Environmental Monitoring and Assessment (2020) 192: 682
https://doi.org/10.1007/s10661-020-08565-y

A multi-criteria decision support framework for municipal solid waste landfill siting: a case study of New South Wales (Australia)

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Received: 28 May 2019 / Accepted: 24 August 2020 / Published online: 7 October 2020

Abstract Sanitary waste disposal and site selection for establishing landfills are challenging problems for environmental planners. This paper aims to take environmental, socio-economic, geological, geomorphological, hydrological and ecological factors into consideration to provide a decision support framework for landfill siting. Analytical hierarchy process (AHP) and Decision Making Trial and Evaluation Laboratory (DEMATEL) are coupled to develop an efficient multi-criteria decision-making method to be utilized in a Geographic Information System (GIS) environment for evaluating the suitability for landfill siting. As the first attempt to employ DEMATEL effectively in a landfill site selection problem, the proposed method is tested with landfill siting scenarios in New South Wales (NSW), Australia. Regional analysis is also performed to identify the potentially most suitable statistical divisions for landfill siting in NSW. The top two ranked zones covering 0.7% and 22% of the study area, respectively, are considered as the optimal areas for establishing landfills, while the bottom two ranked zones are not recommended for further consideration. Further detailed analysis is also conducted on the existing landfills, which shows that 1.0% and 37.0% of them are ranks 1 and 2, respectively. The scenario-based analysis implies that, among the contributing factors; geological and economic factors are highly important.

Keywords Municipal solid waste management · Landfill site selection · Multi-criteria decision-making · Analytical hierarchy process (AHP) · Decision Making Trial Evaluation Laboratory (DEMATEL)

Introduction

Landfill site selection process is one of the most difficult challenges, which necessitates a systemic evaluation process to minimize all contributing economic

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Electronic supplementary material The online version of this article (https://doi.org/10.1007/s10661-020-08565-y) contains supplementary material, which is available to authorized users.

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and environmental costs (Soltani et al. 2015, p. 319). Dealing with a large amount of spatial data leads to a complex process requiring a Geographical Information Systems (GIS) as an indispensable tool (Zamorano et al. 2008, p. 473; Sumathi et al. 2008, p. 2148). GIS has been widely applied to facilitate and decrease the time and cost in landfill site selection studies in many countries (Siddiqui et al. 1996; Hussey et al. 1996; Charnpratheep et al. 1997; Kao et al. 1997; Dörhöfer and Siebert 1998; Vatalis and Manoliadis 2002; Kontos et al. 2003; Sharifi 2004; Javaheri et al. 2006; Wang et al. 2009; Danesh et al. 2019). Capability in solving multi-criteria decision-making (MCDM) problems by factoring both qualitative and quantitative criteria together with easy implementation led to utilize analytical hierarchy process (AHP) (Saaty 1980) as the most applied MCDM method in a GIS environment to find optimal landfill sites for regions in different countries (Soltani et al. 2015, p. 319).

However, while having significant strengths as a MCE method, the remarkable drawback of AHP is disclosed when there are interconnections between the decision factors (criteria) at the same level of the hierarchy. Assuming independency between the criteria results that AHP is not effective to use when interdependencies exist between the decision variables. That is, AHP assumes a one-way hierarchical relationship between the decision levels and, hence, it cannot deal with interconnections between the factors (Najmi and Makui 2010, p. 204; Najmi and Makui 2012, p. 699). Therefore, to tackle this significant deficiency, Decision Making Trial and Evaluation Laboratory (DEMATEL) is utilized in this study. So far, DEMATEL by Fontela and Gabus (1974) has been widely reported as one of the most efficient techniques for multi-criteria evaluation problems where there are relationships among the criteria (Chiu et al. 2006; Wu and Lee 2007; Liou et al. 2007; Tzeng et al. 2007; Tseng and Lin 2009; Sumrit and Anuntavoranich 2013).

However, DEMATEL has been rarely used in Waste Management context including MSW management (Tseng and Lin 2009; Tseng 2009; Kharat et al. 2016). Tseng (2009) applied DEMATEL and Analytic Network Process (ANP) to study the contributing factors of evaluation of MSW management in Metro Manila. The mentioned study utilized DEMATEL to determine the interrelations between the considered criteria and then applied ANP to allocate the weights of the criteria. The study resulted in highlighting the most desired managerial solution to address the challenge of resource recovery and inadequacy of landfills in their studied area. In a similar study, Tseng and Lin (2009) utilized a fuzzy DEMATEL approach to prioritize contributing criteria of efficient MSW management. They coupled fuzzy theory to DEMATEL to address the uncertainty contributed in allocating weights to their considered criteria. They implemented their approach to Metro Manila resulting in prioritizing crucial factors in MSW management by DEMATEL method. Recently, Kharat et al. (2016) studied the contributing criteria for landfill siting to identify, evaluate and prioritize them. Their proposed framework includes application of fuzzy Delphi method to identify the critical factors by utilizing fuzzy AHP to make pairwise comparisons for allocating weights to the criteria and by applying DEMATEL to analyze the importance and causal relationships among the criteria to recognize the influential criteria of landfill site selection, however, their target area for the study was not specified. It should be noted that identifying and prioritizing the factors in landfill site selection is highly dependent on a specific target area and its particular characteristics. That is, a different area requires identifying different crucial criteria and their corresponding weights with respect to the area's limitations and geographical aspects (e.g., lack or abundance of appropriate soil types for landfill siting in an area could result in different prioritization of this factor among other criteria). Thus, the resulted criteria and their ranks in the mentioned study may not work for general purposes. Moreover, the proposed framework by Kharat et al. (2016) did not form an integrated convergent structure where their ranked criteria by the two methods (fuzzy AHP and DEMATEL) have significant differences without supporting each other, which means not benefiting from the DEMATEL outcomes when ranking the criteria.

A variety of combinations of AHP and DEMATEL (AHP-DEMATEL) has been successfully applied in many fields (Wu and Lee 2007; Najmi and Makui 2010; Chang and Chen 2011; Najmi and Makui 2012; Roy et al. 2012; Chou et al. 2012) However, to the best of the authors' knowledge, neither DEMATEL solely nor its combination with other decision-making methods has been yet coupled with GIS for site selection studies especially landfill siting. The present study aims to benefit from the strengths of both AHP and DEMATEL in an integrated framework (AHP-DEMATEL) to utilize it in a GIS environment for analyzing the suitability of the study area for landfill siting. In addition to the governmental regulations and limitations on landfill siting in NSW, several environmental, economic and geological factors have been taken into account to obtain practical results by evaluating the factors through an efficient multi-criteria evaluation method. As the targeted study area is very large in size, regional analysis is also conducted to provide further detailed analysis for the regions within the study area. Moreover, three scenarios are considered to analyze the results and derive specific outcomes with respect to different managerial purposes and preferences.

