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Combining GIS with fuzzy multicriteria decision-making for landfill siting in a fast-growing urban region

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Abstract

Landfill siting is a difficult, complex, tedious, and protracted process requiring evaluation of many different criteria. This paper presents a fuzzy multicriteria decision analysis alongside with a geospatial analysis for the selection of landfill sites. It employs a two-stage analysis synergistically to form a spatial decision support system (SDSS) for waste management in a fast-growing urban region, south Texas. The first-stage analysis makes use of the thematic maps in Geographical information system (GIS) in conjunction with environmental, biophysical, ecological, and socioeconomic variables leading to support the second-stage analysis using the fuzzy multicriteria decision-making (FMCDM) as a tool. It differs from the conventional methods of integrating GIS with MCDM for landfill selection because the approach follows two sequential steps rather than a full-integrated scheme. The case study was made for the city of Harlingen in south Texas, which is rapidly evolving into a large urban area due to its vantage position near the US–Mexico borderlands. The purpose of GIS was to perform an initial screening process to eliminate unsuitable land followed by utilization of FMCDM method to identify the most suitable site using the information provided by the regional experts with reference to five chosen criteria. Research findings show that the proposed SDSS may aid in recognizing the pros and cons of potential areas for the localization of landfill sites in any study region. Based on initial GIS screening and final FMCDM assessment, "site 1" was selected as the most suitable site for the new landfill in the suburban area of the City of Harlingen. Sensitivity analysis was performed using Monte Carlo simulation where the decision weights associated with all criteria were varied to investigate their relative impacts on the rank ordering of the potential sites in the second stage. Despite variations of the decision weights within a range of 20%, it shows that "site 1" remains its comparative advantage in the final site selection process.

Keywords: Fuzzy MCDM; Geographic information systems; Decision support system; Landfill siting; Solid waste management

1. Introduction

New approaches to the sustainable planning, design, and management of urban regions will depend upon improvements in our knowledge of the causes, chronology, and impacts of the urbanization process and their driving forces (Klostermann, 1999; Longley et al., 2001). Worsening conditions of crowding, housing shortages, insufficient or obsolete infrastructure, increasing urban climatological and ecological problems, and the issues of urban security underline a greater than ever need for effective management and planning of urban regions (O'Meara, 1999). Innovative approaches to urban land use planning and management, such as sustainable development and smart growth, have been proposed and widely discussed (American Planning Association, 2002; Kaiser et al., 1995). Landfill selection in an urban area is a critical issue in the urban planning process because of its enormous impact on the economy, ecology, and the environmental health of the region. Landfill site selection can generally be divided into two main steps: the identification of potential sites through preliminary screening, and the evaluation of their suitability based on environmental impact assessment,

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Nomenclature

S_{itj}	average fuzzy appropriateness index rating of alternative
W_t	average importance weight of criterion
$q_{itj}, o_{itj}, p_{itj}, c_{tj}, a_{tj}, b_{tj}$	triangular fuzzy numbers
$\oplus$ and $\otimes$	fuzzy addition and fuzzy multiplication operator
F_i	fuzzy appropriate indices of m alternatives
$U_M(F_i)$	optimistic utility for each appropriate index F_i
$U_G(F_i)$	pessimistic utility for each appropriate index F_i
R	total index of rating attitude
Y	the index of rating attitude of an individual decision maker
m	total number of alternatives
k	total number of criteria
n	total number of decision makers
α	index of rating attitude
L	candidate sites for landfill
E	experts
C	criteria

economic feasibility, and engineering design, and cost comparison (Charnpratheep et al., 1997). As a consequence, landfill siting is a difficult, complex, tedious, and protracted process (Allanach, 1992). Many siting factors and criteria should be carefully organized and analyzed. An initially chosen candidate site may be later abandoned because opposition arises due to previously neglected but important factors. Such a delay increases costs and postpones the final decision of a landfill site. The "not in my backyard" (NIMBY) and "not in anyone's backyard" (NIABY) phenomena is becoming popular nowadays creating a tremendous pressure on the decision makers involved in the selection of a landfill site. Other issues related to the availability of land, public acceptance, increasing amounts of waste generation complicate the process of selection of a suitable site for landfill. An inappropriate waste facility may adversely affect the surrounding environment and other economic and socio-cultural aspects.

Criteria and methodologies used for the initial screening are so pragmatic that areas are excluded as matters of social and environmental significance without removing large numbers of technically advantageous sites from consideration. The criteria used for preliminary screening are primarily to examine the proximity of potential sites with respect to geographic objects that may be affected by the landfill siting (e.g., groundwater wells) or that may affect landfill operations (e.g., areas with steep slopes). Methodologies used are normally based on a composite suitability analysis using thematic map overlays (O'Leary et al., 1986) and their extension to include statistical analysis (Anderson and Greenberg, 1982). With the development of geographical information systems (GIS), the landfill siting process is increasingly based on more sophisticated spatial analysis and modeling. Jensen and Christensen (1986) demonstrated the use of a raster-based GIS with its associated Boolean logic map algebra to identify potential waste sites based on suitability of topography and proximity with respect to key geographic features, while Keir et al. (1993) discussed the use of both raster-based and vector-based GIS for the full-scale site selection process. Sener et al. (2006) integrated GIS and multicriteria decision analysis (MCDA) to solve the landfill site selection problem and developed a ranking of the potential landfill areas based on a variety of criteria. The utilization of GIS for a preliminary screening is normally carried out by classifying an individual map, based on selected criteria, into exactly defined classes or by creating buffer zones around geographic features to be protected. All map layers are then intersected so that the resulting composite map contains two distinct areas. For example, if screening criteria involve the provision of a protective buffer around certain types of spatial objects, the area outside the intersected boundary is considered suitable and that inside is unsuitable. The two distinct classes separated by a sharp boundary reflect the representation of, and GIS operations on, geo-referenced data based on a binary true or false Boolean logic. With the aid of this functionality, GIS have been used in order to facilitate and lower the cost of the process of selection of sites for building sanitary landfills in the last few years (Siddiqui et al., 1996; Kao et al., 1997).

