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ORIGINAL PAPER

Selecting suitable landfill site with multi-criteria evaluation and GIS: a case of Savar upazila in Bangladesh

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Abstract

Sustainable management of solid waste has become a major concern for municipal authorities in rapidly growing cities of many developing countries. Waste management through landfilling is even more challenging, as optimized siting is essential to minimize adverse consequences like damage to the environment and public health. In this study, geospatial techniques were applied to landfill site selection. Savar upazila, a rapidly urbanizing subdistrict of Dhaka, Bangladesh, was taken as a case study. Nine geospatial parameters were used for identification of preferable landfill areas and three for area restrictions. The parameters were integrated in a geographic information system (GIS) environment, using an analytical hierarchy process and weighted linear combination, to generate a comprehensive suitability map. The map revealed 14% (39 km^2) of the entire area as highly suitable for landfill, 16% (45 km^2) as moderately suitable, 11% (30 km^2) as less suitable and 59% (166 km^2) as unsuitable. Twenty-one highly suitable locations were identified, with twelve locations finally recommended as ideal. The present geospatial approach is an advancement over the conventional techniques of landfill site selection, which often result in superficial decisions and mislead urban planners.

Keywords Landfill site · Geospatial techniques · AHP · Savar upazila · Bangladesh

Introduction

Although urban areas constitute only 3–5% of the total land surface of the Earth (Schneider et al. 2009), they are currently home to more than half of the world's population of around 7.7 billion people. Urban populations, particularly in developing countries, are projected to increase in the coming years (Heilig 2012). Since many cities in developing countries lack basic services, a further rise in urban populations could lead to severe environmental degradation (Sumathi et al. 2008) without effective planning and management of urban areas (Corner et al. 2014). One of the critical issues in the urban planning process is the efficient management of municipal solid waste, a significant source of soil, water and air contamination (Chang et al. 2008; Şener et al. 2010).

The increase in the urban population in Bangladesh has been phenomenal, particularly after independence in 1971. In 1951, 1.8 million people were living in urban areas, increasing to 13.5 million in 1981, 22.5 million in 1991, 31 million in 2001 and 33.5 million in 2011 (BBS 2011). Dhaka, the capital of Bangladesh, currently has a population of more than 16 million, and the population density is estimated to be around 10,500 persons/km^2 (Kamruzzaman 2019). This city has become the prime destination for those who want to escape from rural poverty and are in search of better livelihood options. Demand for housing is therefore high and rapidly increasing in the outskirts of the city. With this overwhelming population

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growth, these areas often fail to provide adequate services to the residents, utilizing only the existing infrastructure (Rasheed 2008). For instance, the exponential rise in municipal solid waste and how to manage it is one of the prevailing concerns; ignoring this problem may cause widespread environmental degradation (Bhuiyan 2010; Sujauddin et al. 2008).

Existing solid-waste disposal practices have already resulted in serious environmental contamination in and beyond the Dhaka city (Matter et al. 2015); proper management through the selection of additional appropriate landfill sites is required. Although the government has introduced tax incentives for all waste recycling and treatment plants for up to 10 years (Sinha 2012), the waste management system still appears to suffer from poor governance, lack of resources and technological constraints (Bhuiyan 2010). Waste is also being treated as a ‘burden’ rather than as an opportunity to generate resources such as biogas and nutrients for agriculture (Matter et al. 2015; Sufian and Bala 2007). Open dumping has become a popular method in the low-lying areas of many sub-urban cities because it is cheap and requires minimal planning. However, the scarcity of suitable sites for landfill in terms of environmental safety is a concern for waste management agencies (Akhter et al. 2016). In recognition of this fact, innovative approaches to the management of urban solid waste, particularly the use of geospatial technologies in the selection of landfill sites, have received renewed interest (Gorsevski et al. 2012). GIS has been promoted as an ideal tool for advanced site-selection studies by international researchers because of its provision to store and manage a large volume of data (spatial and non-spatial) from multiple sources and analyze data according to user-defined conditions (Malczewski 2006). It reduces the error, the time required and bias when combining different datasets (Pandey et al. 2012). Positional accuracy is also thought to be higher than the traditional field-based approaches for site selection (Lillesand et al. 2014).

Since the pioneering work of McHarg and Mumford (1969), GIS has become an essential tool for identifying ideal sites for a particular purpose (Malczewski 2004). Geospatial techniques have been utilized for a wide range of applications, such as habitat suitability (Store and Jokimäki 2003), urban development suitability (Corner et al. 2014; Youssef et al. 2011), optimum site selection (Al-Hanbali et al. 2011; Zucca et al. 2008) and route selection (Jankowski and Richard 1994). These studies have demonstrated that, by means of systematically integrating diverse biophysical and socioeconomic data, GIS has the potential to identify the most suitable sites. These spatial attributes need to be assessed through multi-criteria evaluation (MCE), a technique that allows its user to identify appropriate locations for a specific purpose based on multiple features that characterize the area of study. Among the MCE techniques, the analytical hierarchy process (AHP), since its first appearance in 1977, has been used widely in a range of applications, being a robust and flexible technique for supporting priority setting and improved decision-making, and involving both quantitative and qualitative aspects (Saaty 1980).

Of the available approaches to landfill site selection, AHP has been the most popular and is used in many parts of the world. For instance, screening of landfill sites for solid-waste management through the use of fuzzy set theory in a GIS environment was conducted in Thailand by Charnpratheep et al. (1997). Kamdar et al. (2019) combined GIS with AHP to identify municipal solid-waste landfill sites in the same country. A number of studies also used AHP for site selection by integrating geospatial data in Turkey (Bilgilioğlu and Bilgilioğlu 2017; Guler and Yomralioglu 2017; Tercan et al. 2020). Gorsevski et al. (2012) utilized MCE with an ordered weighted average (OWA) technique to identify suitable landfill site in Macedonia. Tayyebi et al. (2010) employed Dempster-Shafer theory integrated with MCE in landfill site selection in Iran. GIS with MCE has also been used elsewhere across the world: in India (Sumathi et al. 2008); Greece (Vasiljević et al. 2012); Jordan (Al-Jarrah and Abu-Qdais 2006); Mexico (Delgado et al. 2008); Tunisia (Aydi et al. 2013); Ethiopia (Sisay et al. 2020); Turkey (Yildirim et al. 2018); Iran (Karimi et al. 2019; Barzehkar et al. 2019); Pakistan (Asif et al. 2020) and Saudi Arabia (Osra and Kajjumba 2020). Data used in these studies were interdisciplinary in nature, representing environmental factors and socioeconomic status; GIS is indispensable as it has the capacity to store diverse datasets, visualizations and analyses at the same scale (Lukasheh et al. 2001). GIS combined with MCE is more useful in identifying a site efficiently (Sumathi et al. 2008), while considering all the criteria that help to reduce environmental and public health hazards, than any other method (Uyan 2014).