Study area

Australia has one of the highest rates of waste generation per capita in the world (ABS 2012). Between 1997 and 2012 the rate of waste generation in Australia has increased by 145% compared with the moderate increase rates of 22% and 64% in the population and gross-value-added, respectively. Australia's population is estimated to become 35.5 million by the year 2056 which will place an increasing pressure on the natural environment and its resources (ABS 2013; Asefi et al. 2015). New South Wales (NSW) is Australia's most populous state with a population of 7.5 million (ABS 2014). The total amount of domestic wastes generated in NSW was 3.47 million tonnes between 2012 and 2013 (EPA 2014). Our study area covers the mainland of NSW, which is located in the south-eastern part of Australia. It covers a land area of 800,792 km^2 lies between latitudes 28° 9′ S and 37° 30′ S and longitudes 141° 00′ E and 153° 38′ N. Figure A.1 (Supplementary Material) shows the case study area.

Materials, sources, and approach

Figure 1 summarizes the implementing steps conducted in this study. The contributing criteria for landfill siting are

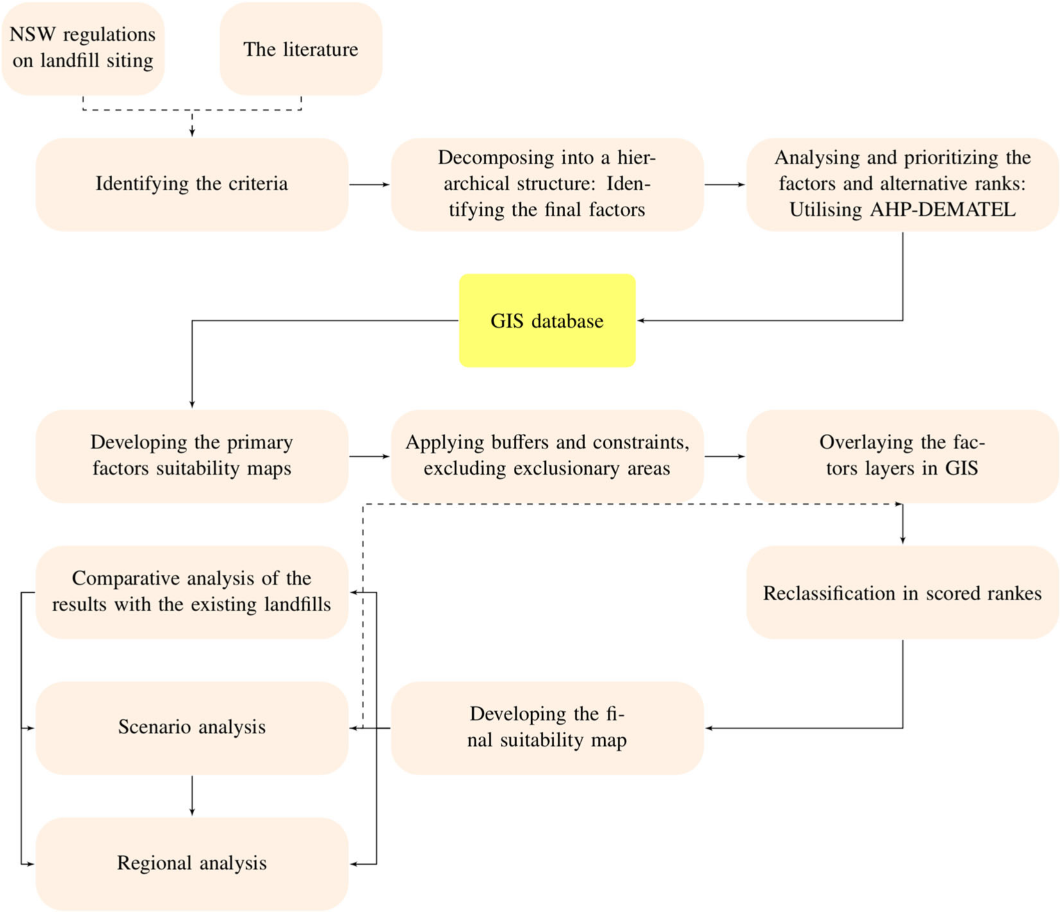


Fig. 1 The study framework and implementation process

extracted by exploring the governmental regulations on landfill siting (EPA 1996; 1999) in addition to deriving from the most relevant and creditable studies (Siddiqui et al. 1996; Charnpratheep et al. 1997; Dörhöfer and Siebert 1998; Kontos et al. 2003; Sharifi 2004; Yesilnacar and Cetin 2005; Sumathi et al. 2008; Akbari et al. 2008; Wang et al. 2009; Sener et al. 2010; Moeinaddini et al. 2010; Sener et al. 2011). The criteria are then analyzed, finalized and formed in a hierarchical structure considering the study area specifications and regulations. Decomposing the problem into a hierarchical structure resulted in identifying the final factors (i.e., the elements in the last levels of the hierarchy) where interrelations could be found among them. The final factors proceed via the adopted AHP-DEMATEL method to be processed in a GIS environment.

To develop the digital GIS database, 14 input map layers have been prepared (Supplementary Material: Table A.1). The primary suitability maps of the factors are produced and the final composite suitability map of the study area is then developed via overlaying. A digital GIS database including all information layers is developed with ArcGIS ver. 10.2. In order to extract geographical features and satisfy the state regulations on landfilling, buffer zones were generated based on criteria mentioned in NSW Environment Protection Authority (EPA) guidelines on Solid Waste Landfills (EPA 1996, 1999.

The adopted AHP-DEMATEL method

This study aims to combine AHP with DEMATEL in an integrated structure (AHP-DEMATEL) to benefit from the advantages of each while overcoming their deficiencies regarding the intended research purpose. That is, while hierarchical decomposing is derived from AHP to form a straightforward structure of all contributing factors, the weights of the final factors are determined by DEMATEL to address their interrelations and provide a causal diagram to represent their influence strengths in the entire system which is resulted by converting the relations between cause and effect of criteria into a visual structural model. Then, final ranking procedure and prioritization of the alternative ranks are performed via pairwise comparisons within the AHP framework. Finally, the validity of pairwise judgments are assessed by incompatibility ratio and reformed as necessary. Figure 2 illustrates the adopted AHP-DEMATEL approach in this study.

The overall framework of the proposed AHP-DEMATEL method is presented in Appendix 1.