Advanced algorithms, however, may further help justify the uncertainty in siting new landfills. Several approaches were proposed for multicriteria decision-making (MCDM) and the relevant methods were developed and applied with more or less success depending on the specific problem. In the past, analytic hierarchy process (AHP) introduced by Saaty (1980), was one of the useful methodologies, which plays an important role in selecting alternatives (Fanti et al., 1998; Labib et al., 1998; Chan et al., 2000). AHP is an analytical tool enables people to explicitly rank tangible and intangible criteria against each other for the purpose of selecting priorities. The process involves structuring a problem from a primary objective to secondary levels of criteria and alternatives. Once the hierarchy has been established, a pair-wise comparison matrix of each element within each level is constructed. The AHP allows group decision-making, where group members can use their experience, values and knowledge to break down a problem into a hierarchy and solve it by the AHP steps. Participants can weigh each element against each other within each level, each level is related to the levels above and below it, and the entire scheme is tied together mathematically. For evaluating the numerous criteria, AHP has become one of the most widely used methods for the practical solution of MCDM problems (Cheng, 1997; Akash et al., 1999; Chan et al., 2000). The main difficulty arises in the estimation of the required input data that express qualitative observations and preferences. The AHP is mainly used in nearly crisp decision applications. It does not take into account the uncertainty associated with the mapping of people's judgment to an evaluation scale (Chen, 1996; Hauser and Tadikamalla, 1996; Cheng, 1997). In order to overcome the shortcomings of the AHP, fuzzy set principle is used to integrate AHP to determine the best alternative (Chen, 1996; Hauser and Tadikamalla, 1996; Levary and Ke, 1998).

Fuzzy set theory was developed and extensively applied in previous decade (Zadeh, 1965). It was designed to supplement the interpretation of linguistic or measured uncertainties for real-world uncertain phenomena. These uncertainties could originate with non-statistical characteristics in nature that refer to the absence of sharp boundaries in information. However, the main source of uncertainties involving in a large-scale complex decision-making process may be properly described via fuzzy membership functions. The practical applications of fuzzy multicriteria decision-making (FMCDM) reported in the literature have shown advantages in handling unquantifiable/qualitative criteria and obtained quite reliable results (Altrock and Krause, 1994; Teng and Tzeng, 1996; Baas and Kwakernaak, 1997; Mcintyre and Parfitt, 1998; Tang et al., 1999). Fuzzy linguistic models permit the translation of verbal expressions into numerical ones, thereby dealing quantitatively with imprecision in the expression of the importance of each criterion. FMCDM utilizes linguistic variables and fuzzy numbers to aggregate the decision makers' subjective assessment about criteria weightings and appropriateness of alternative candidate sites versus selection criteria to obtain the final scores—fuzzy appropriateness indices.

Extended application can be found in developing a decision support system (DSS) (Kuo et al., 2002). The proposed DSS consists of four components: (1) hierarchical structure development for fuzzy AHP, (2) weights determination, (3) data collection, and (4) decision-making (Kuo et al., 2002). Therefore, the integration of fuzzy set and AHP gives a much better and more exact representation of relationship between criteria and alternatives (Lee et al., 1998; Chiadamrong, 1999; Yu and Skibniewski, 1999; Choi and Oh, 2000; Karsak and Tolga, 2001). FMCDM methods have been used in environmental planning and decision-making processes in order to clarify the planning process, to avoid various distortions, and to manage all the information, criteria, uncertainties, and importance of the criteria. This paper presents an integrated approach to construct a spatial decision support system (SDSS) for the selection of landfill sites via a two-stage analysis synergistically. The first-stage analysis makes use of the thematic maps in GIS in conjunction with environmental, biophysical, ecological, and socioeconomic variables leading to support the second-stage analysis using FMCDM as a tool. In essence, in the first stage, the geographical data were analyzed using GIS and a data matrix was created that combines the environmental, transportation, public health, social, and economic criteria for the selection of seven-candidate sites. It eventually generates the ranking of all seven-candidate sites in a preferential order based on different criteria involved collectively in a FMCDM analysis. The case study was made for the city of Harlingen in south Texas, which is rapidly evolving into a large urban area due to its vantage position near the US–Mexico borderlands.

2. Background and study site

The Lower Rio Grande Valley (LRGV or Valley), comprised of Cameron, Willacy, Hidalgo, and Starr counties, is located at the southernmost tip of Texas along the US–Mexico border. The Office of Management and Budget (OMB) ranks Metropolitan statistical area (MSA) according to their population and economic growth. Cameron County, at the tip of Texas, comprises 3266 km^2 (1276 square miles) and includes the 28th MSA, Brownsville-Harlingen-San Benito. Hidalgo County, the largest of the three LRGV counties, covers the western half of the region with an area of 3963 km^2 (1548 square miles). This county is mostly urbanized, containing the McAllen-Edinburg-Mission MSA, the 4th fastest growing areas in Texas. Both of the LRGV's MSAs are experiencing a developmental change due to their strategic location and economic ties with the US–Mexico borderland. The North American Free Trade Agreement (NAFTA) that was enacted in 1994 has increased trade throughout America. The Valley, with a total area of 9216 km^2 (3600 square miles), has emerged as a warehouse and transportation center between Central America and the US (TSHA, 2003). The increasing number of maquiladoras, or twin plants, having manufacturing industries both in the MSAs of the Valley and in nearby Reynosa and Matamoros, Mexico, are positively influencing the economic development in the region. This has been a catalyst for further growth in other Valley cities located in between these two MSAs. As a result, the population of the LRGV is growing at a tremendous pace and yard waste, food waste, and biosolids waste production is increasing over time. Fig. 1 indicates the study area along with the waste disposal sites. The area's population has increased by 39.8% in the last 10 year due to the NAFTA's economic impact. It is expected to continue growing at an estimated rate of 4% per year in the coming years. The population is projected to be over 1.7 million people in 2022 (LRGVDC, 2002).

