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ORIGINAL ARTICLE

Celalettin Simsek
Cem Kincal
Orhan Gunduz

A solid waste disposal site selection procedure based on groundwater vulnerability mapping

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C. Simsek (✉)
Department of Drilling, Torbali Technical Vocational School of Higher Education, Dokuz Eylul University, 35860 Izmir, Turkey
E-mail: celalettin@deu.edu.tr
Tel.: +90-232-8531828
Fax: +90-232-8531606

C. Kincal
Department of Geological Engineering, Dokuz Eylul University, 35100 Izmir, Turkey
E-mail: cem.kincal@deu.edu.tr
Tel.: +90-232-3882919
Fax: +90-232-3887865

O. Gunduz
Department of Environmental Engineering, Dokuz Eylul University, 35160 Izmir, Turkey
E-mail: orhan.gunduz@deu.edu.tr
Tel.: +90-232-4127141
Fax: +90-232-4531143

Abstract In this study, a new, GIS-based solid waste site selection tool (DUPIT) is introduced to obtain a systematic and unbiased methodology during the evaluation phases of alternative solid waste disposal areas with regards to vulnerability to groundwater pollution. The proposed tool is an index technique based on the linear combination of five different hydrogeological parameters including *D*epth to groundwater table, *U*pper layer lithology, *P*ermeability of the unsaturated zone, *I*mpermeable layer thickness and *T*opographic slope. Five different categories are developed to classify each alternative based on the suitability of the site for a solid waste disposal area. As a result, each site is ranked according to the contamination risks for groundwater resources. The proposed technique is applied to the District of Torbali near Izmir, Turkey to determine the most appropriate solid waste disposal site location. The Torbali application is implemented by using a GIS database developed for the area. Based on the results of this application, the best alternative solid waste disposal site for Torbali is selected to be located in the northern portions of the city where the groundwater table is deep, the permeability is low and the topographic slope is mild.

Keywords Environmental hydrogeology · Site selection · GIS · Solid waste · Torbali (Turkey)

Introduction

In recent years, several studies have been conducted on local and regional level to find the most suitable location for solid waste disposal sites (Rao 1997; Dorhofer and Siebert 1998; Dorn and Tantiwanit 2001). During the selection process of a solid waste disposal site, several factors must be considered in detail. In general, the primary selection criterion is the cost of operation of the disposal site. The site must be located close to the city to minimize hauling costs. The environmental concerns typically follow the economical factors. Of the several environmental factors considered during the selection procedure, the most important ones are related to the susceptibility of regional groundwater to contamination. Factors such as the depth to groundwater table, the availability of impervious layers which could naturally minimize the risk of contamination, the type and conductivity of the underlying aquifer, the land use/cover patterns and the site topography are amongst the many that must be taken into account in the site selection procedure.

It is well known that the highly porous alluvial soils with sand and gravel as the main material are potentially very good aquifers with high conductivity and yield values. While such soils are suitable aquifers for groundwater resources development, they form one of the least favorable conditions for locating solid waste disposal sites due to high risks for contamination. Potential sites that lie on such material must be avoided at all costs in order to make environmentally sound decisions. Therefore, solid waste disposal sites must be selected in areas with low vulnerability to contamination including the ones where the groundwater levels are deep and the groundwater movement is limited. In cases where these guidelines are neglected, the groundwater resources become under the elevated risks of contamination as discussed by Schreck (1998), Ekpo et al. (2000) and Simsek (2002).

The analysis of the vulnerability of groundwater to pollution has been an important research area in the last decades. Several models including DRASTIC (Aller et al. 1987), GOD (Foster 1987, 1998), SINTACS (Civita 1994) and CALOD (Edet 2004) are developed to assess the susceptibility of aquifers to pollution. Although these methods have found wide application areas in evaluating the quality status of the groundwater resources, they are generally not used in the screening level site selection process for solid waste disposal areas. Recently, only a few researchers have started to use the vulnerability maps developed by using methods similar to DRASTIC in evaluating the suitability of alternative disposal sites throughout the world (Ibe et al. 2001; Lee 2003).

In Turkey, environmentally friendly disposal of solid wastes has been a problematic area particularly within the last couple of decades. Even today, many municipalities do not have engineered landfills and hence, illegally dump their solid wastes to the nearest available location ignoring all the associated risks. Due to the financial limitations and the lack of sufficient scientific research opportunities, the nearest available site typically becomes a river bed or an agricultural field. In the Aegean region where this study is conducted, most of the solid waste dump areas are located on highly permeable alluvial fields or beds of intermittent rivers. As a consequence of this practice, it has been observed that the groundwater resources are under the influence of significant pollution loads (Simsek 2002).

In accordance with the current setting discussed above, this study is intended to develop a screening level site selection tool (DUPIT index) that concentrates on environmental considerations. Particularly, it focuses on the quantification of the risks associated with groundwater contamination due to solid waste disposal sites. With the integration of a geographic information system (GIS), the proposed tool could hydrogeologically locate the most favorable location that would minimize the contamination risks. The developed tool is then applied to the Torbali Basin located in western Turkey to find the most appropriate site for solid waste disposal. A GIS database associated with the project area is constructed by collecting data from boreholes dug in the area as well as topographic, geologic and land use/cover maps of the region. This GIS-integrated database is then used to create input data layers of the developed tool including the depth to groundwater, upper layer lithology, permeability coefficient, impermeable layer thickness and topographic slope. Finally, a composite suitability map that classifies the region is obtained based on the proposed index technique to evaluate the possible alternative sites for the disposal facility.

Vulnerability mapping

The vulnerability of groundwater to contamination from surface pollution sources has been an important topic for the geo-hydrologist within the last couple of decades. Particularly, the advances in GISs have created the new area called the vulnerability mapping that is based on the idea of analyzing the sensitivity of groundwater to contamination with regards to a group of geo-hydrologic parameters. In this regard, the DRASTIC model (Aller et al. 1987) developed for the US Environmental Protection Agency is considered to be the initiation point of the subject. Following DRASTIC, other models such as GOD (Foster 1987), SINTACS (Civita 1994) and CALOD (Edet 2004) are also developed to provide user friendly tools for analyzing aquifer vulnerability to pollution. In DRASTIC, which has now become an industry-standard technique, several hydrogeological parameters are used to define the conditions of the underlying aquifer and extract the associated susceptibility to pollution. These parameters include the depth to water table, net recharge, aquifer media, soil media, topography, impact of vadose zone and hydraulic conductivity. The linear combination of the ratings and the weighing factors of these parameters provide the numerical value of the DRASTIC index, which is then used to evaluate the vulnerability of the aquifer based on six different categories. These categories classify the aquifer based on very low, low, moderate, high, very high and extremely high vulnerability to contamination. The other techniques mentioned above are based on the same idea and implement similar procedures with slight modifications. Therefore, it is possible to use all of these vulnerability mapping techniques or their modifications in pollution assessment.