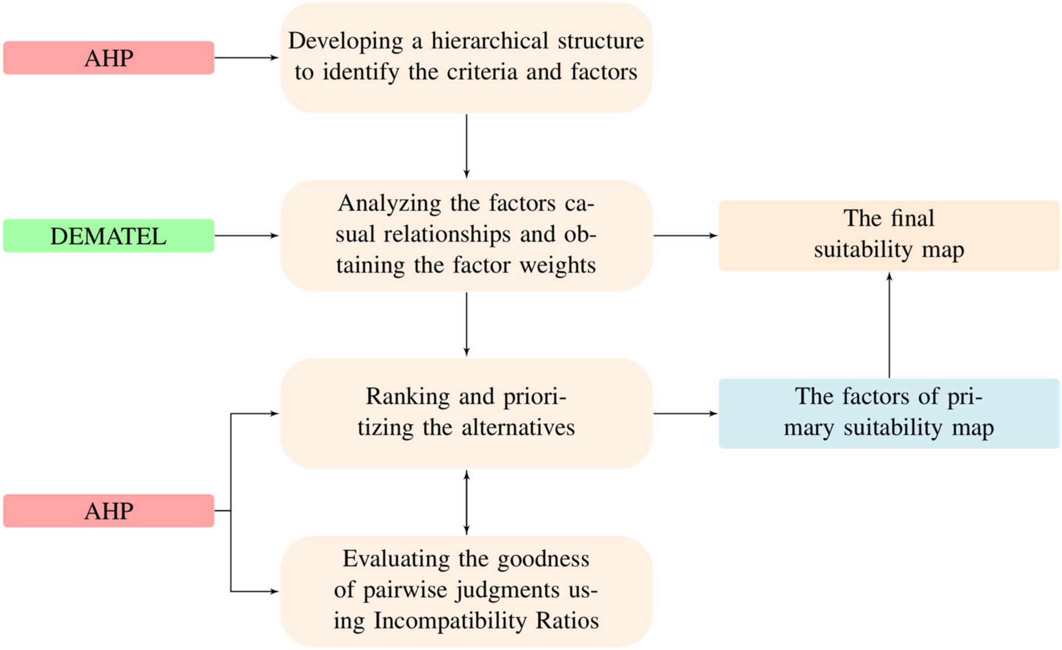


Fig. 2 The adopted AHP-DEMATEL method

Implementation: determining, evaluating, and mapping the criteria

Evaluation of criteria and factors

The explored criteria are summarized and classified in a hierarchy structure which is shown in Fig. 3. The influential criteria on landfill siting in the study area are categorized into the three main factors: (I) Socio-ecological, (II) Economic and (III) Geological and Geo-morphological factors. The developed hierarchy resulted in identifying the eleven final factors (i.e., the elements in the last levels of the hierarchy): (A) Proximity to residential areas, (B) Land cover, (C) Proximity to surface water, (D) Groundwater vulnerability, (E) Proximity to population hubs, (F) Proximity to major roads, (G) Soil permeability, (H) Soil depth, (I) Soil texture, (J) Slope, and (K) Altitude.

The resulted final factors are evaluated in terms of interrelations and their influence strengths in the entire system after gathering the experts' opinions. Accordingly, the average matrix Z, normalized initial direct-relation matrix D and total relation matrix T are calculated as follows were $K = H = 9$:

Table 1 summarizes the direct and indirect effects of eleven criteria (factors). The corresponding digraph of these eleven factors is shown in Fig. 4 where relation arrows are not shown due to the clutter of many relations (α=1.098). As depicted in 1, regarding $r - c$ values, (C) Proximity to surface water, (G) Soil permeability, (H) Soil depth, (I) Soil texture, (J) Slope and (K) Altitude are net causes, whereas (A) Proximity to residential areas, (B) Land cover, (D) Groundwater vulnerability, (E) Proximity to population hubs and (F) Proximity to major roads are net receivers. It can be seen that (J) Slope and (K) Altitude might be the most affecting factors since these two factors highly affect the other factors while receiving much less from the others. The importance of the eleven factors can be prioritized as $B > E > A > C > D > J > F > I > G > K > H$ based on $(r + c)$ values, where Land cover is the most important factor with the value of 3.498, while Soil depth is the least important factor with the value of 1.039. Finally, the normalized values of $(r + c)$ are calculated to represent the factors weights (Table 2).

The applied criteria: developing the factors and constraints maps

Socio-ecological factors and constraints

Residential and sensitive areas

According to Protection of the Environment Operations ACT 1997 (EPA 1999), a landfill site cannot be established within 250 m of a residential zone and some vulnerable areas including national parks,

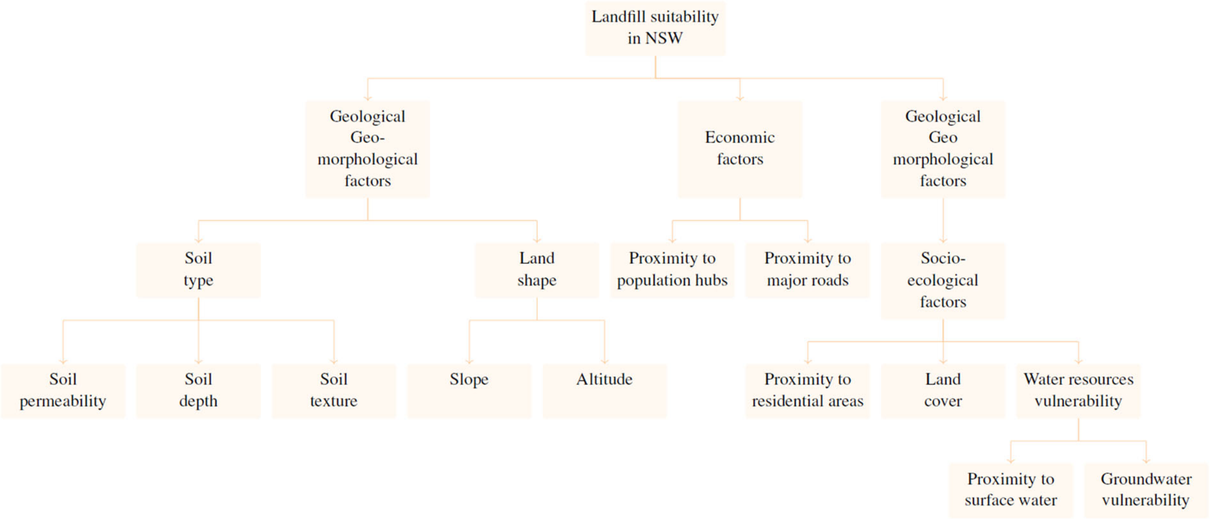


Fig. 3 The hierarchy structure of landfill siting in NSW

Table 1 The direct and indirect effects of eleven criteria (factors)