Solid waste management (SWM) is at the forefront of environmental concerns in the LRGV, South Texas. The complexity in SWM drives area decision makers to look for innovative and forward-looking solutions to address various waste management options. The LRGV is facing the difficult reality of siting new landfills due to their large capital costs and local protests, like those seen as a result of

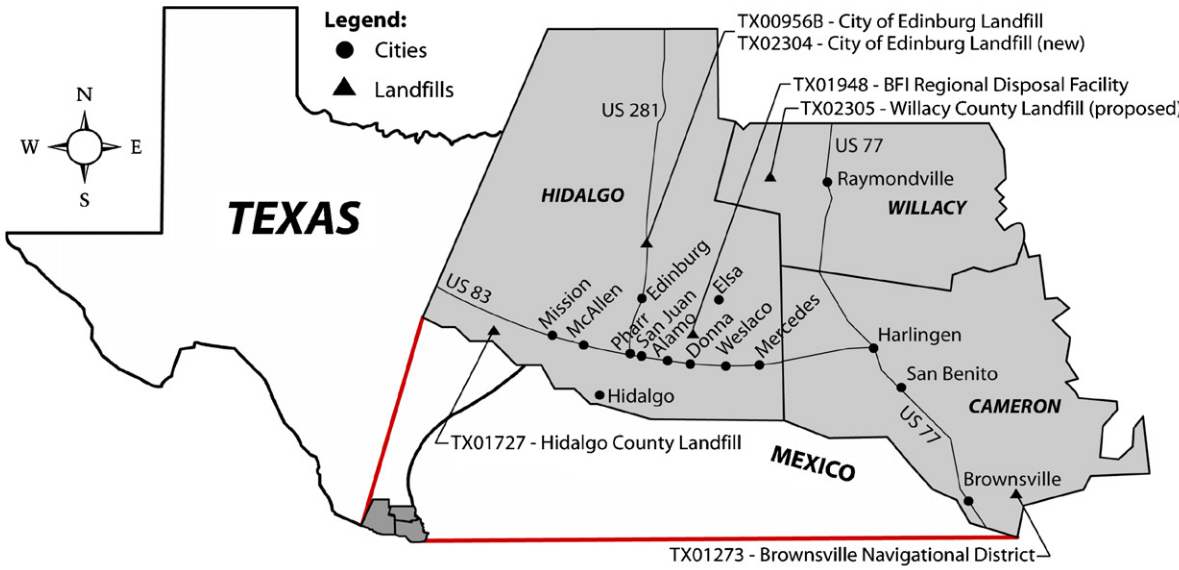

Fig. 1. Map of South Texas indicating the facility location of the study area.

Willacy County's intentions to site a new landfill. The hotly contested landfill permit process culminated in a hearing August 1, 2005 with the decision pending whether to allow the process to continue amid community resistance (Del Valle, 2005). Adding to the complexity of the issue, the realization by local residents of the economic value of their ecosystem from tourism dollars generated from bird watching enthusiasts means siting future landfills could become more contested.

The ability to give planners more options will allow for compromise surrounding potential disposal alternatives. Privately owned landfills have been viewed in a negative light as of late due to litigation against (Browning-Ferris Industries) BFI that has essentially jeopardized its long-term ability to operate and that closed the C&T landfill (Pierson, 2004). These underpinnings place an emphasis on giving regional planning partners like the council of government "Lower Rio Grande Development Council" as many possible alternatives to consider in their planning. The political and environmental climate surrounding SWM in the LRGV lends itself to analysis that embraces uncertainty in as many possible decision making levels as possible. In order to better inform area decision makers about their options to cope with the mounting municipal solid waste (MSW) generation and a general lack of landfill space, a SDSS needs to be developed to address regional planning around issues of waste routing and the hotly contested SWM facility site selection. The study location (Harlingen) is one of the fastest growing cities in the LRGV. Presently the city generates huge amount of solid waste that is disposed off at B.F.I. Landfill in Donna at high cost per ton, which is expected to increase in the next 7 year of period of contract. The transportation cost of ton of solid waste is also high. Due to these huge costs of waste disposal, the city has plans on starting its own landfill.

Development of a landfill in Harlingen can possibly cause environmental impacts on the soil, groundwater, surface water, regional air quality, atmosphere, biodiversity, and landscape. Besides these environmental impacts, there are those related to the economy, employment, attainability and valuation of different areas, services, safety, and health. A landfill in this region can also affect many of the endangered and threatened species that occur at their northernmost limit in the LRGV. In light of such circumstances, there is acute necessity for a careful selection of a landfill site in order to preserve the ecological and environmental quality that's unique to the LRGV.

3. Case study

Landfill siting is a complicated process requiring a detailed assessment over a vast area to identify suitable location for constructing a landfill subject to many different criteria. GIS offers the spatial analysis capabilities to quickly eliminate parcels of land unsuitable for landfill site. This study employed GIS to perform a screening process that led to identification of a couple suitable candidate sites based on given criteria. The suitability criteria are defined with the focus to minimize any potential health risks from direct or indirect contamination due to the proximity of a landfill site with respect to key geographic features. Thus, the first-stage analysis using GIS is essential for the initial identification of a couple suitable landfill sites prior to undertaking further analyses or field investigations. Although, the initial screening is based on criteria related to environmental and ecological factors involved in the site selection process, there are certain criteria, such as impact on historical markers, public comfort, and economic factors for which data are not always readily available, which cannot be included in the first stage. A second-stage analysis based on a handful of suitable sites from the initial GIS screening was performed with the objective of including the opinions of domain experts in the region through a FMCDM approach. FMCDM was useful in addressing the issue of lack of availability of data for certain important criteria as well as to incorporate human judgment into the selection process that can prove useful in solving political debates in the future. The second-stage analysis using FMCDM was applied to rank the proposed candidate sites and summarize the final selection. Such method followed in the process of identifying the most suitable landfill site is described in the next two sub-sections. To ease the illustration, the following sub-sections would delineate or review the methods briefly and then come up with the results and discussions directly. The list of variables and parameters that were used in the FMCDM analysis is summarized in Nomenclature.

3.1. Data collection and analysis

GIS data sets of land-use, rivers, wetlands, roads, demography, wildlife parks, airports, soil types, groundwater wells, and digital elevation models (DEMs) were collected for the Cameron, Hidalgo and Willacy counties from different sources, such as Texas Natural Resources Information Systems (TNRIS), Texas Department of Transportation, US Geological Survey (USGS), and US Environmental Protection Agency (USEPA). They were summarized as shown in Table 1. Geographical features required fir the first-stage analysis could be extracted by using ArcGIS® software. For example, to obtain GIS data sets of buffer zone, the land in the LRGV was classified by creating buffer zones around geographic features to be protected using literature values widely used in landfill selection process. The buffer maps were then converted into raster maps of uniform grid sizes and the raster calculator available in spatial analyst tool in ArcGIS® was utilized to eliminate unsuitable land parcels based on the different criteria leading to identification of seven potential landfill sites in the first stage.