The proposed methodology

Considering the wide applicability of DRASTIC type index techniques in aquifer vulnerability, a similar tool is proposed to assess the suitability of solid waste disposal sites based on the linear combination of five different hydrogeological parameters. The proposed *DUPIT* index is formed by the combination of: (1) *D*epth to groundwater table, (2) *U*pper layer lithology, (3) *P*ermeability of unsaturated zone, (4) *I*mpermeable layer thickness and (5) *T*opographic slope. The selection of these parameters is optimized such that any non-technical decision maker would be able to use the method without any difficulty.

The depth to groundwater table is defined to be the distance between the ground surface and the water table and is an important parameter in assessing the risk of groundwater contamination via surface pollutants. It is generally accepted that the time required for a surface contaminant to reach the groundwater gets higher as the distance to water table becomes larger. Although the travel time is also a function of other parameters including the hydraulic conductivity of the domain between the surface and the water table, this generalization usually holds true. In terms of disposal site selection, it is always preferable to have large depths to groundwater table.

The mostly desired lithologic units in solid waste site selection process consist of massive rocks that do not contain any cracks. Without the presence of discontinuities, these units normally do not contain groundwater. On the other hand, discontinuous rocks with cavities, cracks and fractures are considered to be the type of strata that contain and transmit groundwater. Therefore, these units must be carefully protected from surface contamination. In contrast to discontinuous rocks, consolidated sediments are generally considered to be impervious layers and are believed to serve very good candidates for solid waste disposal sites. Such formations have been the topic of several researches with respect to their imperviousness and their potential use as bottom barriers in solid waste disposal facilities (Dorhofer and Siebert 1998; Dorn and Tantiwanit 2001). Finally, the unconsolidated deposits are composed of sand, clay, gravel and silt. The impervious clays are one of the ideal materials for solid waste disposal sites when observed in continuous, thick layers. In contrast, the porous and previous materials such as sand and gravel contain and transmit significant amounts of groundwater similar to the rocks with fractures and cracks; and hence, must be avoided for solid waste disposal areas.

The permeability of the unsaturated zone is also an important parameter in solid waste disposal site selection as it has a direct influence on the contaminant transport between the ground surface and the water table. While the contaminants are rapidly transported to lower layers with the infiltrating precipitation in high permeability regions, they slowly migrate downwards in low permeability layers. In the case of disposal sites located on fractured rocks and high permeability sand and gravel zones, the highly contaminated leachate is observed to travel downwards rapidly with the infiltrating precipitation. It is also observed that the surface and subsurface domains strongly interact with each other in such high permeability regions (Simsek 2002).

The impervious geological barriers are another criteria used in solid waste site selection procedure. They provide extra environmental safety without additional costs. In general, geological units with permeability values less than 1×10^{-7} m/s are considered to be impervious (Terzaghi et al. 1996). It is, however, important to note that the impervious layer must have a minimum thickness of 5 m for it to be a geologically significant barrier unit (Dorn and Tantiwanit 2001). With this thickness and permeability values, these layers practically prevents the downward movement of surface pollutants and hinders the mixture of contaminated surface infiltration to groundwater. Therefore, the impervious layer thickness must be known in advance during the site selection procedure of a solid waste disposal facility.

Last but not the least, the solid waste disposal facilities must be constructed in low topography areas with fine slopes. High topography areas reduce the stability of the side slopes and increase the risk of landslides. Moreover, the leachate formation and movement is observed to be higher in high topography disposal facilities (Crawford and Smith 1985; Bagch 1994).

In the proposed technique, each one of the parameters discussed previously are given a weighing coefficient (Table 1) from 1 to 5 such that the most and the least important factors in solid waste disposal site selection are given the highest (5) and lowest (1) points. In solid waste disposal site selection, the depth to groundwater table is considered to be the most important factor. On the other hand, the topographic slope is the least important factor for the decision maker. Although it might be argued that these factors might show radical differences in different geographical settings, it is believed that the importance classification given in Table 1 is a generalization that could be used for preliminary site selection procedure at all hydrogeological conditions. For conditions that deviate from the generalization presented in this study, the decision maker could easily modify the procedure and use alternate weighing coefficient for the five parameters introduced in this work. In addition to the weighing coefficients, the technique assigns rating coefficients for each parameter as shown in Table 1. The proposed DUPIT index is then calculated as:

$$\text{DUPIT index} = D_r D_w + U_r U_w + P_r P_w + I_r I_w + T_r T_w \qquad (1)$$

where D_r and D_w are the rating factor and weighing coefficient for depth to groundwater, U_r and U_w are the rating factor and weighing coefficient for upper layer lithology, P_r and P_w are the rating factor and weighing

Table 1 Index parameters and their classification

Factor	Weight	Range	Rating	Suitability
Depth to groundwater table (m)	5	< 5.0	1	Very low
		5.0–15.0	2	Low
		15.0–30.0	3	Medium
		30.0–50.0	4	High
		> 50.0	5	Very high
Upper layer lithology	4	Fractured rocks	1	Very low
		Sand and gravel	2	Low
		Silty sand, clayey and silty gravel	3	Medium
		Silty and clayey sand	4	High
		Clay, schists and flysch, massive rocks	5	Very high
Permeability of unsaturated zone (m/s)	3	$> 1.0\times10^{-2}$	1	Very low
		1.0×10^{-2}–1.0×10^{-3}	2	Low
		1.0×10^{-3}–1.0×10^{-5}	3	Medium
		1.0×10^{-5}–1.0×10^{-7}	4	High
		$< 1.0\times10^{-7}$	5	Very high
Impermeable layer thickness (m)	2	< 3	1	Very low
		3–6	2	Low
		6–12	3	Medium
		12–24	4	High
		> 24	5	Very high
Topographic slope (°)	1	> 60	1	Very low
		40–60	2	Low
		20–40	3	Medium
		10–20	4	High
		< 10	5	Very high

Table 2 DUPIT index and site suitability

DUPIT index	Suitability
> 67	Very high
52–67	High
37–51	Medium
22–36	Low
< 22	Very low

coefficient for the unsaturated permeability, I_r and I_w are the rating factor and weighing coefficient assigned to the impermeable layer thickness and T_r and T_w are the rating factor and weighing coefficient assigned to topography slope factor. After computing the index, the suitability analysis is done based on the five different categories given in Table 2. The values given in the table are obtained by assigning different rating factors (i.e., 1, 2, 3, 4 and 5) to each parameter without changing its weighing factor, thus yielding five different index values (i.e., 15, 30, 45, 60 and 75). The medians of these values are used to set the upper and lower limits used in each category specified in Table 2.