A considerable number of studies have been carried out on solid-waste management in the Dhaka district from various perspectives (Afroz et al. 2009; Afroz et al. 2011; Aissi et al. 2012; Akhter et al. 2016; Alam 2011; Alamgir and Ahsan 2007; Bari et al. 2010; Bhuiyan 2010; Hasan et al. 2009; Islam et al. 2004; Matter et al. 2015; Sufian and Bala 2007; Yedla 2012; Yousuf and Rahman 2007). These studies generally focused on the estimation of total waste over time, factors affecting household solid-waste generation, the impact of policy on solid-waste recycling and separation of solid waste at the household level. Unfortunately, little has been done to exploit geospatial techniques to identify suitable solid-waste disposal sites. For example, Akhter et al. (2016) used spatial analysis to investigate suitable composting sites for the promotion of urban agriculture. Hasan et al. (2009) used weighted linear combination (WLC) plus AHP in a GIS interface to identify potential solid-waste sites in Dhaka but a number of crucial parameters such as human settlement, land use, land price and depth of groundwater table were not considered.

From an extensive literature survey, it is evident that the current landfill sites in Bangladesh neither conform to environmental regulations nor consider the storage capacity for future waste. However, in selecting suitable sites for landfill in urban areas, safety measures concerning health and environment should be prioritized (Vlahov et al. 2007). Use of spatial technologies for waste disposal site selection in Dhaka could therefore be a valuable option. With this motivation, the current study aimed towards selecting suitable landfill sites using GIS techniques, taking a considerable number of relevant parameters into account. These techniques are novel in that areas where a landfill site could be lethal in terms of environmental integrity and public health were first identified; this information was then spatially combined with the preferable areas for selecting suitable sites for landfill. Moreover, rather than providing an apparent decision, this study thrives on ultraprecision, therefore scrutinized the essential preconditions of the identified locations to find out the sites where the plan could be certainly actualized.

Description of the study area

Of all the upazilas[1] (sub-districts) of the Dhaka district, Savar upazila has received the most attention due to its close proximity to the central business district (CBD) of Dhaka. This upazila consists of 13 administrative units (unions), is located about 30 km from the CBD and has an area of 280 km^2 lying between 90° 11′ E and 90° 22′ E longitudes and 23° 44′ N and 24° 02′ N latitudes. To the north, it is bounded by the Kaliakair and Gazipur Sadar upazilas, to the south by the Keraniganj upazila and to the east by Dhaka (north) city corporation (Fig. 1). Elevation of the area ranges from 3 to 25 m. Physiographically, around 47% of the total landmass is comprised of Madhupur tracts of the Pleistocene age; the rest is a recent floodplain of the Holocene period and a few highlands (Hasan et al. 2019). The floodplains are drained by perennial and ephemeral waterbodies, and the highlands are dissected by a number of shallow and deep gullies. The Bangshi-Dhaleshwari river system is located to the west of the study area, and the Turag river to the east. The study area enjoys a sub-tropical climate, with annual average rainfall about 2000 mm (Hasan et al. 2019).

Savar has experienced substantial urbanization and development activities over recent times, primarily driven by an increase in population and the establishment of major industries. According to the most recent population census (BBS 2011), the total population of this area was estimated to be 1,385,910, with a density of 4948/km^2; in 2001, the population was 587,041 (density 2095/km^2) and 378,034 in 1991 (density 1349/km^2), an exponential growth in population in the last two decades.

According to the upazila information center, an average of about 200 g of solid waste per capita is generated daily in Savar upazila. Masud (2013) found that only 23% of the population of Savar were provided with waste management services. Because of poor services and rudimentary systems of waste collection, the bulk of the waste is either disposed in low-lying lands or left uncollected, causing severe damage to the environment (Jahan et al. 2016; Khanam et al. 2011). Following the establishment of an export processing zone (EPZ) in this region, the growth in industry and consequently in the urban population has been rapid; a significant increase in waste volume is therefore likely in the coming decade. Therefore, the municipal authority needs to take necessary measures to identify suitable locations for future waste disposal.

Materials and methods

Method overview

Selection of the twelve parameters for identifying suitable landfill sites in this study was based on the literature (Al-Jarrah and Abu-Qdais 2006; Aydi et al. 2013; Bagdanavičiūtė and Valiūnas 2013; Donevska et al. 2012; Drobne and Lisec 2009; Ekmekçioğlu et al. 2010; Eskandari et al. 2012; Kumar and Hassan 2013; Moeinaddini et al. 2010; Nazari et al. 2012; Şener et al. 2011; Şener et al. 2010; Shahabi et al. 2014; Vasiljević et al. 2012) and the availability of relevant geospatial databases; parameters that represented terrain characteristics were chosen. Table 1 gives a list of the parameters used in this study.

An overview of the working procedure is given in Fig. 2. The selection of landfill sites using geospatial analysis involved the following steps: (1) create a preference raster by combining nine parameters, land use/land cover (LULC), depth to groundwater table (DGT), clay thickness, terrain slope, land price, population density, geomorphology, aspect and elevation, to classify locations in the study area somewhere in the range high to low in terms of suitability for landfill; (2) create a restriction raster by taking roads, settlements and water bodies into account to identify areas where situating a landfill site might be lethal in terms of the environment and public health; (3) integrate the preference raster and the restriction raster to identify high, moderate and low suitability, as well as non-suitability, for landfilling across the study area and (4) recommend the most suitable locations for future landfills. An ArcGIS desktop package (version 10.1) was used for data processing and analyses in this study. The model-builder tool in the ArcGIS software was used for

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[1] The administrative boundaries of Bangladesh are categorized into five major units. In descending order of size, the units are (1) division; (2) district; (3) upazila; (4) union and (5) mouza/village.