Table 1
GIS map layers used in the study

Data	Scale	Data source
Rivers	1:500 000	EPA
Lakes	1:250 000	EPA
Wetland	1:250 000	EPA
Land use/land cover	1:250 000	EPA
Roads	1:100 000	EPA
Ground water wells		TWDB (Texas Water Development Board)
Urban areas	1:24 000	EPA
Soil map STATSGO	1:250 000	USGS
Digital elevation model	1:250 000	EPA basins
County census data	1:2 000 000	Tiger data

3.2. Application of GIS in landfill candidate site selection

Fig. 2 illustrates the typical procedure applying the GIS for initial landfill siting. The landfill site selection process was completed in two stages with the first stage utilizing GIS to identify a few candidate sites that were later ranked using FMCDM method in the second stage. There are several different criteria involved in the selection of a landfill site in the first stage. Literature review was conducted to identify the most important criteria. According to Dikshit et al. (2000), a landfill site must be situated at a fair distance away from biophysical elements such as water, wetlands, critical habitats, and wells to reduce the risk of contamination from landfill. Different studies used different buffer distances from stream and rivers based on the size of the watershed, such as buffer of 0.8 km (Siddiqui et al., 1996), 180 m (Zeiss and Lefsrud, 1995) and 2–3 km (Lin and Kao, 1999). Considering the size of Harlingen city, a buffer distance of 1 k was used for river system in this study.

Proximity of a landfill to a groundwater well is an important environmental criterion in the landfill site selection so that wells may be protected from the runoff and leaching of the landfill. For this study, groundwater wells data were obtained from Texas Water Development Board (TWDB), and a buffer distance of 50 m from the wells was used to prevent contamination from landfill due to leaching of pollutants. Slope is also an important factor when siting a landfill since higher slopes would increase runoff of pollutants from the landfill, and thereby increasing the contamination zone area (Lin and Kao, 1999). Lin and Kao's (1999) study suggested that a slope less than 12% would be suitable for the prevention of contaminant runoff. Based on this study, regions with slope greater than 12% were defined as unsuitable for a landfill site. DEM data sets with 30 M resolution obtained from USEPA basins data source were used to calculate the slope percentage area wide. In addition, the landfill should be situated at a significant distance away from urban residential areas due to public concerns, such as aesthetics, odor (Tagaris et al., 2003), noise, decrease in property value (Zeiss and Lefsrud, 1995), and health concerns, which may avoid contamination of freshwater aquifers through leaching (Nagar and Mizra, 2002). Urban buffers may range from 150 m (Lin and Kao, 1999) to 5 km (Zeiss and Lefsrud, 1995). A buffer distance of 3 km was chosen for the study area.

Economic considerations include finding the most cost effective route for transporting wastes and locating the most suitable land for the candidate sites based on land value (Siddiqui et al., 1996). Developments on or too close to existing road and rail networks would hinder transportation and may have an impact on tourism in the region (Zeiss and Lefsrud, 1995). Baban and Flannagan (1998) used a 50-m buffer for roads, while Dikshit et al. (2000) used a 1-km buffer in his study. However, a study done by Lin and Kao (1999) stated that a 1 km buffer was too far

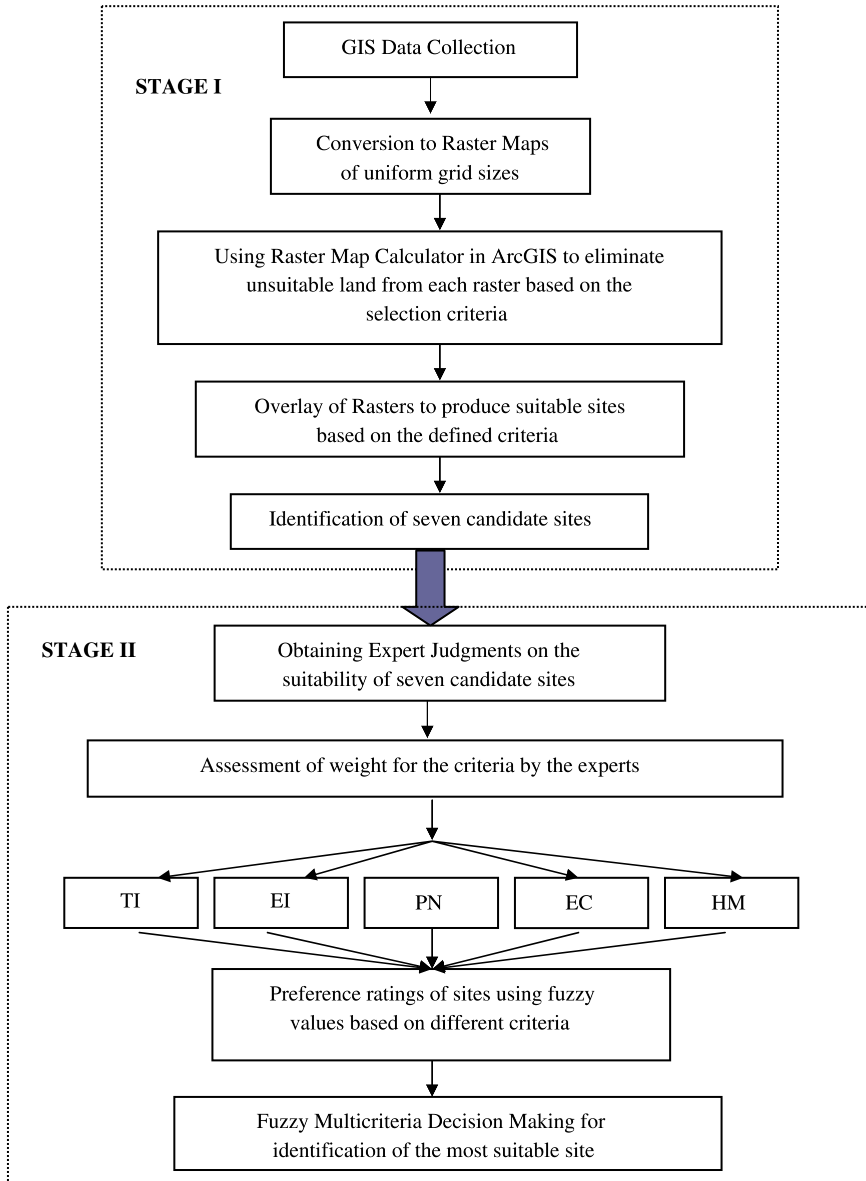

Fig. 2. Flowchart of the methodology. *Note*: EI = environmental and ecological impact, TI = transportation issues, PN = public nuisance, EC = economical Impact, HM = impact on historical markers.

from roadways, and would result in incurring more economic costs to the project over the long term by constructing new roads. Considering the huge cost of transportation, a 75-m buffer for roads was finally selected for this study.

