebook on Mapping Groundwater Vulnerability*, IAH International Contributions to Hydrology, Hannover/FRG (Heise Publ.) **16**, 131.