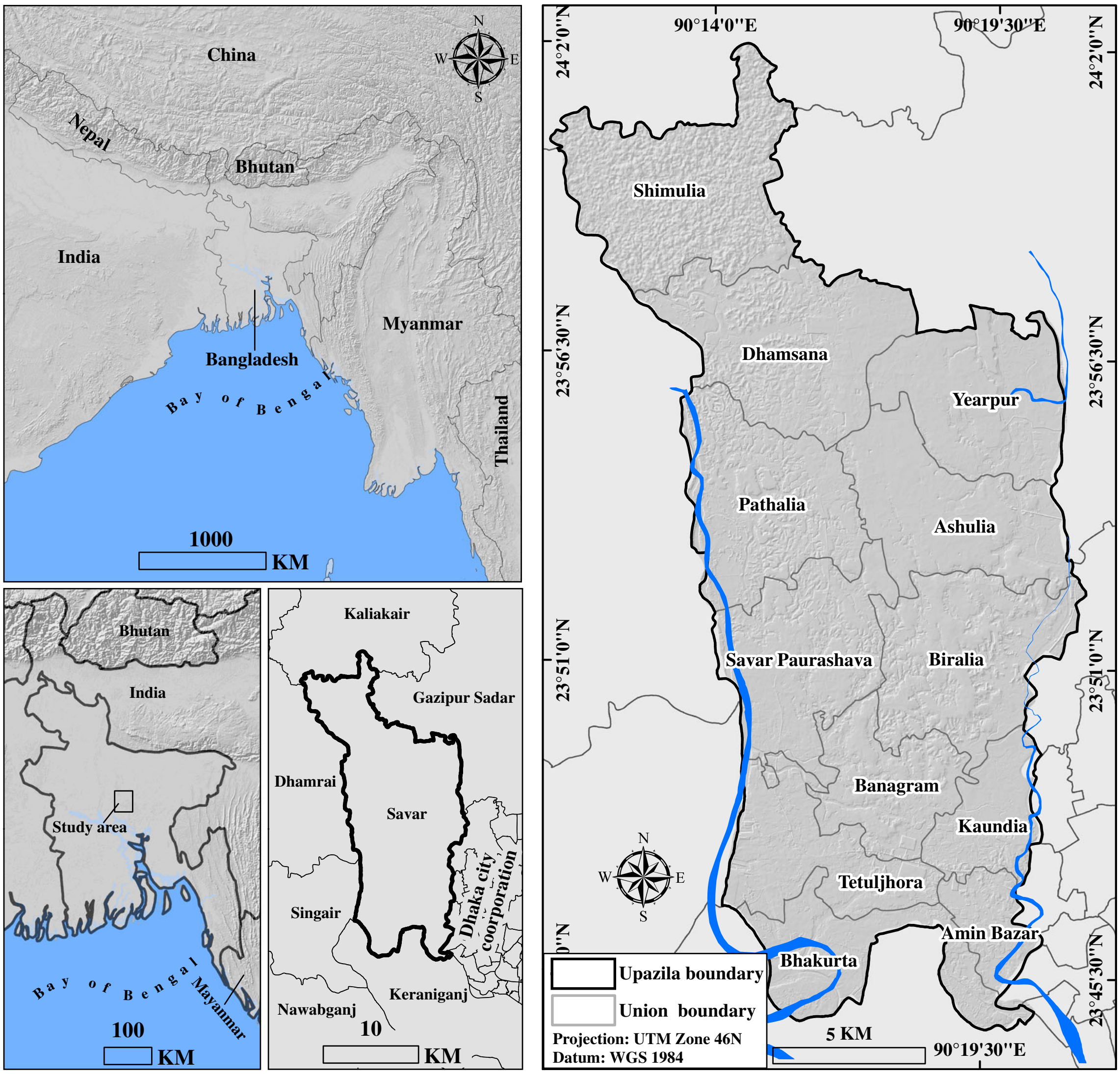


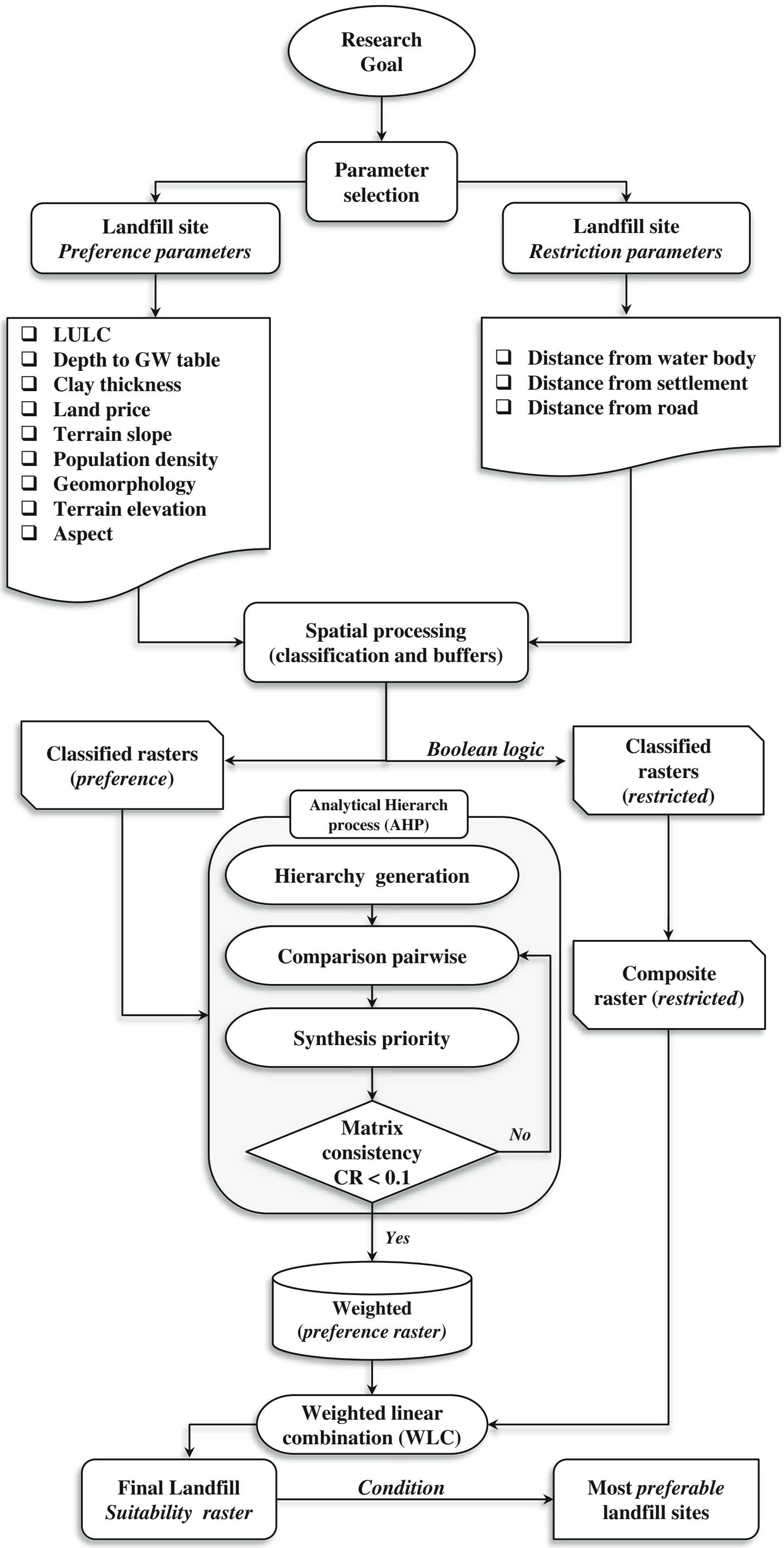
Fig. 1 Study area

Table 1 Sources of data used in this study

Function	Data utilized	Source
Site suitability analysis	(1) Land use/land cover	Visual interpretation (Google Earth)
	(2) Depth of water table	Water level data from BWDB*
	(3) Thickness of clay	Published borelog data from GSB** and BWDB
	(4) Land price	Local land survey office
	(5) Terrain slope	SRTM*** DEM of 30 meter
	(6) Population density	Bangladesh Bureau of Statistics (BBS)
	(7) Geomorphology	Visual interpretation (Landsat 8)
	(8) Apsect (wind direction)	SRTM DEM of 30 meter
	(9) Elevation	SRTM DEM of 30 meter
Restriction analysis	(1) Distance from road	LGED road map
	(2) Distance from water body	Visual interpretation (Google Earth)
	(3) Distance from settlement	Visual interpretation (Google Earth)

* Bangladesh water development board; ** Geological Survey of Bangladesh; *** Shuttle Radar Topography Mission

Fig. 2 A generalized flowchart constitutes the study's methodological approach



the preference and restriction raster creation (Fig. S1 and Fig. S2).