The proposed technique is implemented via grid datasets and grid processing procedures of GIS. The point-based database is first converted to grid datasets for each parameter discussed above. During this conversion, the cell size of grid datasets depends on the resolution of the point data. In general, a 100 m×100 m grid is believed to be sufficient for screening level analysis with limited data points. The procedure, however, is flexible such that fine grids could also be used in the analysis provided that there is sufficient point-wise data to support this selection. It is also important to note that the datasets must be in projected coordinate systems for the proper processing of grids. During the conversion from point to grid datasets, an interpolation procedure is implemented. This interpolation phase is extremely important since the interpolated grid is only as good as its point input data. In this particular study, an inverse distance weighing interpolation method is used. Yet, a more important point than the interpolation technique used is the extent of the domain (i.e., the domain of interest). The domain of interest represents the area where the point database could be gridded with highest possible accuracy. Within the domain of interest, the conversion from point to grid dataset is efficient and dependable and hence, the output grid highly represents the spatial distribution of the actual field conditions. Once the grid datasets are ready within the domain of interest, they are transformed to index values (i.e., 1, 2, 3, 4 and 5) based on the criteria specified in Table 1. The transformation is performed by a computer program that uses the interpolated parameter grid as an input file. The output of the program is an index grid, which only contains index values from 1 to 5. Finally these index grids (i.e., one for each parameter of the DUPIT index) are combined according to Eq. 1 to obtain the total DUPIT index value. The DUPIT index grid map that is developed as a result of this analysis is later evaluated based on the suitability criteria given in Table 2.

Case study: Torbali solid waste disposal site

General characteristics

The district of Torbali is located about 50 km south of the city of Izmir in western Anatolia (Fig. 1). Recently, Torbali and its immediate vicinity has been a major attraction center for industrial development in Izmir Province. Currently, there are more than 150 medium-to-large scale industrial establishments within the boundaries of the district. In general, textile, tobacco, automotive, marble and paint industries are among the many sectors that are developed in the region. This development trend created a significant population growth primarily due to the immigration to the region from central and southeastern Anatolia. Consequently, the total population of Torbali and its immediate vicinity has exceeded 100,000 by the end of year 2002.

Hydrography

The 3-D topography of Torbali is presented in Fig. 1. As seen from the figure, the City of Torbali is located in the so-called Torbali plain, which is surrounded by high mountain ranges to the north and southwest of the city. Torbali and its vicinity are drained by Fetrek River and its tributaries covering a total of 600 km^2 surface area

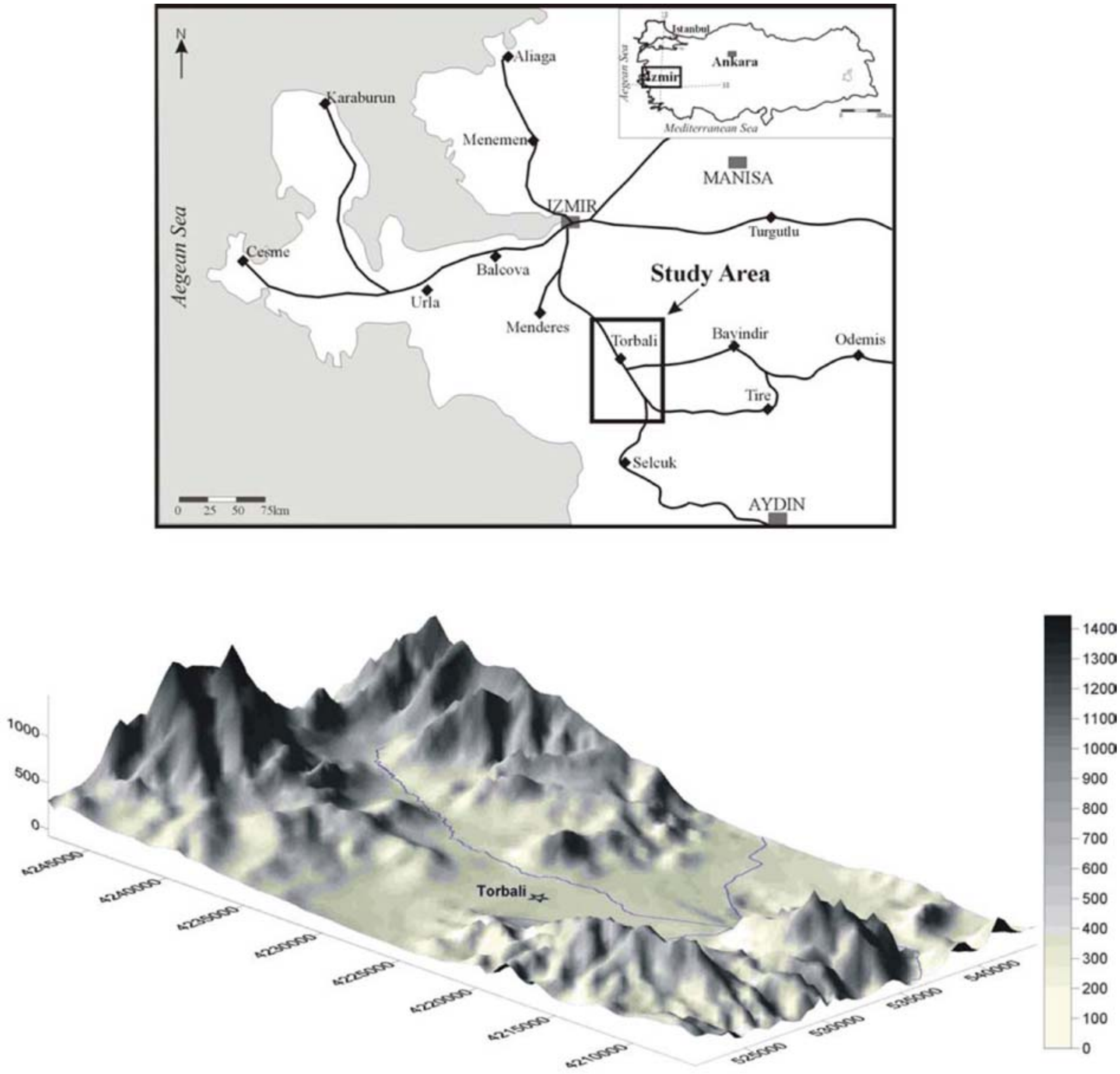


Fig. 1 Location map of the study area

(Fig. 2). The so-called Torbali Basin forms the northern portions of the Kucuk Menderes River Watershed that has an annual groundwater potential of 127.5×10^6 m^3 (Sakiyan and Yazicigil 2004). The Torbali Basin is located within the Kucuk Menderes River basin, which contains about 0.6% of the total annual water potential of Turkey (Simsek 2002). Torbali and its vicinity are situated in the Mediterranean climate zone. According to the 20 years of meteorological data, the region receives a total precipitation of 718 mm/year, most of which occurs during the months of December, January, February, March and April. The highest and lowest values of precipitation occur in December and July, with monthly totals of about 150 and 1.5 mm, respectively. The yearly average temperature and relative humidity in the region are measured to be 17°C and 58%, respectively (Simsek et al. 2005). The winds in the Torbali Basin are from south–southwest during December, January and May; and from northwest during other months of the year.