$$Z = \left[\begin{array}{llllllllllll}
\text{Factor} & (A) & (B) & (C) & (D) & (E) & (F) & (G) & (H) & (I) & (J) & (K) \\
(A) & 0 & 0.0994 & 0.0000 & 0.0884 & 0.1492 & 0.1492 & 0 & 0 & 0 & 0 & \\
(B) & 0.1105 & 0 & 0.0497 & 0.1271 & 0.1436 & 0.0608 & 0 & 0 & 0.0497 & 0 & 0 \\
(C) & 0.0994 & 0.1381 & 0 & 0.0994 & 0.1326 & 0.0939 & 0.1381 & 0 & 0.0939 & 0.0884 & 0 \\
(D) & 0.0608 & 0.1436 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
(E) & 0.1436 & 0.0994 & 0 & 0.1271 & 0 & 0.0994 & 0 & 0 & 0.0497 & 0 & 0 \\
(F) & 0.1492 & 0.1381 & 0 & 0 & 0.0994 & 0 & 0 & 0 & 0 & 0 & 0 \\
(G) & 0 & 0.0994 & 0.0994 & 0.1436 & 0.0552 & 0 & 0 & 0 & 0 & 0.0939 & 0 \\
(H) & 0 & 0.0608 & 0.0608 & 0.1436 & 0.0552 & 0.0552 & 0.0994 & 0 & 0 & 0 & 0 \\
(I) & 0.0608 & 0.0994 & 0.1381 & 0.1436 & 0.0552 & 0.0939 & 0.1381 & 0 & 0 & 0.0552 & 0 \\
(J) & 0.1436 & 0.1381 & 0.0994 & 0.0994 & 0.1326 & 0.1381 & 0.0939 & 0.0497 & 0.0497 & 0 & 0.0552 \\
(K) & 0.1050 & 0.1381 & 0.0994 & 0.0608 & 0.1326 & 0.0994 & 0.0497 & 0.0497 & 0.0497 & 0.0497 & 0
\end{array}\right]$$

$$D = \left[\begin{array}{llllllllllll}
\text{Factor} & (A) & (B) & (C) & (D) & (E) & (F) & (G) & (H) & (I) & (J) & (K) \\
(A) & 0 & 0.1840 & 0.0129 & 0.1523 & 0.2128 & 0.1989 & 0 & 0 & 0 & 0 & 0 \\
(B) & 0.1999 & 0 & 0.0687 & 0.2083 & 0.2188 & 0.1342 & 0 & 0 & 0.0732 & 00 & \\
(C) & 0.2553 & 0.3168 & 0 & 0.2626 & 0.2805 & 0.2154 & 0.1780 & 0 & 0.1360 & 0.1187 & 0 \\
(D) & 0.0951 & 0.1707 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
(E) & 0.2200 & 0.1917 & 0 & 0.1956 & 0 & 0.1614 & 0 & 0 & 0.0657 & 0 & 0 \\
(F) & 0.2125 & 0.1999 & 0 & 0 & 0.1698 & 0 & 0 & 0 & 0 & 0 & 0 \\
(G) & 0 & 0.2089 & 0.1301 & 0.2327 & 0.1446 & 0 & 0 & 0 & 0 & 0.1109 & 0 \\
(H) & 0 & 0.1537 & 0.0853 & 0.2158 & 0.1204 & 0.1008 & 0.1164 & 0 & 0 & 0 & 0 \\
(I) & 0.1987 & 0.2669 & 0.1853 & 0.2803 & 0.1925 & 0.1939 & 0.1792 & 0 & 0 & 0.0912 & 0 \\
(J) & 0.3153 & 0.3389 & 0.1568 & 0.2744 & 0.3050 & 0.2739 & 0.1411 & 0.0543 & 0.1011 & 0 & 0.0572 \\
(K) & 0.2581 & 0.3081 & 0.1492 & 0.2169 & 0.2817 & 0.2219 & 0.0966 & 0.0538 & 0.0971 & 0.0776 & 0
\end{array}\right]$$

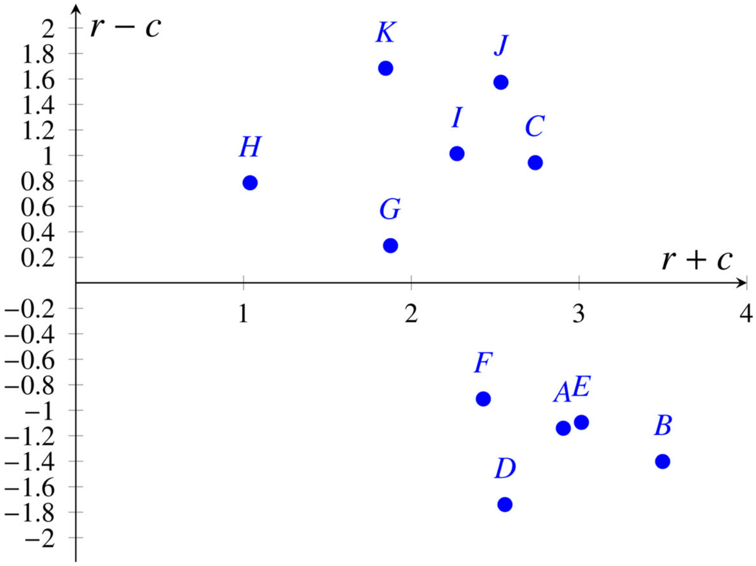
$$T = \left[\begin{array}{llllllllllll}
\text{Factor} & (A) & (B) & (C) & (D) & (E) & (F) & (G) & (H) & (I) & (J) & (K) \\
(A) & 0 & 0.1840 & 0.0129 & 0.1523 & 0.2128 & 0.1989 & 0 & 0 & 0 & 0 & 0 \\
(B) & 0.1999 & 0 & 0.0687 & 0.2083 & 0.2188 & 0.1342 & 0 & 0 & 0.0732 & 0 & 0 \\
(C) & 0.2553 & 0.3168 & 0 & 0.2626 & 0.2805 & 0.2154 & 0.1780 & 0 & 0.1360 & 0.1187 & 0 \\
(D) & 0.0951 & 0.1707 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
(E) & 0.2200 & 0.9117 & 0 & 0.1956 & 0 & 0.1614 & 0 & 0 & 0.0657 & 0 & 0 \\
(F) & 0.2125 & 0.1999 & 0 & 0 & 0.1698 & 0 & 0 & 0 & 0 & 0 & 0 \\
(G) & 0 & 2089 & 0.1301 & 0.2327 & 0.1446 & 0 & 0 & 0 & 0 & 0.1109 & 0 \\
(H) & 0 & 0.1537 & 0.0853 & 0.2158 & 0.1204 & 0.1008 & 0.1164 & 0 & 0 & 0 & 0 \\
(I) & 0.1987 & 0.2669 & 0.1853 & 0.2803 & 0.1925 & 0.1939 & 0.1792 & 0 & 0 & 0.0912 & 0 \\
(J) & 0.3153 & 0.3889 & 0.1568 & 0.2744 & 0.3050 & 0.2739 & 0.1411 & 0.0543 & 0.1011 & 0 & 0.0572 \\
(K) & 0.2581 & 0.3081 & 0.1492 & 0.2169 & 0.2817 & 0.2219 & 0.0966 & 0.0538 & 0.0971 & 0.0776 & 0
\end{array}\right]$$

nature reserves and historic sites. Accordingly, a 250-m buffer zone is created for residential areas (urban and rural residential zones) and sensitive areas (natural conservation areas) extracted from the Catchment-scale Land Use Management (CLUM) data provided by Australian Bureau of Agricultural and Resource Economics and Bureau of Rural Sciences (DAWR 2015). Accordingly, prioritization was performed in five ranges where a 0.5-km buffer zone was allocated as the lowest priority and 40 km was set as the maximum preferred distance (see Table 2) (Moeinaddini et al. 2010, p. 915). The map of applying this criterion is then developed as shown in Fig. 5a.