Data preparation

Data preparation was carried out in the GIS environment, with all the data resampled to a resolution of 30 × 30 m to maintain spatial consistency. The Universal Transverse Mercator projection with Zone 46N was used as the spatial referencing system for all data. The data were classified into different subclasses. Except the LULC, geomorphology and aspect, all were classified based on inherent data distributions of the respective parameters. For example, we used an equal-interval classification technique with five classes for the parameters population density, land price and elevation that showed near-normal distributions. For the parameters, DGT, clay thickness and terrain slope involving data that were skewed towards either end, a natural-break classification was applied, and divided into four distinct classes. This was done to attain the best possible accuracy in the classification and to achieve the maximum contrast between the individual classes. A brief account of the procedures for data preparation is given in the following section.

A detail LULC map of the study area was created by heads-up digitizing techniques via a visual image interpretation of a cloud-free image (dated 29/01/2017), downloaded from the Google Earth Pro interface (Fig. 3a). The resulting LULC map of the study area yielded five subclasses: agricultural land; open space; waterbody; built-up area (settlements with vegetation and industrial areas) and flood flow zone. An accuracy assessment was performed to validate the reliability of the generated map (Jensen 1996). This study used 100 random reference points (30 points collected from the study area; the rest extracted from the high-resolution Google Earth image) for accuracy assessment. The overall accuracy of the classification was found to be 89%, with a Kappa coefficient of 0.85 (Table S1).

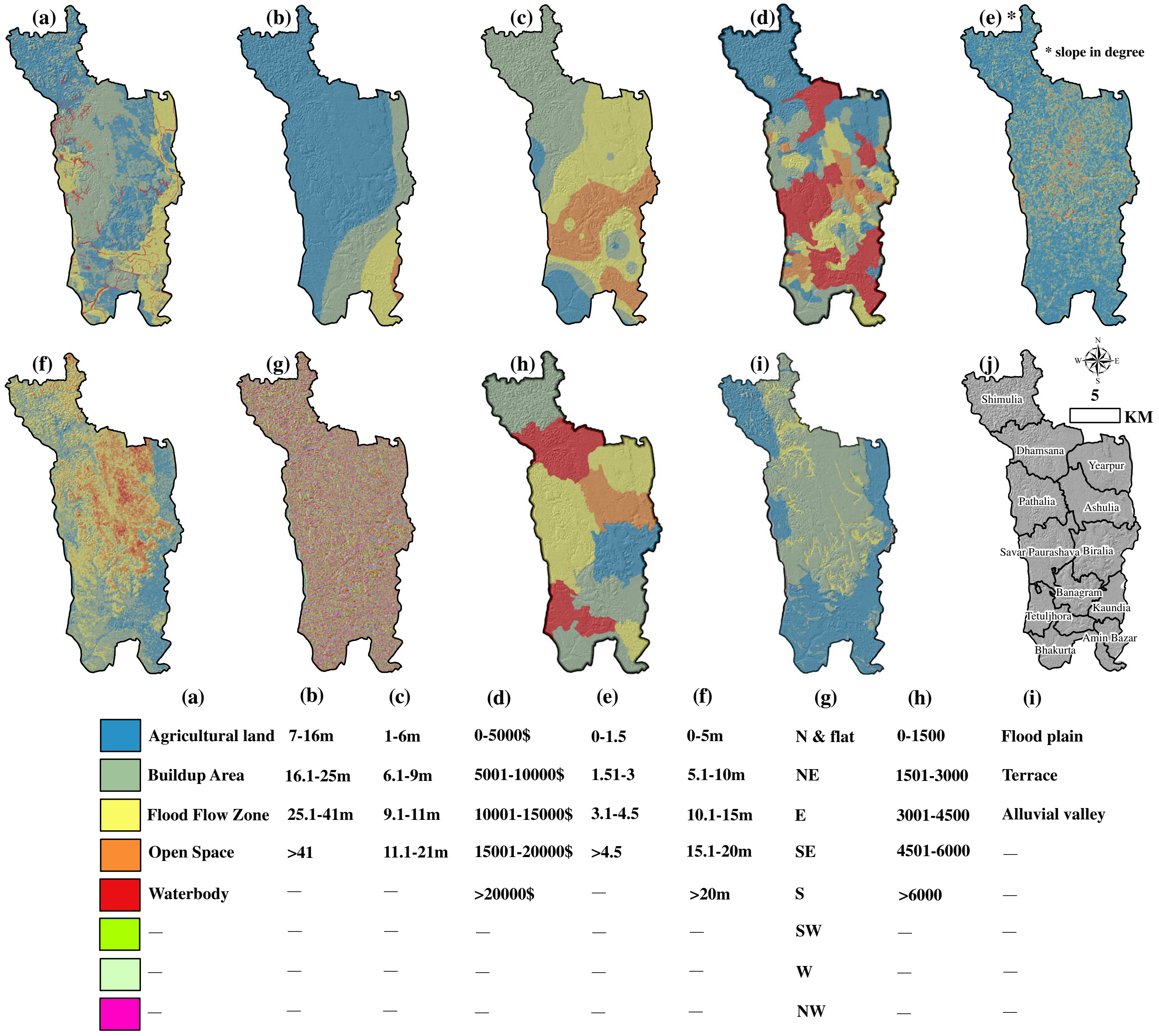
To construct a map of DGT across the study area, mean values from 20 years of data from 15 piezometric wells were used in an inverse-distance-weighted (IDW) interpolation technique (Fig. 3b), and subsequently classified into four subclasses, 7–16 m, 16.1–25 m, 25.1–41 m and > 41 m. A clay thickness map (iso-pack) was constructed using log data from 26 shallow bores (up to 30 m in depth) (Fig. 3c). The IDW interpolation technique was used for exhibiting the spatial distribution of clay thickness. Only the upper clay thickness at each bore was considered for this analysis. The clay thickness map was then subdivided into four subclasses: 1–6 m; 6.1–9 m; 9.1–11 m and 11.1–21 m.

A map representing the per decimal land price was created for each lowest administrative unit (mouza/village) of the study area (Fig. 3d). The mean value of the land in 2015 was used, and local currency converted to US$. The land price subclasses were $0–5000, $5001–10,000, $10,001–15,000, $15,001–20,000 and > $20,000. Three topographic parameters, terrain slope, elevation and aspect, were taken from the digital elevation model (DEM). A majority filter was applied to the DEM prior to the spatial analysis to remove error artefacts in order to obtain accurate terrain information. Terrain slope was classified into four subclasses: 0–1.5°; 1.51°–3°; 3.1°–4.5°; and > 4.5° (Fig. 3e). Elevation represented by a hypsometric tinting map was classified into five subclasses: 0–5 m; 5.1–10 m; 10.1–15 m; 15.1–20 m and > 20 m (Fig. 3f). Aspect subclasses were N, NE, E, SE, S, SW, W and NW (Fig. 3g).