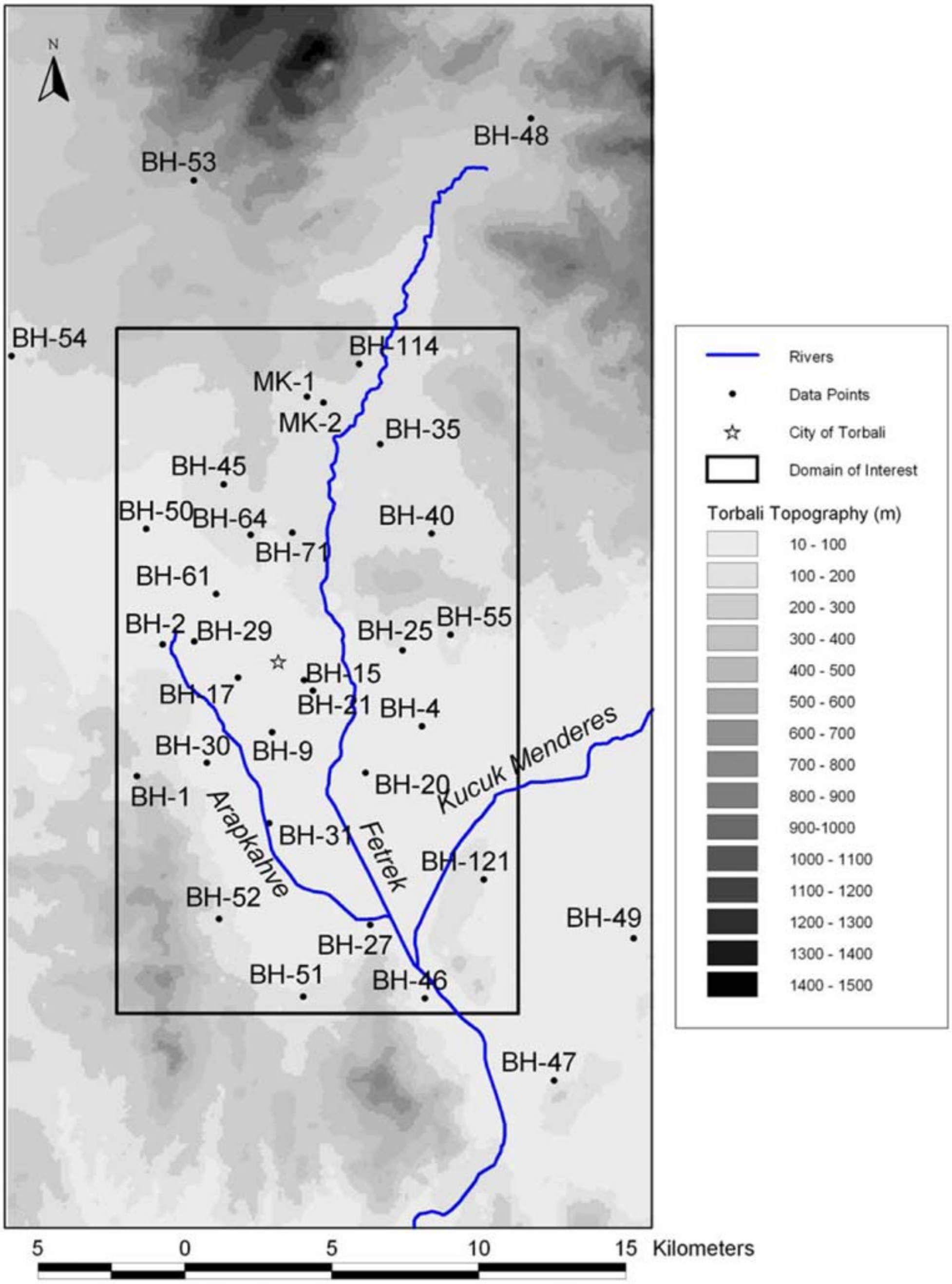


Fig. 2 Topographic map of the Torbali Basin and the domain of interest

As the main drainage unit of the Torbali Basin, Fetrek River has a highly variable flow pattern with extremely high flows during rainy seasons and almost no flow during summer. The average Fetrek River discharge is measured to be 35.5×10^6 m^3/year during 1960–1998 period. Furthermore, about 90% of this flow is observed during the rainy season (Simsek et al. 2005). The Torbali plain consists of an unconfined alluvial aquifer with extremely permeable gravel and sand texture, which is formed as a result of the long-term deposits of Fetrek River and its tributaries. Due to its high water supply capacity, numerous wells are developed in this aquifer to supply the urban, agricultural and industrial water demands of the region. In the 1980s, the State Hydraulic Works has constructed a series of infiltration ponds on Fetrek River to increase the amount of water seepage to the alluvial aquifer. According to Simsek (2002), the total infiltration from the river and its tributaries to the aquifer is estimated to be 28.5×10^6 m^3/year.

Solid waste production

Based on the estimations made by Torbali Municipality, around 100,000 tons of domestic and industrial solid waste is produced annually in Torbali and its immediate vicinity (Torbali Municipality 2002). Currently, there is no engineered solid waste landfill serving the area and the majority of this waste is dumped into 10–15 m deep trenches dug in a 80 ha agricultural field located along the banks of Fetrek River. This area is mainly composed of high permeability alluvial material and no engineered control structures (i.e., impervious top and bottom liners, leachate and gas collection systems) are constructed for the prevention of environmental contamination. The characteristics of the natural soil material of the area is such that it allows not only the rapid movement of leachate towards the surfacial aquifer but also the accelerated infiltration of precipitation from the surface to the waste core since the top of these trenches are also covered by the same high conductivity material.

Table 3 The database of the project area

Data no.	*X*	*Y*	Permeability of unsaturated zone (m/s)	Impermeable layer thickness (m)	Upper layer lithology	Depth to groundwater (m)
BH-1	526,251	4,221,350	1.7×10^{-2}	0.0	Marble	34
BH-2	527,125	4,225,850	2.70×10^{-3}	0.0	Gravel and marble	24
BH-4	535,950	4,223,053	4.80×10^{-4}	3.2	Silty and clayey sand	18
BH-9	530,852	4,222,856	5.40×10^{-4}	9.0	Clayey lenses and gravel	24
BH-15	531,931	4,224,635	7.10×10^{-4}	4.8	Clayey, silty sand and gravel	21
BH-17	529,689	4,224,715	2.90×10^{-5}	1.9	Clayey sand with gravel lenses	22
BH-20	534,025	4,221,475	2.50×10^{-5}	4.2	Silty and clayey sand	14
BH-21	532,235	4,224,274	3.90×10^{-4}	0.7	Silt lenses sand and gravel	12
BH-25	535,285	4,225,650	1.50×10^{-3}	0.0	Gravel, sand and limestone	26
BH-27	534,185	4,216,289	6.30×10^{-4}	6.8	Silty sand and clayey sand	13
BH-29	528,200	4,225,950	3.20×10^{-6}	5.0	Clayey and silty sand	18.7
BH-30	528,625	4,221,810	1.50×10^{-4}	3.4	Silty sand and clayey sand	20
BH-31	530,750	4,219,745	9.20×10^{-6}	8.2	Silty and sandy clay	28
BH-35	534,526	4,232,680	4.80×10^{-6}	12.6	Clay	42
BH-40	536,275	4,229,625	2.30×10^{-5}	6.4	Sandy and silty clay	31.6
BH-45	529,200	4,231,310	6.10×10^{-6}	7.3	Silty clay	26
BH-46	536,053	4,213,784	1.30×10^{-6}	12.8	Silty clay and schist	11.3
BH-47	540,438	4,210,982	2.30×10^{-6}	0.0	Marble	5.8
BH-48	539,658	4,243,786	5.30×10^{-6}	6.9	Flychs and schist	28
BH-49	543,150	4,215,830	6.30×10^{-6}	7.3	Schist	6
BH-50	526,574	4,229,786	4.40×10^{-6}	6.8	Silty sand and gravel lenses	22.4
BH-51	531,910	4,213,845	6.30×10^{-6}	9.5	Schist	10
BH-52	529,050	4,216,487	6.30×10^{-6}	5.0	Schist	13
BH-53	528,187	4,241,674	1.70×10^{-2}	0.0	Limestone	47
BH-54	521,987	4,235,685	6.20×10^{-3}	14.8	Clayey limestone	39
BH-55	536,925	4,226,180	6.30×10^{-6}	12.0	Schist	11
BH-61	528,950	4,227,564	2.40×10^{-6}	14.5	Sandy clay	28
BH-64	530,125	4,229,582	6.50×10^{-5}	2.5	Silty and clayey sand	21
BH-71	531,532	4,229,658	5.40×10^{-4}	8.5	Clayey sand and sandy silt	21
BH-114	533,817	4,235,410	8.00×10^{-7}	40.0	Clay	45
BH-121	538,057	4,217,832	7.20×10^{-4}	6.8	Clay and silt	7.5
MK-1	532,040	4,234,300	9.60×10^{-8}	48.0	Clay	47
MK-2	532,600	4,234,100	8.80×10^{-7}	54.0	Clay	47