The different constraint maps developed in this study include an environmental constraint map, a stream constraint map, a wells constraint map, a slope constraint map, an urban constraint map, a water body constraint map, and a transportation constraint map. The obtained constrained map layers are overlaid as shown in Fig. 3, and final constraint maps were developed with the candidate sites, as shown in Fig. 4. Fig. 5 shows the seven-candidate sites in GIS, which are subject to advanced assessment in the second-stage analysis.

Besides, ecological assessment study states that the region is divided into several ecoregions based on topographic, climatic and edaphic factors, and plant community similarities. These ecoregions are characterized by high summer temperatures, high evaporation rates, and periodic droughts. The seven-candidate sites are currently in use as agricultural cropland and have been cleared of native vegetation. Soils have a direct effect on the types of vegetation and ultimately the animal species that will occur in an area. The US Department of Agriculture (1977 and 1982) rated the potential for soil types throughout Cameron and Willacy counties to provide elements of habitat for various species of wildlife. The soils are also rated on their potential for wildlife species to occur. Based on the criteria of the US Department of Agriculture (1977,

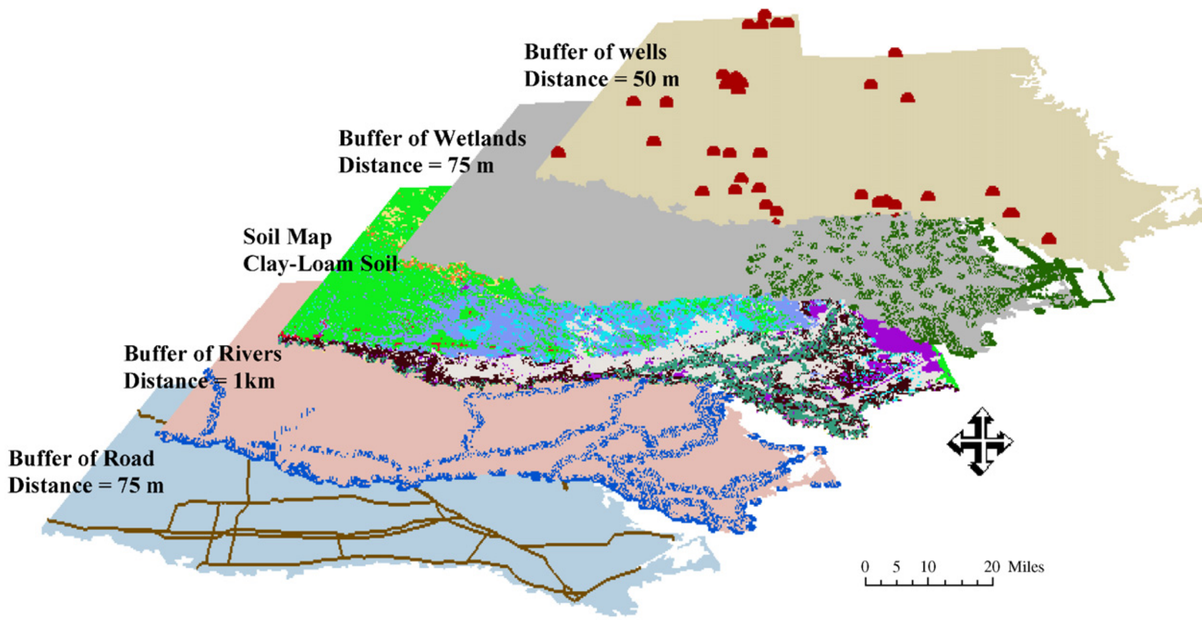

Fig. 3. Overlay of different constrained maps.

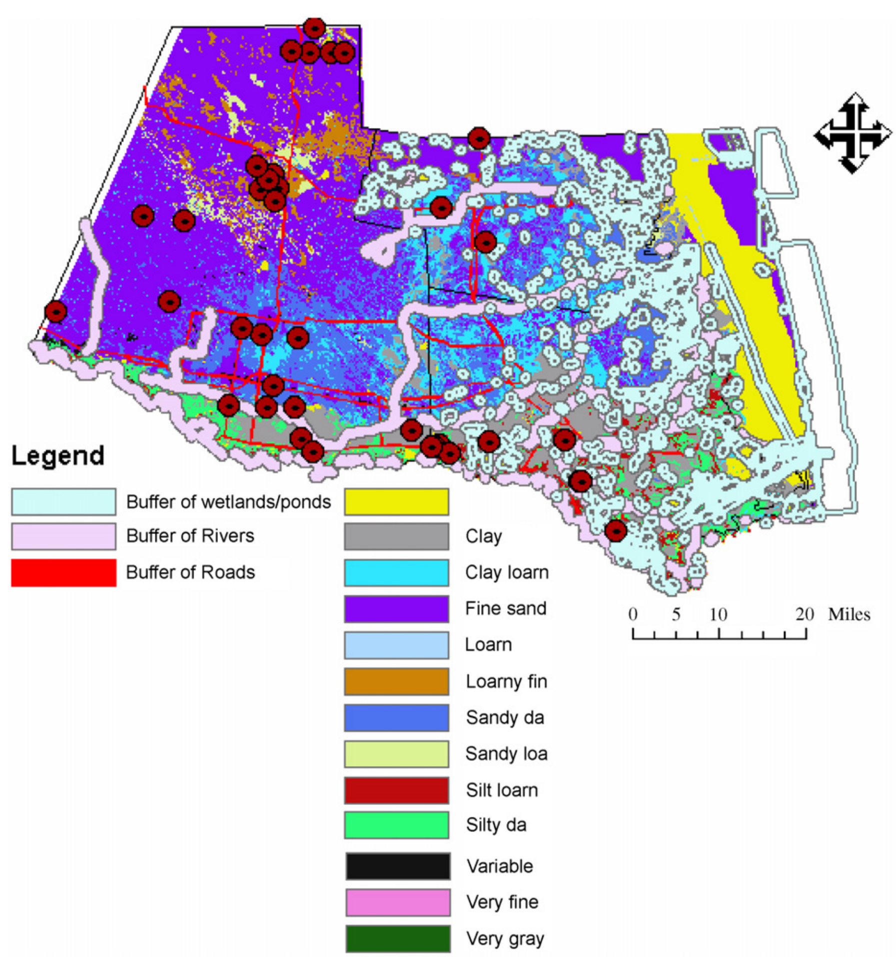

Fig. 4. Final map showing different constrained maps.