The population-density map was created from the most recent population census (BBS 2011). Population data for each union were stored in a union shape file, then classified into five subclasses (persons per km^2): 0–1500; 1501–3000; 3001–4500; 4501–6000 and > 6000 (Fig. 3h). A single image from Landsat 8 in 2015 was used to delineate the existing units of geomorphology in the study area using on-screen digitization in the GIS interface (Fig. 3i). Prior to the digitization process, a histogram equalization algorithm was used to enhance the image. Three major geomorphic units (subclasses) were identified, flood plains, terrace and valleys, which were further validated with field information and auger-derived lithology (depth up to 5 m). Finally, three buffer distance maps were created for roads, settlements and waterbodies with distances of 300 m, 500 m and 500 m, respectively, using the geoprocessing tools in GIS (Fig. 4a–c).

Analytical hierarchy process

Assigning weights to individual parameters as well as their respective subclasses is one of the major tasks in any multi-criteria evaluation technique (MEC). We used the analytical hierarchy process (AHP)—pairwise comparison for weight calculation for both the cases. AHP followed three basic steps. The first step was to decompose the decision-making problem (in this study, selection of the landfill site) into a hierarchical structure including nine parameters for generating the preference raster and its respective subclasses (Şener et al. 2010). The second step was to create decision tables in a matrix format at each level of the hierarchical decomposition. The resulting matrices at the bottom level therefore contained pairwise comparisons of the relative importance of the subclasses (Rezaei-Moghaddam and Karami 2008; Şener et al. 2010). The comparison is made on a scale from 1 to 9, where 1 means equal preference, 3 weak preference, and 5 and 7 obvious and strong preferences, respectively (Table S2). Pairwise comparison, like this one, is proven to be an independent assessment that signifies the influence of each parameter, thus simplifying the decision-



	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)
🟦	Agricultural land	7-16m	1-6m	0-5000$	0-1.5	0-5m	N & flat	0-1500	Flood plain
🟩	Buildup Area	16.1-25m	6.1-9m	5001-10000$	1.51-3	5.1-10m	NE	1501-3000	Terrace
🟨	Flood Flow Zone	25.1-41m	9.1-11m	10001-15000$	3.1-4.5	10.1-15m	E	3001-4500	Alluvial valley
🟧	Open Space	>41	11.1-21m	15001-20000$	>4.5	15.1-20m	SE	4501-6000	—
🟥	Waterbody	—	—	>20000$	—	>20m	S	>6000	—
🟩	—	—	—	—	—	—	SW	—	—
🟩	—	—	—	—	—	—	W	—	—
🟪	—	—	—	—	—	—	NW	—	—

Fig. 3 Spatial data used to create the preference raster: (a) land use/land cover; (b) depth to groundwater table; (c) thickness of clay; (d) land price; (e) terrain slope; (f) elevation; (g) aspect; (h) population density; (i) geomorphology and (j) reference map for union information

making process (Rezaei-Moghaddam and Karami 2008). As the comparisons were subjective, the consistency of the pairwise comparison was assessed by the consistency ratio (CR) (Saaty 1980) in the third step. Generally, the closer the consistency ratio to zero, the higher the consistency of the calculation (Malczewski 1999). For this study, the consistency ratio of all parameters and their respective subclasses was well below the threshold 0.10 (Kontos et al. 2005; Yal and Akgün 2013), indicating good consistency. To calculate the AHP-derived weight, we used the AHP online calculator (https://bpmsg.com/ahp-online-calculator). The pairwise-comparison matrix and weight values for individual parameters and their subclasses are given in Table 2 and Table S3, respectively.

AHP-derived weight for parameters and their subclasses

According to the AHP calculation, LULC received the highest weight (0.30). This is because suitable site selection for any particular purpose requires accurate LULC information to avoid any conflict such as adverse impacts on settlements, industrial areas or cropland (Aydi et al. 2013). DGT had the second-highest weight (0.20) because groundwater is the only source of water for drinking and irrigation in the study area, and could be contaminated by leachate from waste materials if the water table exists at shallow depths (Gorsevski et al. 2012). The third-highest weight (0.14) was assigned to clay thickness; clay layers of considerable thickness occurring at

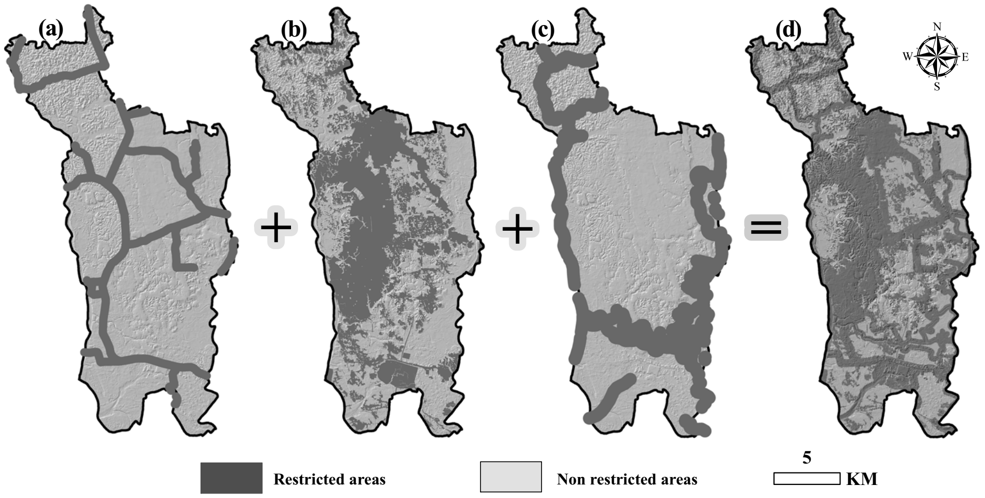


Fig. 4 Spatial data used for creating restriction raster: (a) distance to road; (b) distance to settlement; (c) distance to waterbodies and (d) integrated restriction raster

the subsurface can prevent leachates from wastes percolating further down to the groundwater (Gbanie et al. 2013; Aydi et al. 2013). Land price received fourth-highest weight (0.12). Being the hub of economic activity, the price of land is generally higher in the central areas of cities so that only the outlying regions are considered suitable for landfill sites (Gbanie et al. 2013).

The remaining parameters, terrain slope, population density, geomorphology, aspect (wind direction) and elevation received less weight in comparison with the previous parameters. Of these, terrain slope gained a slightly higher weight (0.07) than the others because it affects run-off; moreover, constructing landfill sites on steeper slopes increases the cost of maintenance (Wang et al. 2009). Population density, geomorphology, aspect and elevation had lower weights, 0.05, 0.03, 0.02 and 0.02, respectively, signifying less influence. However, these four parameters have been acknowledged as still important in many other studies targeting site selection in different countries across the world. For instance, densely populated areas usually generate greater volumes of solid waste but have a higher operational cost for landfilling than other areas (Donevska et al. 2012). The geomorphology influences the physical processes acting in the area over a long time, and hence deserves serious attention when selecting landfill sites (Lin and Kao 1999). A landfill site should not be built on elevated ground, as there is the potential for leachate running off into low-lying areas, particularly water bodies, e.g., ponds, lakes and rivers (Akbari et al. 2008). Geographical factors such as aspect play a vital role in determining wind effects. A landfill site should not be aligned to the prevailing wind direction to avoid dispersal of waste material into the environment (Şener et al. 2011).