By the year 2030, the population of Torbali region is expected to reach 250,000 and the estimated total solid waste production is projected to be around 250,000 tons/year (Torbali Municipality 2002). Moreover, it is also planned to select the next solid waste landfill site of the City of Izmir within the Torbali region. Regardless of the realization of this plan, planners must find a suitable location for the 250,000 tons/year solid waste originating from the region itself. Therefore, it is extremely important to find an appropriate location, which in addition to other technical criteria, would also minimize the contamination risks associated with groundwater resources.

Data preparation

The database used in this study is created by utilizing the data obtained from the 32 boreholes (Fig. 2) drilled by the Department of Drilling of the Torbali Technical Vocational School of Higher Education and several private drilling companies. The details pertaining to the database is presented in Table 3. The GIS integration of the database is performed on ArcView platform developed by Environmental Systems Research Institute, Inc. (ESRI 1999). The general project area is revised and reduced based on the locations of the boreholes given in Table 3 and a domain of interest is formed as shown in Fig. 2. This area is believed to be better represented by the 32 boreholes than the larger project area. Although the domain of interest does not contain five of the 32 boreholes (i.e., BH-47, BH-48, BH-49, BH-53 and BH-54), their parameter values are still used in the interpolation procedure discussed previously. Hence, the domain of interest could be considered as an area where the interpolation of the 32 borehole values is more accurate and the interpolation errors are minimized.

Depth to groundwater table

The depths to groundwater table in the study area are measured in April 2005 when the water levels are at its maximum and are presented in Fig. 3. These measurements are believed to represent the worst case conditions