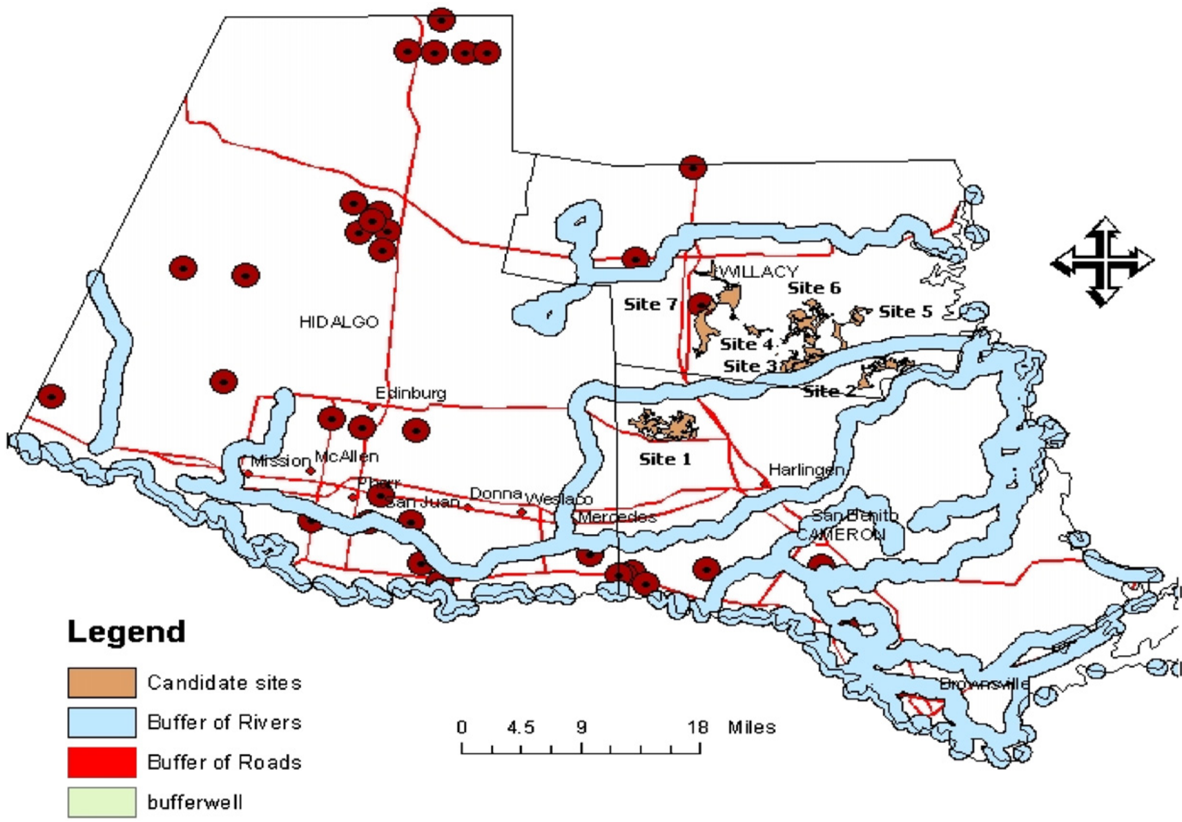

Fig. 5. Map showing the candidate sites for landfill with different constraints.

Table 2
Comparison of seven-candidate sites using potential for elements of wildlife habitat

	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	
Soil type[a]	1	1	1	1	1	1	1	2
Coverage %	95	99	99	100	100	100	79	17
Grains	Good	Good	Good	Good	Good	Good	Good	Fair
Grasses	Good	Good	Good	Good	Good	Good	Good	Fair
Herbaceous plants	Fair	Fair	Fair	Fair	Fair	Fair	Fair	Fair
Shrubs	Good	Good	Good	Good	Good	Good	Good	Fair
Wetland plants	Poor	Poor	Poor	Poor	Poor	Poor	Poor	Good
Shallow wetlands	Very poor	Very poor	Very poor	Very poor	Very poor	Very poor	Very poor	Good

[a] 1—Raymondville clay loam, 2—Mercedes clay.

1982), a rating of good indicates that the kind of habitat is easily established and maintained. A rating of fair indicates that the kind of habitat can be established with moderately intensive management. A poor rating indicates that the habitat type can be established, but with intensive and difficult management. A very poor rating indicates that creating or maintaining the habitat type is impractical or impossible.

The terrain in south Texas is quite flat and all candidate sites are managed as agricultural land at present except site 7. Future landfill to be built in this area should be designed as a plain-type rather than a gully-type landfill so that soil thickness was not an obvious issue on site. Thus, the proposed criteria did not include soil thickness and depth to bedrock, which may hamper the excavatibility of the site in some cases.

The potential for elements of wildlife habitat to occur and their ratings are compared across the seven-candidate sites in Table 2. Table 3 lists and compares the potential for types of wildlife species to occur in the seven-candidate sites. Based on the ecological assessment study, all candidate sites are similar in soil type and similar in the potential for wildlife habitat and wildlife species. Because of the similarity between all sites, the potential effects on endangered and threatened species are the same for all candidate sites. Candidate sites 1–6 would result in the same ecological effect of any actions. Candidate site seven is slightly different than the other six sites because an

Table 3
Comparison of potential types of wildlife species occur in the seven-candidate sites

	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	
Soil type[a]	1	1	1	1	1	1	1	2
Coverage %	95	99	99	100	100	100	79	17
Rangeland Wildlife	Fair	Fair	Fair	Fair	Fair	Fair	Fair	Fair
Open land Wildlife	Good	Good	Good	Good	Good	Good	Good	Fair
Wetland Wildlife	Very poor	Very poor	Very poor	Very poor	Very poor	Very poor	Very poor	Good

[a] 1—Raymondville clay loam, 2—Mercedes clay.

additional soil type occurs there. This soil type is better suited for the potential occurrence of wetland habitat and wetland wildlife species than the predominant soil type found in the other candidate sites. It is commonly known that wetlands are an important component of the ecosystem and are diminishing across the country. Therefore, candidate site seven would be the most ecologically sensitive site by any action because of the potential impact on wetland habitat.

3.3. Fuzzy multicriteria decision-making

The second-stage analysis for landfill site selection requires having a careful evaluation of the advantages and disadvantages of different candidate sites with respect to different predetermined criteria because landfill siting is a complicated process that leads to different impacts in the area. Due to lack of crisp data, the evaluation of different alternatives against different criteria requires assessment using fuzzy numbers. FMCDM method is therefore chosen for ranking different landfill sites for Harlingen city based on decisions given by a group of experts. Experts or planners were called on for participating in a questionnaire survey using linguistic variables or fuzzy numbers to give the preference ratings for each individual candidate sites.