AHP-derived weights were also obtained for the subclasses of each parameter (details given in Tables S3a; S3b; S3c; S3d; S3e; S3f; S3g; S3h and S3i). Due to the absence of human settlement or any other important infrastructure or activity, open space is always preferable for a landfill site in terms of LULC; the subclass open space, therefore, had the highest

Table 2 Pairwise comparison matrix for AHP calculation (preference parameters)

Preference parameters	Pairwise comparison matrix										Weight	**PEV	*CR
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	Priority			
(1) Land use/land cover	1									30.4%	0.3041	9.609	0.052
(2) Depth of water table	1/2	1								20.8%	0.2077		
(3) Thickness of clay	1/3	1/2	1							14.9%	0.1489		
(4) Land price	1/4	1/3	1/5	1						12.8%	0.1278		
(5) Terrain slope	1/5	1/4	1/3	1/3	1					7.4%	0.0741		
(6) Population density	1/6	1/4	1/4	1/4	1/2	1				5.0%	0.0502		
(7) Geomorphology	1/6	1/5	1/4	1/5	1/3	1/5	1			3.8%	0.0378		
(8) Aspect (wind direction)	1/7	1/5	1/5	1/5	1/4	1/3	1/5	1		2.8%	0.0276		
(9) Elevation	1/7	1/6	1/5	1/6	1/5	1/3	1/3	1/5	1	2.1%	0.0218		

***PEV* - principal eigenvalue; **CR* - consistency ratio weight (0.40), with the subclasses build-up areas and flood flow zones having lesser weights (0.07 and 0.06, respectively). Regarding DGT, a greater depth is generally more suitable for site selection because chances of contamination through leachate are minimal; hence, the subclass > 41 m depth received the highest weight (0.52), with lower weights assigned to the shallower depths. With the conjecture the greater the thickness of the clay layer in the subsurface, the less chance there is of contaminant percolating to groundwater, subclass 11.1–21 m received the highest weight (0.52), with lower weights for the other subclasses. Higher land price is often a major constraint in establishing landfill sites in many less developed countries. Hence, in this study, land with the lowest price gained the highest weight (0.46), with lower weights assigned to the higher land price subclasses. Gentle terrain slope received a relatively higher weight than steeper slope because leachate can spread faster from a steeper slope, particularly after heavy rainfall. Accordingly, slope subclass 0–1.5° had the highest weight (0.50), the subclass > 4.5° the lowest weight (0.09). Lower population density is preferable for selection of landfill sites, as relocating fewer people is more viable than a mass relocation. Therefore, the subclass of lowest population density derived the highest weight (0.47), and highest density the lowest weight (0.04). In regard to geomorphology, the subclass flood plain received the highest weight (0.55), with lower weights for terrace (0.31) and valley (0.12). Both terrace (convex) and valley (concave) exhibit undulating landscape; the possibility of contaminant spreading is high due to the higher slope on a terrace, whereas a valley could suffer from waterlogging, resulting in severe air pollution. Again, with a similar consideration to that applied to geomorphic units (e.g., terrace), highly elevated land gained the lowest weight (0.04), flat land a much higher weight (0.47). Moreover, the financial cost for site construction is much higher on elevated land than on flat land. There is no specific wind direction that should be avoided to prevent air pollution from landfill sites; hence, all directions received more-or-less similar weights with a slightly higher weighting for north (0.19) and northeast (0.16).

Assigning weight for restriction parameters

Three restriction rasters were created from the buffer distance maps of roads, settlements and waterbodies to indicate unsuitable areas for landfill. The distance from a road network is important not only for good accessibility (Aydi et al. 2013) but also for ensuring less exposure to bad odours from a landfill site (Moeinaddini et al. 2010). Public health and the environment are serious concerns in establishing such sites. Therefore, it is vital to ensure a sufficient distance of a proposed site from the nearest settlements (Ekmekçioğlu et al. 2010). According to environmental legislation, landfill sites should not be located near water bodies, which can lead to significant water pollution (Inanc et al. 2004). All three distance buffer maps were merged with the study area boundary, then converted to a binary raster by assigning the value 0 for restricted areas and 1 for non-restricted areas.

Spatial integration for the final landfill site suitability map

A total of nine parameters, LULC, DGT, thickness of clay, land price, terrain slope, population density, geomorphology, elevation and aspect, were integrated through the weighted overlay technique in GIS to create the preference raster. A restriction raster was created through the integration of the three individual restriction rasters, distance to road, distance to settlement and distance to waterbodies, using the raster calculator. The same raster calculator was used to combine the weighted preference and restriction rasters in order to obtain the suitability raster using the formula:

$$S = \sum_{i=1}^{n} W_i C_i \prod_{j=1}^{m} r_j \qquad (1)$$

where S is the suitability, W_i the weight of parameter i, C_i the weight of subclasses of the parameter i and r_j the criterion score of restriction j.

Once the suitability map was generated, a conditional tool was applied only to the highly suitable areas to extract the recommended sites for landfill. For this purpose, the areal extents (i.e. ≥ 0.4 km^2) of the existing major landfill sites in Dhaka city (Matuail in the south, Gabtali in the north) were ultimately used as a reference threshold.

Results and discussion

The site preference raster alone revealed that the three preference subclasses, low 32% (89 km^2 in total area), moderate 35% (98 km^2) and high 33% (93 km^2), each occupied almost equal proportions of the total area (Fig. 5a). The restriction raster however identified 59% (166 km^2) of the total area as unsuitable for landfilling (Fig. 5b). The preference raster and restriction raster were spatially combined according to Eq. (1) to determine the suitable sites, those where landfill would have a minimal effect on the urban environment and public health. The comprehensive suitability map (Fig. 5c) ultimately identified an area of 114 km^2 (41% of the total area) as suitable for landfilling. Integration of the restriction criteria into the suitability model has resulted in a significant reduction in the area that was identified by the preference raster as suitable for landfill sites. The primary intention behind such an approach was to discard the areas where dumping waste would be inappropriate in terms of environmental and health regulations. We believe that combining all the parameters into a