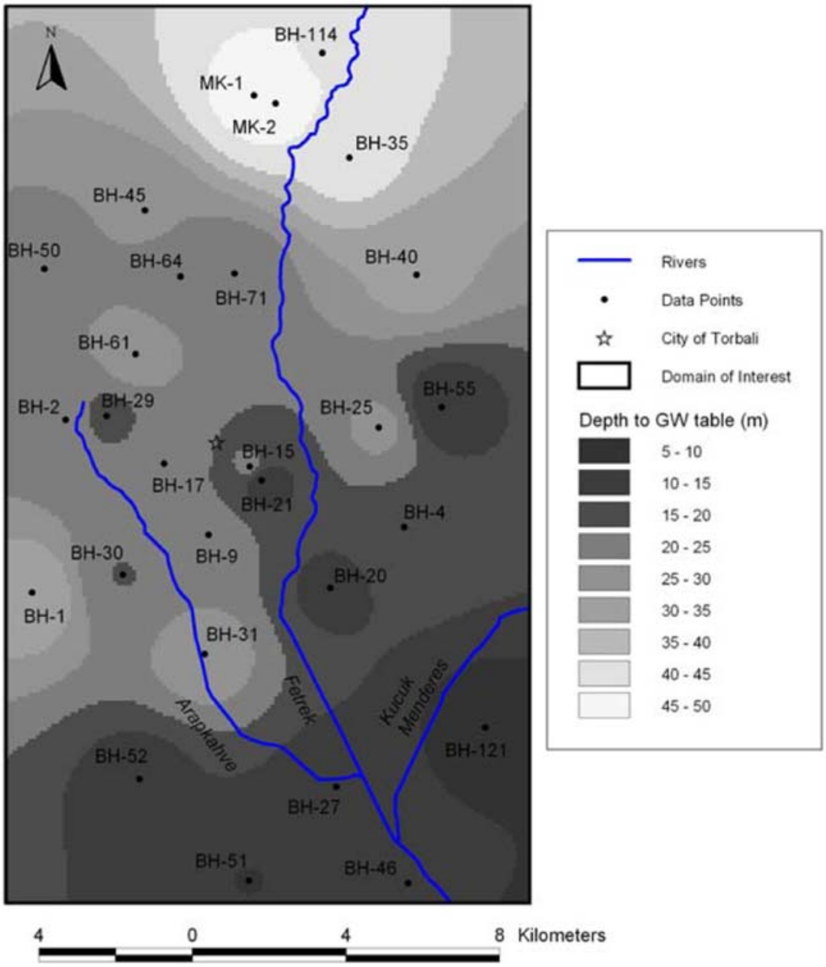


Fig. 3 Depth to groundwater table in the domain of interest

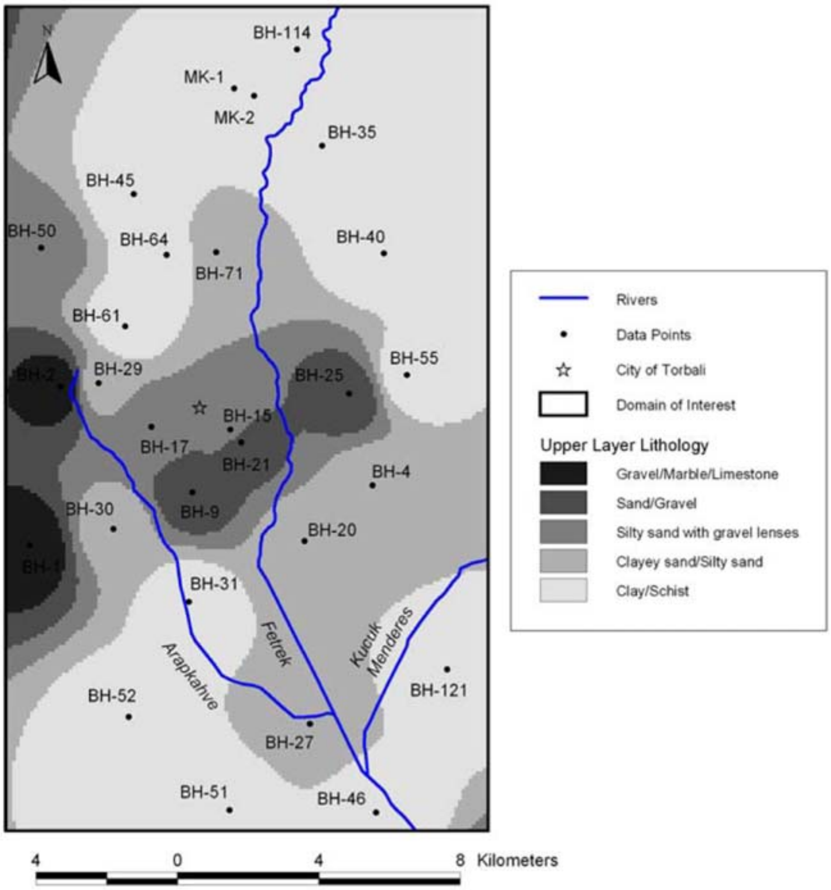


Fig. 4 Lithologic map of the domain of interest

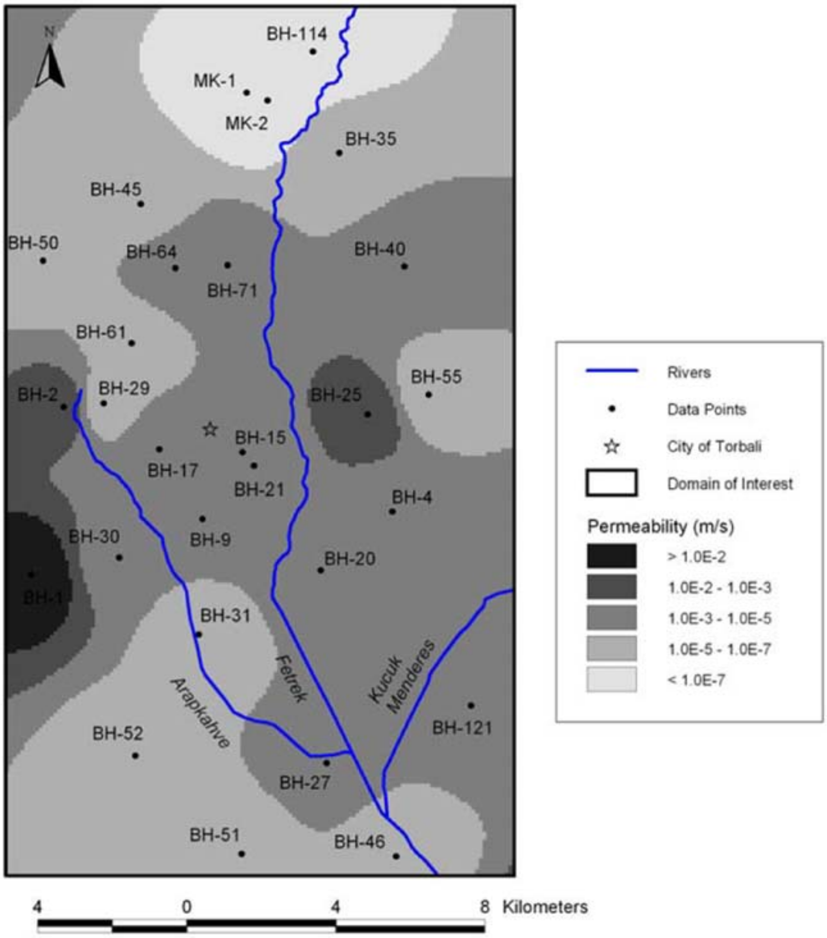
(i.e., water table closest to surface) that could be observed in the area with respect to this particular parameter. Based on the analysis of the water depths that range between 1 and 71 m, the groundwater flow direction in the project area is determined to be from north to south–southeast. The deepest points of the water table (i.e., > 50 m) are observed in the northern portions of the domain of interest as seen from Fig. 3. The shallowest parts (i.e., < 5 m), on the other hand, are found in the southern lowlands where the alluvial plain is relatively flat. It is important to mention that more than 90% of the groundwater pumped is supplied from the alluvial surfacial aquifer where the depth to water table is typically less than 30 m. Therefore, these portions of the project area are not favorable for solid waste disposal. When Fig. 3 is analyzed, it can be seen that the northern portions of the domain of interest represents the most suitable locations for locating the solid waste disposal facility with respect to depth to groundwater table parameter.

Upper layer lithology

When the lithology of the general project area is investigated, it is seen that Mesozoic-aged marbles and Neogene-aged limestones are the two main units of the Torbali Basin. These karstic rocks are highly discontinuous and provide significant amounts of groundwater. Hence, these units must be avoided during the site selection of a solid waste disposal facility. On the opposite extreme, the sedimentary layers of the Torbali plain are composed of reddish-green colored claystones in the northern portions and grayish-white colored clayey limestones in the eastern portions (Fig. 4). As the claystones are highly weathered, it is not possible to observe fracture zones that might indicate structural components. The sedimentary stratas of the region do not demonstrate the fingerprints of layers and hence are regarded as impervious rocks. Schists, on the other hand, are evaluated within the class of slightly fractured rocks as they have a heterogeneous schistosity and contain local marble bands.

When the lithology of the domain of interest is analyzed as shown in Fig. 4, it is seen that unconsolidated alluvial material as well as clays and schists dominate the area. The surfacial aquifer in Torbali plain is mainly composed of unconsolidated alluvial material including sands and gravels and is the main aquifer that supplies water for various purposes. The pervious sand and gravel zone reaches a total thickness of 25–40 m in the

Fig. 5 Permeability map of the domain of interest



eastern portions and 15–25 m in the northern portions of the Torbali plain. The finely graded silt and clays are generally observed in the southern and northwestern parts of the plain. While their thickness is highly variable, the highest thickness is observed in the northwestern parts of the plain. With respect to disposal site location, the most suitable areas are the northern and southern portions of the domain of interest as shown in Fig. 4. These areas are mainly composed of clays with low permeability and demonstrate suitable alternatives.

Permeability of unsaturated zone

The permeability map of the domain of interest is shown in Fig. 5. Based on the pressurized and non-pressurized permeability experiments conducted in the study area, the permeability of the karstic rocks is measured to be 1.5×10^{-3} m/s. On the other hand, the permeability of the alluvial layer composed of sand and gravel is measured to be in the 1.0×10^{-4}–8.8×10^{-4} m/s range as shown in the figure. Hence, both the karstic rocks and the alluvial sand and gravel layers are considered to be pervious units. On the opposite extreme, the Neogene-aged clays and Quaternary-aged alluvium clays, with respective permeability values of 1.7×10^{-7} and 9.6×10^{-8} m/s, are considered to be impervious bottom layers. In addition, the schists of the region are also considered to be impervious due to their low fractured structure and low permeability coefficients. They have a permeability value of around 10^{-6} m/s that makes them behave as impervious/semi-pervious rocks. When Fig. 5 is analyzed, it is seen that the most suitable alternative for a solid waste disposal site is located to the north of the city where the boreholes MK-1, MK-2 and BH-114 are situated.