Land cover

The land cover source map is derived from the MODIS Land Cover Type product (also known as MCD12Q1)

Fig. 4 Causal diagraph for the eleven factors



(NASA-LP-DAAC 2013) which identifies 17 classes at a global scale. Bare, agricultural and unused lands are highly suitable for landfill siting whereas mountains, rock outcrops, dense and sparse forest are infeasible or highly unsuitable to establish a landfill (Wang et al. 2009, p. 2417; Oyinloye and Fasakin 2013, p. 10). Accordingly, the land cover map excluding residential areas, permanent wetlands and water bodies is re-classified into five primary classes and ranked in a range from the most suitable to the least suitable in the order of: (1) barren areas; (2) savannas and grasslands; (3) croplands and cropland/natural vegetation mosaics; (4) shrublands; (5) forests (Table 2 and Fig. 5b).

Surface water and drinking water storages

Landfills potentially can contaminate rivers, streams, drainage and lakes due to leaching unless adequate dissuasive factors are applied. It is stated by NSW Environment Protection Authority (EPA 1999) that a 40-m buffer must be applied for landfills from a permanent or intermittent waterbodies. Therefore, the above-mentioned buffer zones were applied to the map of surface water (DAWR 2015) and mentioned storages (GA 2003). Then, a 0.5-km buffer zone was prioritized as the least suitable and buffer zones greater than 2 km as the most suitable while 0.5 km intervals were considered within these two classes

Table 2 The sum of direct and indirect influences given and received among the eleven factors

Dimensions	$(r - c)$	$(r + c)$	W
(A) Proximity to residential areas	− 1.141	2.906	0.109
(B) Land cover	−1.402	3.498	0.131
(C) Proximity to surface water	0.943	2.739	0.103
(D) Groundwater vulnerability	− 1.740	2.558	0.096
(E) Proximity to population hubs	− 1.095	3.014	0.113
(F) Proximity to major roads	− 0.911	2.429	0.091
(G) Soil permeability	0.292	1.876	0.070
(H) Soil depth	0.785	1.039	0.039
(I) Soil texture	1.014	2.272	0.085
(J) Slope	1.574	2.534	0.095
(K) Altitude	1.684	1.847	0.069

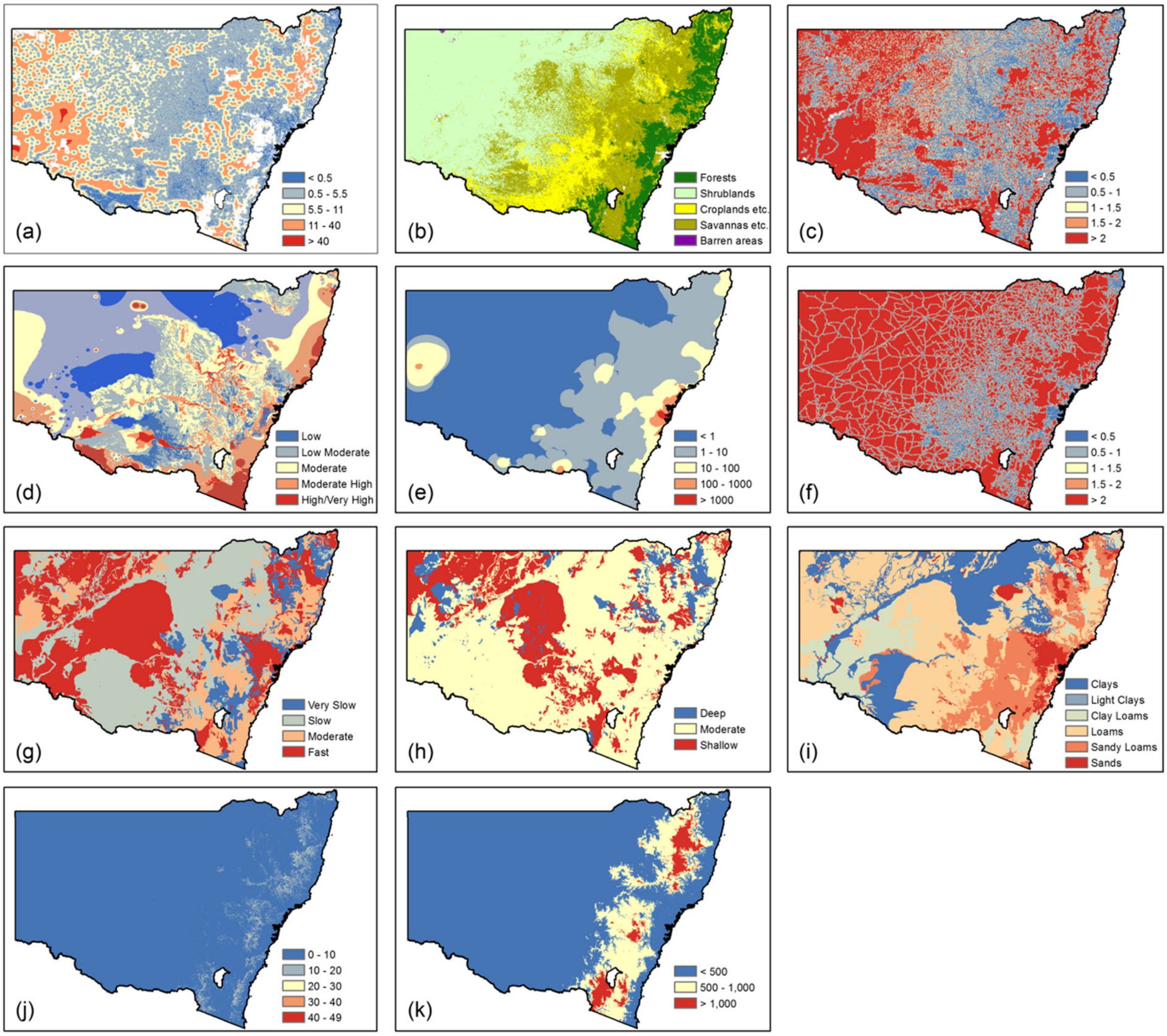


Fig. 5 Factors suitability maps for the study area: **a** proximity to residential areas, **b** land cover, **c** proximity to surface water, **d** groundwater vulnerability, **e** proximity to population hubs, **f** proximity to major roads, **g** soil permeability, **h** soil depth, **i** soil texture, **j** slope, and **k** elevation

to make five priority ranges in total (Table 2) (Wang et al. 2009, p. 2417). The resulted map of this criterion is shown in Fig. 5c.