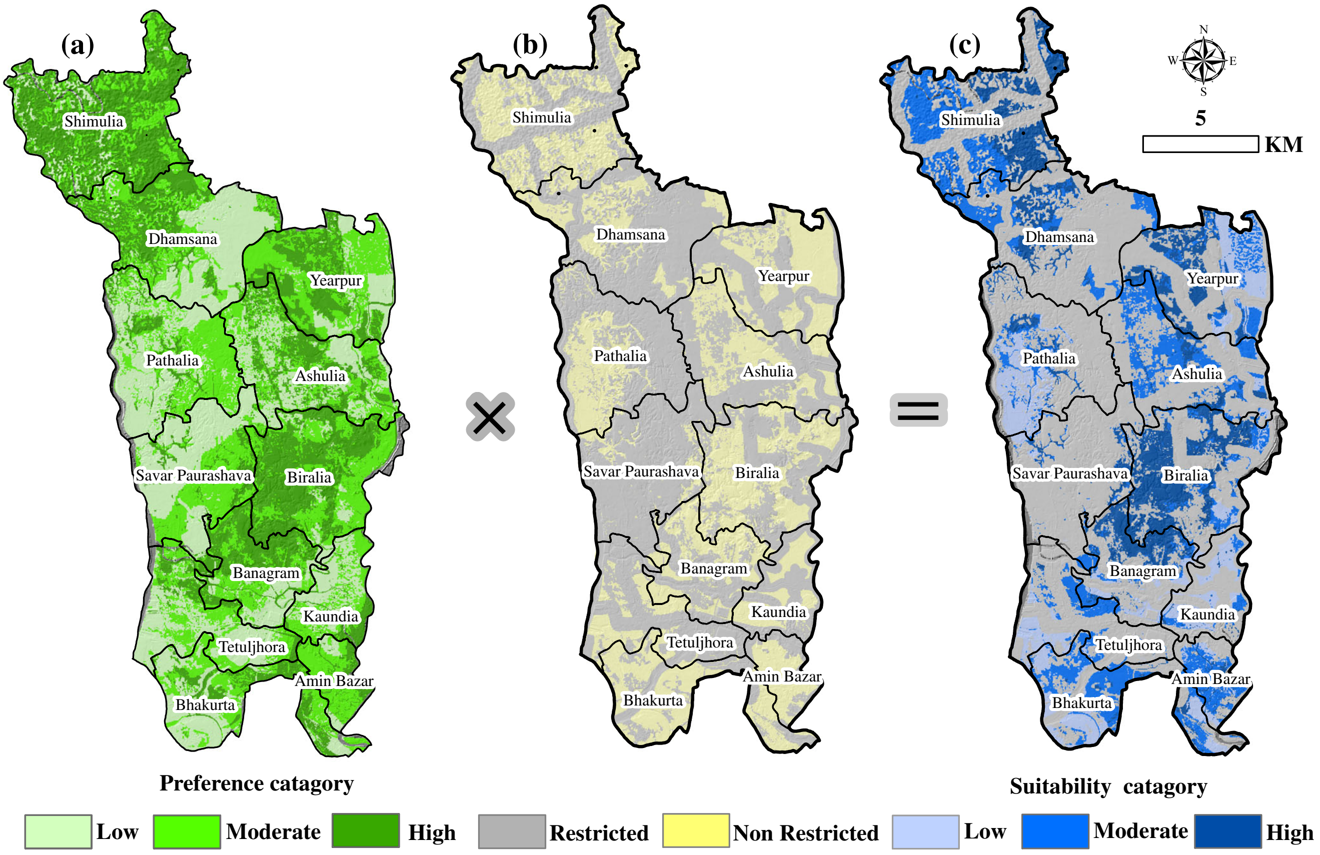


Fig. 5 (a) Preference raster; (b) restriction raster and (c) suitability raster

single index increases the risk of reaching an inappropriate decision and misleading the planners. For instance, considering all the parameters as a single set, including the restriction parameters, could generate a low suitability score for unsuitable areas which is impractical. Areas on the final suitability map were classified into three classes, low suitability (0.109–0.231), moderate suitability (0.232–0.301) and high suitability (0.302–0.475) using the natural-break classification technique. The result indicated that 14% (39 km^2) of the study area is highly suitable, 16% (45 km^2) moderately suitable and 11% (30 km^2) less suitable for landfill sites.

The parameters used in this analysis had different levels of influence in determining whether an area was suitable or not. According to the final landfill suitability map, the middle/eastern part of the study area, in the Biralia and Banagram unions, and the north-western part, in the Shimulia union and part of the Dhamsana union (Fig. 5c), together contained the greatest number of highly suitable areas (~ 27 km^2). The relatively lesser influence of restrictions like the presence of fewer water bodies and low settlement density was considered the key factor that rendered these areas highly suitable. In addition, the predominance of agricultural land, with occasional open spaces (mostly fallow land), occurrence of thick clay layers, low-to-moderate population density and relatively cheaper land prices collectively contributed to make this area highly suitable for landfilling.

Conversely, the southern and western regions of the study area, belonging to the Amin Bazar, Bhakurta, Tetuljhora, Savar Paurashava and Pathalia unions, were found to be unsuitable for landfill sites (Fig. 5c). Despite the presence of considerable number of favourable conditions for landfilling, such as low-to-moderate elevation, moderate clay thickness and greater water depth, these areas were found to be unsuitable. This is primarily attributable to the significant influence of the two major restriction criteria, extremely high settlement density including industrial zones and drainage density. Two major rivers, the Bangshi passing through the western side and its southern course, the Dhaleswari and the Turag, passing along the eastern side of the study area, and their tributaries/distributaries, lessened the suitability of this part of the study area for the purpose of landfill. Being situated in flood flow zones, with higher land prices and low-to-moderate water depth, may also have led to the unsuitability of this particular region.

Several small patches were identified in the final suitability map as highly suitable for landfilling (Fig. 6a), but most lack the capacity to accommodate a standard landfill site because of their small area. Hence, these patches were subjected to

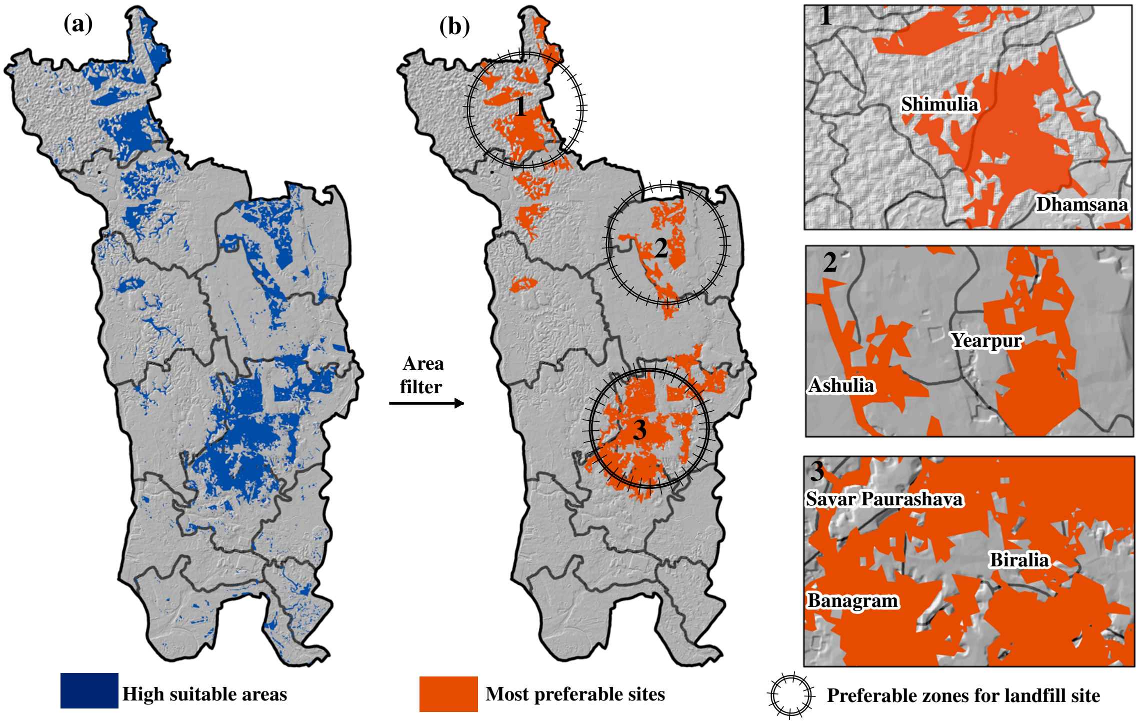


Fig. 6 (a) Highly suitable areas; (b) most preferable sites for landfill in the study area