Impermeable layer thickness

Based on the logs of the wells drilled within the study area, the general thickness of the impervious layer varies between 0.7 and 54 m as shown in Fig. 6. The thickness of the alluvial claystones ranges from 0.70 to 12.70 m where as that of Neogene-aged claystones varies between

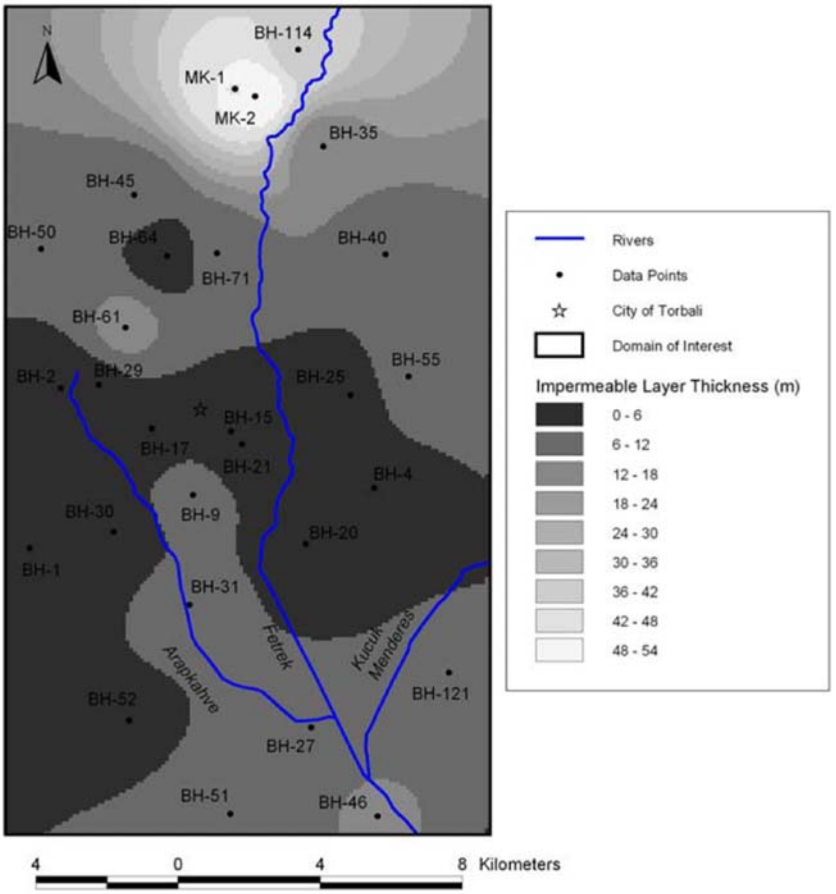


Fig. 6 Impervious barrier thickness map of the domain of interest

17.0 and 54.0 m. On the other hand, the Mesozoic-aged schists have an overall thickness of 4.0–15.0 m. The thickest impervious layer in the region is located to the north of the city of Torbali and is observed in Neogene-aged claystones as seen from Fig. 6. When the figure is analyzed, it is seen that the most suitable alternative for locating the solid waste disposal facility is located to north of the domain of interest where the boreholes MK-1 and MK-2 are situated. This area has a thick barrier that makes it suitable for solid waste disposal.

Topographic slope

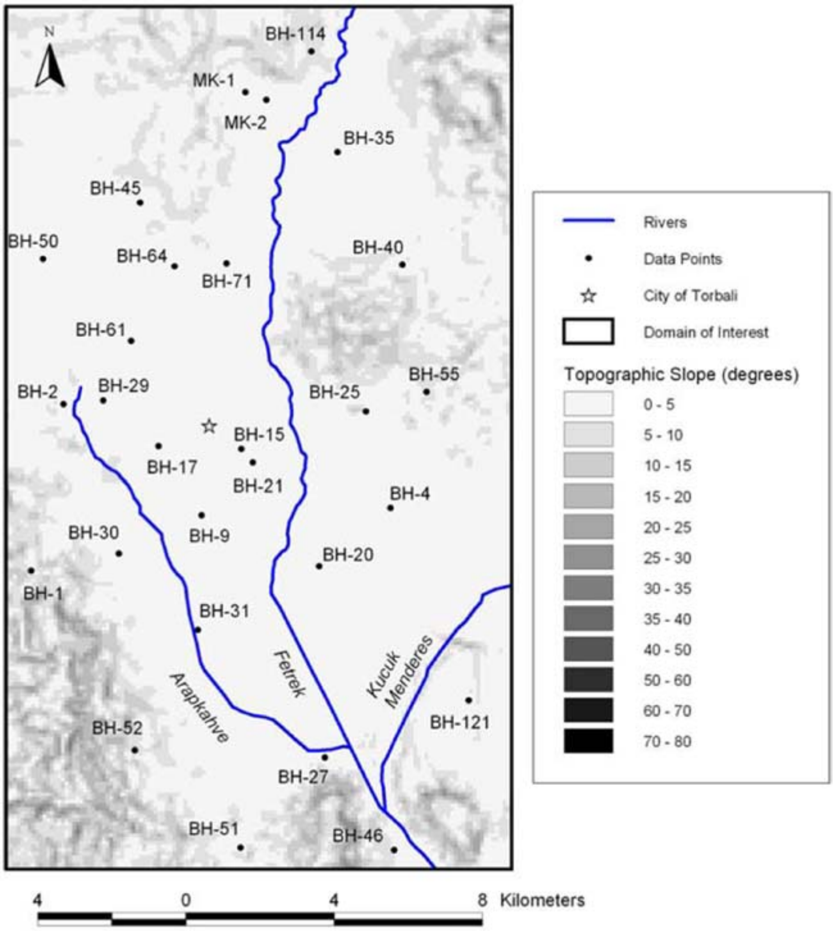
The topography of the project area is presented in Figs. 1 and 2. The topographic slopes derived from local topography are presented in Fig. 7. As seen from the figure, the northeastern, southwestern and eastern parts of the domain of interest have relatively higher slopes. The mildly sloping (i.e., $<10\%$) areas are generally observed in the alluvial plain and in the skirts of the northern highlands around BH-35. In general, the natural drainage network is less dense in areas with mild slopes than in areas with high slopes. The highly sloping areas with a dense natural drainage network must be avoided during site selection of the disposal facility.

Results and discussion

After the database is created for the project area, grid files are created for each parameter using inverse distance interpolation technique. Then, these grids are transformed into index grids using a computer program developed for this study. The linear combination of these index grids according to Eq. 1 gives the DUPIT suitability index map as shown in Fig. 8. This figure represents the spatial distribution of the DUPIT index within the domain of interest and is named as the suitability map for locating the solid waste disposal facility. Since the map shows the spatial distribution of the DUPIT index, it is now very easy for the decision maker to locate the most suitable site for the disposal facility with regards to susceptibility to groundwater pollution.