Groundwater vulnerability

According to Protection of the Environment Operations ACT 1997 (EPA 1999), for landfill siting purposes the NSW DLWC should be consulted to determine if the area has been assessed as having high or very high vulnerability to groundwater pollution. Therefore, in this study, the important factor of groundwater is taken into consideration using the map of Groundwater Vulnerability (DLWC-LPI 2001). Accordingly, based on the vulnerability map, the study area was assessed in five ranges: High, Moderately high, Moderate, Low moderate and Low (Fig. 5d). Higher ranks are allocated to low risk areas as declared in Table 2.

Economic factors and constraints

Proximity to population hubs

Although locating landfills in most remote areas may satisfy environmental criteria, such areas could be unattractive when economic factors are considered. Locating landfills too far from waste generation sources will significantly increase transportation and operation costs (Wang et al. 2009, p. 2417). As locating landfills in densely populated areas is economic, the population density is considered as an economic factor where higher ranks are given to densely populated areas (Table 2). To do this, the weighted average of population density is calculated for every point where the weights represent the proportion of overlap between a neighboring Voronoi polygon and the areas of local government areas (LGAs) surround each point (Sibson 1981). The map is then re-classified in the five ranges as shown in Fig. 5e.

Proximity to major roads

Additional costs for constructing roads in areas remote from the available roads make the areas unsuitable in terms of economic factors (Yesilnacar and Cetin 2005, p. 383; Sener et al. 2010, p. 547). On the other hand, however, the landfill should not be too close to major roads and interfere with the current traffic (Akbari et al. 2008, p. 42; Wang et al. 2009, p. 2417). Hence, a 100-m buffer zone was applied on each side of roads and railways (Wang et al. 2009, p. 2417; Oyinloye and Fasakin 2013, p. 14) extracted from CLUM (DAWR 2015). Beyond the applied buffer was given higher priority where five grades were set to evaluate this criterion (Table 2). The finally resulted map of proximity to major roads is depicted in Fig. 5f.

Geological and geomorphological factors

Soil permeability

Leachate contamination and consequent possible ground water pollution is subjected to occur when the permeability of soil is not low enough. The waste disposal site's soil should have low permeability, not higher than 0.05 m per day (Sharifi 2004, p. 4; Moeinaddini et al. 2010, p. 914). Accordingly, the map of soil permeability for the study area sourced from soilAtlas2M (NRIC 1991) and interpreted by McKenzie and Hook (1992) is utilized where four ranges of permeability are considered to rank the study area (Fig. 5g): very slow, slow, moderate, and fast where the values of ranges are given in Table 2. As can be seen in Table 2 the priorities are allocated to the four zones in an order from the highest priority to "very slow" to the least priority for "fast."

Soil depth

Soil depth is significant to find suitable areas with enough depth to obtain soil for covering waste and to sit lift (Moeinaddini et al. 2010, p. 914). Accordingly, the map of soil depth sourced from soilAtlas2M (NRIC 1991) and interpreted by McKenzie and Hook (1992) was used to divide the study area into the three zones in terms of soil depth (shallow, moderate and deep). Prioritizing is then applied as shown in Table 2 where deep zone has received the highest priority and shallow zone ranked as the least suitable (Fig. 5h).

Soil texture

Soil texture and clay content are also emphasized to be considered for landfill siting to minimize destructive environmental threats including water resources contamination (Dörhöfer and Siebert 1998, p. 57; Sharifi 2004, p. 4). Among different soil texture groups, clay-rich soils (preferably more than 50% clay) are highly suitable for constructing landfill site (Sharifi 2004). To consider clay content of soils in the evaluating process, the map of texture grades sourced from soilAtlas2M (NRIC 1991) was utilized where the grouping base is adapted from McKenzie et al. (2000). Accordingly, the study area was divided into five zones as shown in Table 2 where higher priorities were given to more clay-rich areas (see Table A.3 in Supplementary Material). The developed map of this criterion is illustrated in Fig. 5i.

Slope

Not only a low slop land results in economizing excavation and construction costs, but also it leads to minimize erosion and water runoff (Yesilnacar and Cetin 2005, p. 381; Oyinloye and Fasakin 2013, p. 11). The slope of the study area was calculated using the 9-arcsecond Digital Elevation Model (DEM) $v3$ (GA 2008) and then divided in five ranges giving higher priorities to low slope ranges (Table 2 and Fig. 5j).

Elevation

Low altitude areas are often subject to flooding and high levels of erosion. On the other hand, however, locating landfills on a relatively high land raises establishment and operation costs such as excavation and transportation costs; and, may also constitute a groundwater recharge zone (Charnpratheep et al. 1997, p. 546; Sener et al. 2010, p. 200). Generally, the most suitable zones for landfill siting are areas with medium level of altitude surrounded by hills with no more than 20% slope (Charnpratheep et al. 1997, p. 200; Yesilnacar and Cetin 2005, p. 381; Akbari et al. 2008, p. 4).

The study area is divided into the three zones with respect to the elevation degree: high (those areas below 500 m), moderate (areas where elevation is between 500 and 1000 m) and low (areas with altitude above 1000 m) as presented in Fig. 5k. The moderate zone was given higher priority while the zone of high elevation is graded the least suitability (Table A.8 in Supplementary Material).

Results and discussion

The distinguished ranked areas

The final suitability map of the study area is developed by aggregating all factors and constraints via the overlaying technique based on the resulted factors' weights (Table 1). Scoring the alternative ranks resulted in distinguishing five ranked areas for landfill siting (ranks 1–5) from the most suitable to the least suitable.

Figure 6 represents the final map of ranked suitability for landfill siting in NSW. Proportional areas of the suggestive sites are also presented in Table 3. As can be seen, the mostly preferred areas to establish municipal solid waste landfills (ranks 1 and 2) are found in the areas of 5349.7 and 156,690.8 km^2 that account for 0.7% and 22.2% of the ranked areas. These preferred areas are primarily located in the middle part of NSW. The unsuitable areas for landfill siting (ranks 4 and 5), however, are mostly located in western and eastern mountainous areas of NSW where the land cover mostly includes forests and shrublands.