further filtering. The areas of the two big landfill sites located in Dhaka were taken as thresholds for this calculation. The filtering operation, performed within the highly suitable class, reduced its area from 45 km^2 (16%) to 28 km^2 (10%); 21 highly suitable sites for landfill were subsequently identified (Fig. 6b). To locate these sites, the suitability map was integrated with union boundary of the study area. Of the 21 sites, thirteen were located in the northern part of the study area (Shimulia, Dhamsana and Yearpur), seven sites in Ashulia, Biralia, Banagram and Savar Paurashava, and one in the Pathalia union in the northwestern corner. None of these sites was located in the Amin Bazar, Bhakurta, Kaundia and Tetuljhora unions (Fig. 6b).

The current study looked to improve on the selection of landfill site by traditional techniques. Therefore, every aspect was scrutinized rigorously. With this motivation, although 21 locations were identified by the geospatial analysis as suitable for landfill, we recommend only 12 of them as ideal for future sites as they more than satisfied the criteria, with larger areas than recommended (more than 0.4 km^2), a smaller number of households, the absence of major water bodies and optimum distance from major roadways. These sites are located in the Biralia (3 sites), Shimulia (6 sites) and Yearpur (3 sites) unions (Table 3).

Conclusion

Finding locations for landfilling that meet all the essential conditions for environmental safety is quite challenging and may not be achievable using traditional field-survey techniques. A geospatial approach has, so far, proved to be the most effective tool for such investigations. The prime objective of the current work was to identify suitable landfill sites in the Savar upazila of Dhaka. Considering environmental and public health safety as the topmost priorities, the current study addressed several geo-environmental conditions of a rapidly growing metropolitan area in locating suitable landfill sites. Using the AHP technique with weighted linear combination (WLC) in a GIS environment, suitable landfill sites were identified based on twelve parameters (nine for the preference analysis and three for the restriction analysis). The study revealed that nearly 14% of the area is highly suitable, 16% moderately suitable, 11% less suitable and the remaining 59% unsuitable for landfill sites. Twenty-one sites were identified in the highly suitable areas as suitable for landfilling, most located in the northern part of the study area, in the Shimulia, Dhamsana and Yearpur unions; we recommended twelve of these as ideal for future landfill.

Despite the successful implementation of geospatial and AHP techniques in landfill site selection, the current study experienced a number of challenges worth mentioning. The unavailability of relevant data for modelling and mapping was the first and foremost hindrance. Geospatial data are usually scarce and domain specific in Bangladesh (Dewan and Yamaguchi 2009). Moreover, sharing and coordination among various organizations working with these data is lacking, as a national spatial data infrastructure (NSDI) for this country is yet to be developed (Islam et al. 2017). Budget

Table 3 Union-wise statistics of landfill site suitability analysis

GC	AU	TA	PD	TH	HSC	WB	NPS	RS/NRS
30267215	Amin Bazar	7.88	3428	8786	-	0.84	-	-
30267218	Ashulia	27.15	5515	36395	1.11	1.11	02	Not recommended
30267222	Banagram	16.88	1863	7742	3.35	2.19	01	Not recommended
30267227	Bhakurta	18.45	2135	9366	-	3.41	-	-
30267233	Biralia	29.5	1367	9829	10.64	2.12	03	Recommended
30267239	Dhamsana	33.47	9399	89316	2.42	0.88	04	Not recommended
30267250	Kaundia	12.35	2423	6107	-	1.86	-	-
30267272	Pathalia	29.01	3241	21636	0.50	4.66	01	Not recommended
30267278	Savar Paurashava	27.82	4498	73465	0.66	4.45	01	Not recommended
30267283	Shimulia	36.4	2574	18730	6.62	0.59	06	Recommended
30267289	Tetuljhora	20.08	6876	25867	-	4.21	-	-
30267294	Yearpur	26.4	4434	30613	3.60	1.25	03	Recommended

GC - Geocode; *AU* - administrative units; *TA* - total areas in km^2; *PD* - population density; *TH* - total households; *HSC* - highly suitable class; *WB* - waterbodies; *NPS* - number of preferable sites; *RS/NRS* - recommended and not recommended sites

constraints are also a perennial problem in countries like Bangladesh. For instance, the freely available SRTM DEM dataset at 30 m resolution was used in this study instead of ideal high-resolution topographic data, primarily due to funding constraints. Also, because of the lack of an up-to-date economic land survey dataset, the study had to rely on out-of-date land price data. Furthermore, the current modelling did not consider some integral factors like urban planning (Adeli and Khorshiddoust 2011). The scope of urban planning is narrow, as the study area is already urbanized except for some ongoing developmental activities. Therefore, considering LULC was deemed appropriate for the purpose of the study. Similarly, the parameters clay thickness and geomorphology were used in our model as an alternative to leaching factor or soil permeability, the parameters conventionally used by most researchers (Qin et al. 2014; Eskandari et al. 2015). Given the extent of the study area, incorporating variations in hydrometeorological parameters, such as precipitation (EL Baba et al. 2015), was found less important. Other factors like storage capacity (Alam et al. 2008), length of service (Seok Lim and Missios 2007), convenient transportation (Kumar et al. 2009) and engineering conditions (Djokanović et al. 2016) could not be included, predominantly due to the scarcity of contemporary data, time and budget constraints. Since precise statistics regarding the volume of daily waste generated in the study area were unavailable, the current study focused on identifying suitable sites for the dumping of waste, irrespective of the size and capacity of the landfills.

Since the population of the study area is increasing exponentially, with a concurrent increase in municipal waste, the outcome of this study is expected to be useful to urban planners in the intelligent selection of landfill sites that enshrines the principles of environmental integrity, health safety and sustainable land use. The approach could be applied elsewhere with similar intention. Based on our observations and experience, we would like to provide some guidance for future planners. For instance, in the current study, most of the locations identified as suitable according to the modelling are occupied by residents. Therefore, settlements and other critical infrastructure should be relocated before construction of landfill sites. A weather station should be installed nearby for the proper monitoring of atmospheric conditions (e.g., wind direction and rainfall). A piezometric nest surrounding the final site could be effective for continuous monitoring of leachate in the groundwater. Considering these aspects prior to the construction of a landfill site in the study area would maximize the benefits and minimize the likelihood of harmful effects.

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