The suitability map obtained from the computed index value is evaluated according to five categories given in Table 2. When the computed index value is bigger than 67, the corresponding area is considered to overlie an impervious layer and have a deep groundwater table. Such sites also contain thick impervious barriers and are situated on mildly sloping topography. With these specifications, these sites represent ideal locations for

Fig. 7 Topographic slope map of the domain of interest



solid waste disposal facilities. When the suitability map presented in Fig. 8 is analyzed, it is seen that the most suitable sites are located to the north of the domain of interest with Neogene-aged impervious clays as the base unit and deep groundwater table with very limited or no groundwater production. Totally weathered brownish-green impervious claystones are cut in the two boreholes (i.e., MK-1 and MK-2) drilled in this region. This formation presents extremely suitable locations for disposal sites. Moreover, this region is not densely vegetated that also increases the suitability for a disposal site.

When the computed index value is between 52 and 67, the corresponding area demonstrates high suitability for solid waste disposal sites. These areas generally obtain high scores from the most important parameters including depth to groundwater and upper layer lithology. When the suitability map presented in Fig. 8 is analyzed, it is seen that these areas are located to the north and south of the domain of interest. In general, the northern portion displays better alternative sites, particularly in the region located close to the most suitable zone discussed previously. The lithology of these areas consists of Neogene-aged clays and Mesozoic-aged schists and the groundwater table is observed at moderate depths. Moreover, the topography of these areas demonstrate moderate to mild slopes making them suitable for disposal site location.

The areas with a DUPIT index value of 37–51 are considered to be moderately suitable for a solid waste disposal site. In the study area, these areas are generally located in the mid-sections of the domain of interest. This region is dominated by alluvial material, Mesozoic-aged marbles and Neogene-aged limestones. The northern parts of this region demonstrate a suitable alternative for the disposal site since it has relatively low permeability and depths to groundwater table values and a mildly sloping topography. The southern parts of the region, however, has a steeper topography compared to north, which increases the investment and the operational costs of the disposal facility and smaller depths to groundwater table. Moreover, these areas are mostly covered by residential areas and agricultural fields that further reduce their suitability. It is also important to note that this region is mostly located on alluvial material from which groundwater extraction is performed. Nevertheless, some portions of the southern

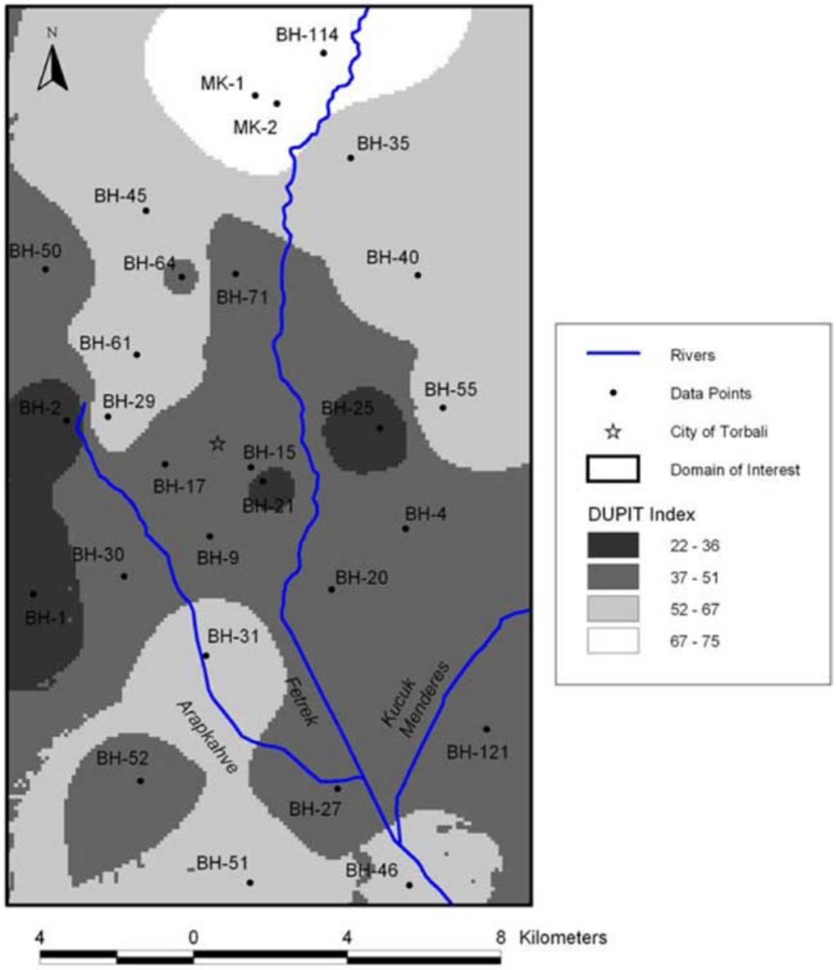


Fig. 8 DUPIT index suitability map of the domain of interest

region could still be used as a disposal site alternative if certain precautions (i.e., improving the stability of the slopes and using additional bottom liners) are implemented.

When the computed index value is between 22 and 36, the corresponding area demonstrates low suitability for solid waste disposal sites. These areas generally have low scores from the most important parameters including depth to groundwater and upper layer lithology. Such sites are generally considered to be not suitable for solid waste disposal areas unless no better alternative is available in the vicinity. Under extreme conditions, these sites could be used by taking all the necessary precautions to avoid groundwater contamination. In the study area, these areas are generally located in the central and eastern parts of the domain of interest. The lithology of these areas is mostly alluvial gravel and sand that are potential aquifers for groundwater production. Hence, these sites must carefully be avoided.

Finally, the areas with a DUPIT index value of less than 22 are considered to be the least suitable alternatives for a solid waste disposal site. As a rule of thumb, such areas should not be utilized for solid waste disposal since they represent areas which overlie major aquifers with significant groundwater production. They are regional groundwater resources that should be protected at all costs, particularly when surface water resources are scarce. These areas are mainly composed of karstic formations with highly fractured structures or gravel and sand dominated alluvial layers. Within the scope of this study, there are no such areas within the domain of interest that must be avoided when the site selection decision is made.

Conclusions and recommendations

In this study, a new GIS-integrated site selection procedure is proposed to find the most suitable solid waste disposal site location taking into account the vulnerability of groundwater to pollution. The proposed procedure is mainly an index method that utilizes five hydrogeological parameters: (1) depth to groundwater table, (2) upper layer lithology, (3) permeability of unsaturated zone, (4) impermeable layer thickness and (5) topographic slope. A linear combination of these parameters forms the so-called DUPIT index, which is then evaluated with respect to five classes. These classes rank alternative sites according to their suitability as a disposal area. The integration of GIS simplifies the entire analysis procedure and introduces a spatially distributed assessment of the available alternatives. The developed technique is then applied to find the solid waste disposal site for the Torbali Basin located in western Anatolia in Turkey. Based on this analysis, the most suitable site is found to be located in the northern portions of the City of Torbali, where the underlying material is composed of weathered claystones that are generally impervious and does not contain significant groundwater potential. It is, however, important to mention that the proposed method is developed as a screening level tool. The selected site must always be analyzed in detail with respect to other factors that are crucial for solid waste disposal site selection. Hence, a detailed feasibility study should be done on the selected alternative in order to verify that the site is entirely appropriate for solid waste disposal and minimizes all the associated contamination risks and environmental pollution.

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