Chang and Chen (1994) proposed a new MCDM method to solve the distribution center location selection problem under fuzzy environment. The ratings of each alternative and the weight of criterion are described by linguistics variables that can be expressed in triangular fuzzy numbers. The evaluation value of each facility site is also expressed in a triangular fuzzy number. By calculating the difference of evaluation value between each pair of candidate sites, a fuzzy preference relation matrix is constructed to represent the intensity of the preferences of one plant location over another. Then, a stepwise ranking procedure is proposed to determine the ranking order of all candidate locations. When conducting the inference, triangular fuzzy numbers (TFN) are commonly used by the experts to describe vagueness and ambiguity in the real-world system. Many methods, such as max, min, median, addition, multiplication, and mixed operators, are available to aggregate TFNs. Related literature can be found in (Kaufmann and Gupta, 1988; Paek et al., 1992).

The experts can employ an assumed weighting set $W = \{$Very poor, Poor, Fair, Good, and Very good$\}$ to evaluate the appropriateness of the alternatives versus various criteria. The membership functions of the linguistic values in the weighting set W represented by the approximate reasoning of triangular fuzzy numbers are shown in Fig. 6. If one does not agree with the assumed preference rating system, one can give his own rating by using the triangular fuzzy number, showing perception of the linguistic variables, 'importance' and 'appropriateness'.

The different criteria that were selected for evaluating the merits of the different landfill sites are: (1) environmental and ecological impact, (2) transportation issues, (3) impacts on historical markers, (4) economic impacts of the landfill and (5) public nuisance. These criteria are described below. Transportation of waste loads from the hauling station to the landfill causes disruption of traffic within the city limits that cannot be clearly quantified in the decision-making process, thereby requiring fuzzy description of the criteria. Similarly, the possible impacts that can be caused by landfill on historical markers in terms of aesthetical impairment; bad odors etc. are critical and vague and hence, require fuzzy concepts to represent the importance of historical makers on the landfill selection process. The criterion of economical impact reflects the possibility of decrease in land value in the neighborhood and also in the farming productivity of the region, thereby affecting the economy of the city directly, which is also vague in many other ways. Public nuisance is another vague but important factor that refers to the feeling of discomfort caused to the public due to the construction and operation of a landfill in the middle of a populous place.

The decision objective is to select the most appropriate landfill from seven different candidate sites. The different alternatives are defined as $L = \{L1, L2, L3, L4, L5, L6, L7\}$ and the decision criteria are defined as $C = \{\mathrm{TI, EI, PN, EC, HM}\}$, where $\{$TI = transportation issues, EI = environmental and ecological impact, PN = public nuisance, EC = economical impact, HM = historical markers$\}$. Linkage between different alternatives with different criteria is shown in Fig. 7. There is a committee of two experts (E1 and E2) who are called on for assessing the appropriateness of 'm' alternatives ($\{L1, L2, L3, L4, L5, L6, L7\}$) under each of '$k$' criteria ($\{\mathrm{TI, EI, PN, EC, HM}\}$) as well as the importance weight of the criteria.

Let S_{itj} ($i = 1, 2,\ldots,m$; $t = 1, 2,\ldots,k$; $j = 1, 2,\ldots,n$) be the rating assigned to alternative A_i by expert E_j under criterion C_i. Let W_{tj} be the weight given to C_t by decision

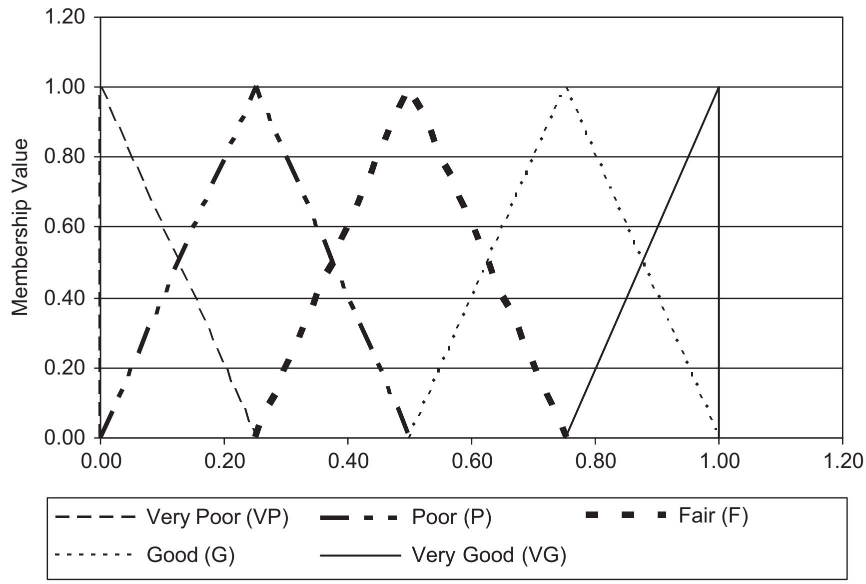

Fig. 6. Fuzzy membership functions.

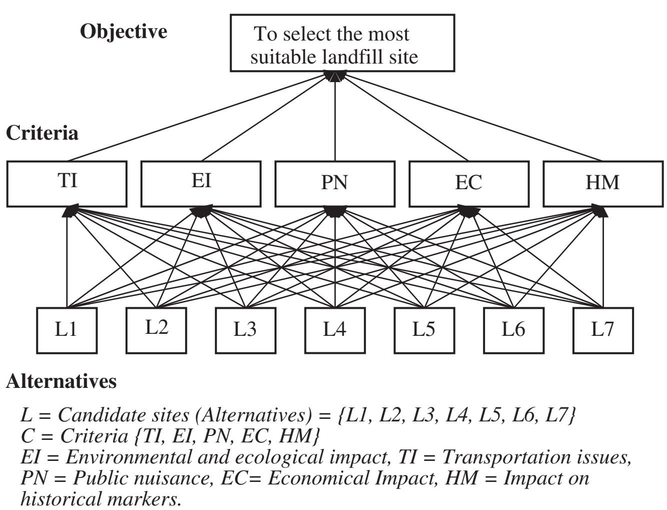

Fig. 7. Description of decision-making process.

maker E_j. The rating S_{itj} of n experts for each alternative vs. each criterion is aggregated. Each pooled rating is further weighted by weight W_t according to the relative importance of the k criteria. Then the final score F_t, fuzzy appropriate index, of alternative A_i is obtained by aggregating S_{itj} and W_t, which is finally ranked to obtain the most suitable alternative (Chang and Chen, 1994). The experts give their own preference rating for the different alternatives and weights for different criteria by using the triangular fuzzy numbers. Tables 4 and 5 present the rating done by the two experts comparing the seven alternatives (i.e., candidate sites) against the five criteria. The weights assigned to the different criteria for decision-making are presented in Table 6.