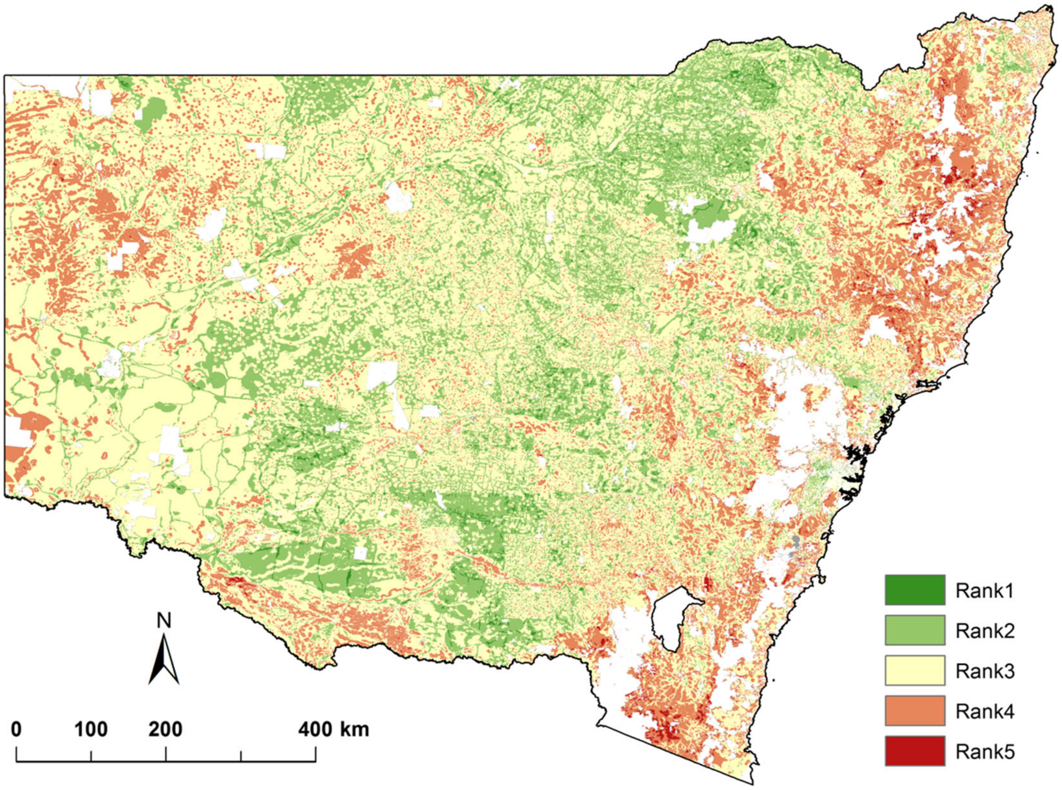


Fig. 6 Final suitability map of landfill siting in NSW

Table 3 The ranked areas for landfill siting and existing landfills in NSW

	The study results		Existing landfills	
Suitability rank	Area (km^2)	Proportional area (%)	Area (km^2)	Proportional area (%)
Rank 1	5349.7	0.7%	0.5	1.0%
Rank 2	156,690.8	22.2%	16.6	37.0%
Rank 3	417,599.0	59.0%	22.1	49.3%
Rank 4	123,243.2	17.4%	5.5	12.2%
Rank 5	4443.9	0.6%	0.2	0.5%

The existing landfills in NSW and their corresponding locations (DAWR 2015) are shown in Fig. A.2 in Supplementary Material where their corresponding locations compared with the resulted ranks are mapped to analyze the suitability of the existing landfills with respect to the study results. The comparative results imply that 1.0% and 37% of the existing landfills match in ranks 1 and 2 respectively. The results of categorizing the existing landfills into the five ranked areas are presented in Table 3.

Regional analysis

Further detailed analysis is also conducted for different regions. NSW is divided into 12 statistical divisions (SDs) where their estimated populations and areas together their proportional ratios within the state are mentioned in Table A.4 in Supplementary Material (ABS 2014). The regional analysis show Sydney and Hunter divisions have the largest areas of existing landfills which can be reasoned by the high populations of them or their adjacent divisions. The regional analysis shows that Murrumbidgee, Northern, Central West and North Western divisions have the largest proportion of suitable areas for landfill siting where more than 28% of distinguished areas are ranked as ranks 1 and 2. However, the challenge of finding highly suitable areas for landfill siting is in divisions such as Mid-North Coast, Illawarra and South Eastern, where less than 6% of their ranked areas are distinguished as ranks 1 and 2 while they count 4.4%, 6.1% and 4% of population of the state. Figure A.3 in Supplementary Material represents the areas of existing landfills (in the five ranks) and the distinguished rank 1 areas per capita for different SDs.

Scenario analysis

The finally obtained results by multi-criteria decision-making methods are highly dependent on preferences and adjusted priorities in view of decision-makers. The resulted suitability maps for solely consideration each of the main three criteria are shown in Figs. A.4, A.5, and A.6 in Supplementary Material.

The details of the ranked areas for each of the three criteria are reported in Table A.5 in Supplementary Material. The results show that the economic factors are the most challenging among the three criteria where only 0.5% of the ranked areas are distinguished as rank 1 with respect to this criterion. On the other hand, more highly suitable areas in terms of the geological and geomorphological factors could be found within the study area. Moreover, comparing the results with the existing landfills, the proportional areas of existing landfills located in rank 1 are 1.5%, 40.7% and 44.4% for socio-ecological, economic, and geological and geomorphological factors, respectively. It means higher importance of geological and geomorphological, and economic factors in view of planners for landfill siting in the study area. The results of individual analysis of the three criteria for different SDs are reported in Tables A.6, A.7, and A.8 in Supplementary Material for socio-ecological, economic, and geological and geomorphological factors respectively.

Conclusion

In the present study, DEMATEL was coupled to AHP to make an integrated decision-making method

(AHP-DEMATEL). The integrated method benefits from the strengths of the two by addressing the interrelations among the factors and providing the implementation of the hierarchy structure and pairwise comparisons. The adopted AHP-DEMATEL was used to compute appropriate ranges of weights. While prioritization of the ranks was performed by pairwise comparisons through the AHP method, smooth ranges of weights were obtained due to the DEMATEL method. This is critical because AHP tends to exaggerate weights (Yuen 2014). The integrated AHP-DEMATEL was then successfully implemented in a GIS environment.

Among the identified areas, the areas ranked 1 and 2 have the highest priorities to be selected for establishing landfills while the last two ranks are recommended be avoided for further analysis for landfill siting. The top two ranks are identified as the most suitable and preferably suitable areas for landfill siting with the areas of 5349.7 and 156,690.8 km^2 respectively. These areas take 0.7% and 22% of the study area, respectively, and are mostly located in the middle part of NSW where land is mostly covered by forests and shrub lands. Regional analysis was also conducted for different SDs, which shows that Murrumbidgee, Northern, Central West and North Western have the largest proportion of highly ranked areas for landfill siting while the most of existing landfills (53% of the total area) are located in Sydney and Hunter.

The scenario analysis implies that geological and geo-morphological factors and economic factors are highly important for the planners when the existing landfills match with the ranked areas. Overall, the present study utilized an efficient site selection methodology reaching to a supportive structure for municipal solid waste landfill siting especially for those authorities and decision-makers.

Appendix 1. The framework of the proposed AHP-DEMATEL

Phase 1: Developing the hierarchical structure

The hierarchical structure is a graphic presentation of a complex problem where the top involves the overall goal and the other levels and sub-levels include criteria, sub-criteria and alternatives (Saaty 1980; Dyer and Forman 1991; Çimren et al. 2007).

Phase 2: Evaluating the factors and allocating the weights

To provide analysis of the identified factors and address the interrelations among them, DEMATEL is implemented by the following steps based on Tzeng et al. (2007) and Wu (2008):

- Step 1: Gathering experts' opinions and computing the average matrix Z Each expert was asked to evaluate the degree of direct influence between any two factors by an integer score ranging from 0 (no influence), 1 (low influence), 2 (medium influence) and 3 (high influence). The level of influence to which the respondent believes factor i affects factor j is denoted as x_{ij}. The diagonal elements ($i = j$) are set to zero. For each respondent, a $n \times n$ non-negative matrix is constructed as $X^k = [x_{ij}^k]$, where k is the number of respondents participated in the evaluation process ($1 \ll k \ll H$) and n denotes the number of factors. Accordingly, $X^1, X^2, \ldots, X^H$ are matrices gathered from H respondents. To aggregate and conclude all opinions from H respondents, first it is assumed in this study that if more than a half of respondents allocate zero to one relation, the independency of the relation is proven. Then, for the rest of relations the average matrix $Z = [z_{ij}]$ is established by using Eq. A1.1 as below:

$$z_{ij} = \frac{\sum_{k=1}^{H} x_{ij}^k}{H} \tag{A1.1}$$

- Step 2: Computing the normalized initial direct-relation matrix D The normalized initial direct-relation matrix $D = [d_{ij}]$ where $0 \ll d_{ij} \ll 1$ is calculated by Eq. A1.2 as below :

$$D = Z \times S \tag{A1.2}$$

  where S value can be obtained from Eq. A1.3 as below:

$$S = \frac{1}{\mathrm{Max}_{1 \ll i \ll n} \sum_{j=1}^{n} z_i} \tag{A1.3}$$

- Step 3: Deriving the total relation matrix T
  The total relation (influence) matrix $T = [t_{ij}]$ is obtained as $T = D(I - D)^{-1}$ where I is a $n \times n$ identity matrix. Let r and c be $n \times 1$ and $1 \times n$ vectors representing the sum of rows and sum of columns of matrix T respectively. Let r_i

denotes the sum of ith row in matrix T, then r_i summarizes both direct and indirect effects given by factor i to the other factors. Suppose that c_j is the sum of jth column in matrix T, then c_j represents both direct and indirect affects by factor j. If $j = i$, the sum $(r_i + c_i)$ shows the total effects given and received by factor i. Therefore, $(r_i + c_i)$ is a representing measure for the degree of importance that factor i plays in the entire system. In contrast, the value of $(r_i - c_i)$ indicates the net effect that factor i contribute to the system. In addition, when $(r_i - c_i)$ is positive, factor i is a net cause, and factor i is a net receiver if $(r_i - c_i)$ is negative (Liou et al. 2007; Yang et al. 2008).

In this study, the normalized values of $(r_i + c_i)$ are utilized to represent the weights of the factors in Eq. A1.4 as below:

$$W_i = \frac{(r_i + c_i)}{\sum_{i=1}^{n}(r_i + c_i)} \tag{A1.4}$$

where W_i represents the weight of ith factor, n is the total number of the factors.

- Step 4: Setting a threshold value (α) The threshold value (α) in this study is computed by the average of elements in matrix T. This value aimed to filter out some negligible effects (Yang et al. 2008).
- Step 5: Depicting causal diagram

  The causal diagraph is acquired by mapping the dataset of $(r + c, r - c)$ to visualize interrelationships among the factors and provide information to judge which factors are the most influential (important) and how influence affected the factors (Shieh et al. 2010; Sumrit and Anuntavoranich 2013).

Phase 3: Prioritizing and scoring the alternative ranks

In the present study, five alternative levels are considered for each factor which represents the suitability from the highest level (rank 1) to the lowest level (rank 5). Scoring the alternatives (factor levels) is performed via the AHP framework. Here, pairwise comparisons were performed based on the most relevant studies (Kontos et al. 2003; Yalcin 2008; Wang et al. 2009) and considering the characteristics of the study area for all factor levels to identify the relative importance and score of the factor levels.

To compute the weights of the alternatives, each element in pairwise comparison matrix (a_{ij}) is divided by summation of its corresponding column to generate the normalized matrix (Eq. A1.5). Then, the arithmetic mean of elements of each row (w_i) of the normalized matrix is calculated as the weight of each alternative (Eq. A1.6).

$$r_{ij} = \frac{a_{ij}}{\sum_{i=1}^{m} a_{ij}} \tag{A1.5}$$

$$w_i = \frac{\sum_{i=1}^{n} r_{ij}}{n} \tag{A1.6}$$

where m and n denote the number of columns and rows in the pairwise comparison matrix; a_{ij} and r_{ij} show the elements in pairwise comparison and normalized matrices respectively and w_i denotes the importance weight of the ith alternative (factor level).

Phase 4: Evaluating validity of pairwise comparisons

To evaluate the goodness of performed judgments in pairwise comparisons, the incompatibility degree is calculated and assessed. To compute the Incompatibility Index $(I.I)$, first the pairwise comparison matrix (A) is multiplied by the Weight vector (w) to establish an applicable approximation of $\lambda_{\max}$ where $\lambda_{\max}$ denotes the biggest eigenvalue which can be obtained once we have its associated eigenvector. Then, incompatibility index is calculated by Eq. A1.7 where n is the number of columns of matrix A.

$$I.R = \frac{\lambda_{\max} - n}{n - 1} \tag{A1.7}$$

Further, Incompatibility Ratio (I.R) is calculated using Eq. A1.8 as follows:

$$I.R = \frac{I.I}{I.I.R} \tag{A1.8}$$

where $I.I.R$ is the random index extracted from Saaty (1980). The incompatibility ratio for values lower than 0.10 $(I.R < 0.10)$ indicates a reasonable level of consistency for pairwise comparisons. Greater values for this ratio $(I.R \geq 0.10)$ represent inconsistent judgements implying that the decision-maker should reconsider judgements in pairwise comparisons (Boroushaki and Malczewski 2008).

Phase 5: Final ranking the alternatives

The final scores of the alternatives are determined at this step by incorporation of the interrelated factors (Eq. A1.9).

$$S_j = \sum_{i=1}^{n} W_i \times w_{ij} \tag{A1.9}$$

where S_j is the final score of jth alternative, W_i is the weight of ith factor and w_{ij} is the weight of jth alternative for ith factor.

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