Following the method developed by Chang and Chen (1994), this paper utilizes mean fuzzy operator to aggregate the expert's assessment. Let $\oplus$ and $\otimes$ be the fuzzy addition and fuzzy multiplication operator, respectively. The aggregation of the different ratings is given by

$$S_{itj} = (S_{it1} \oplus S_{it2} \oplus \cdots S_{itn}) \otimes (1/n), \tag{1}$$

$$W_t = (W_{t1} \oplus W_{t2} \oplus \cdots W_{tn}) \otimes (1/n), \tag{2}$$

where S_{itj} is the average fuzzy appropriateness index rating of alternative A_i under criterion C_j, and W_t is the average importance weight of criterion C_j. Thus, the fuzzy appropriateness index F_i of the ith alternative can be obtained by aggregating S_{itj} and W_t, expressed as

$$F_i = [(S_{i1} \oplus W_1) \oplus (S_{i2} \oplus W_2) \oplus \cdots \oplus (S_{ik} \otimes W_k)] \otimes (1/k). \tag{3}$$

Let $S_{itj} = (q_{itj}, o_{itj}, p_{itj})$ and $W_{itj} = (c_{tj}, a_{tj}, b_{tj})$ be triangular fuzzy numbers. Then F_i can be expressed as

$$F_i = (Y_i, Q_i, Z_i), \tag{4}$$

where

$$Y_i = \sum_{i=1-k} (q_{it}c_t/k), \quad Q_i = \sum_{i=1-k} (o_{it}a_t/k),$$
$$Z_i = \sum_{i=1-k} (p_{it}b_t/k),$$

$$o_{it} = \sum_{j=1-n} (o_{itj}/n), \quad p_{it} = \sum_{j=1-n} (p_{itj}/n),$$
$$q_{it} = \sum_{j=1-n} (o_{itj}/n),$$

$$c_t = \sum_{j=1-n} (c_{tj}/n), \quad p_t = \sum_{j=1-n} (p_{tj}/n),$$
$$a_t = \sum_{j=1-n} (a_{tj}/n)$$

for $i = 1,2,\ldots,m$; $t = 1,2,\ldots,k$; $j = 1,2,\ldots,n$.

Table 4
Evaluation of different alternative against all criteria by expert E1

Criteria	Alternatives						
	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7
TI	(0.6, 0.7, 0.8)	(0.6, 0.7, 0.8)	(0.6, 0.7, 0.8)	(0.6, 0.7, 0.8)	(0.6, 0.7, 0.8)	(0.6, 0.7, 0.8)	(0.6, 0.7, 0.8)
PN	(0.9, 0.95, 1.0)	(0.4, 0.5, 0.6)	(0.4, 0.5, 0.6)	(0.4, 0.5, 0.6)	(0.4, 0.5, 0.6)	(0.4, 0.5, 0.6)	(0.4, 0.5, 0.6)
EI	(0.7, 0.85, 0.9)	(0.6, 0.65, 0.75)	(0.4, 0.45, 0.55)	(0.50, 0.55, 0.60)	(0.4, 0.45, 0.55)	(0.5, 0.55, 0.65)	(0.5, 0.55, 0.65)
EC	(0.65, 0.75, 0.8)	(0.40, 0.45, 0.5)	(0.5, 0.55, 0.65)	(0.55, 0.6, 0.65)	(0.55, 0.6, 0.65)	(0.50, 0.60, 0.75)	(0.50, 0.60, 0.75)
HM	(0.50, 0.60, 0.75)	(0.55, 0.6, 0.65)	(0.55, 0.6, 0.65)	(0.55, 0.6, 0.65)	(0.55, 0.6, 0.65)	(0.55, 0.6, 0.65)	(0.55, 0.6, 0.65)

Table 5
Evaluation of different alternative against all criteria by expert E2

Criteria	Alternatives						
	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7
TI	(0.55, 0.6, 0.70)	(0.35, 0.4, 0.45)	(0.4, 0.45, 0.5)	(0.45, 0.5, 0.55)	(0.4, 0.45, 0.5)	(0.5, 0.55, 0.6)	(0.3, 0.35, 0.4)
PN	(0.4, 0.45, 0.5)	(0.5, 0.55, 0.6)	(0.4, 0.45, 0.5)	(0.35, 0.4, 0.45)	(0.5, 0.55, 0.60)	(0.5, 0.55, 0.6)	(0.35, 0.4, 0.45)
EI	(0.75, 0.8, 0.85)	(0.5, 0.55, 0.60)	(0.55, 0.60, 0.65)	(0.30, 0.35, 0.40)	(0.50, 0.55, 0.60)	(0.30, 0.35, 0.40)	(0.55, 0.60, 0.65)
EC	(0.7, 0.75, 0.8)	(0.4, 0.45, 0.5)	(0.6, 0.65, 0.7)	(0.5, 0.55, 0.60)	(0.6, 0.65, 0.7)	(0.5, 0.55, 0.60)	(0.5, 0.55, 0.6)
HM	(0.45, 0.5, 0.55)	(0.45, 0.5, 0.55)	(0.45, 0.5, 0.55)	(0.45, 0.5, 0.55)	(0.45, 0.5, 0.55)	(0.45, 0.5, 0.55)	(0.45, 0.5, 0.55)

Table 6
Weights of different criteria by two experts

Criteria	Experts	
	E1	E2
TI	(0.8, 0.9, 0.95)	(0.8, 0.9, 0.95)
PN	(0.9, 0.95, 1)	(0.75, 0.8, 0.9)
EI	(0.7, 0.75, 0.8)	(0.85, 0.9, 0.99)
EC	(0.8, 0.9, 0.95)	(0.7, 0.75, 0.8)
HM	(0.45, 0.55, 0.6)	(0.45, 0.55, 0.6)

Based on the aggregation functions, the fuzzy appropriate indices are obtained and presented in Table 7. This information may help justify the final ranking among these seven-candidate sites. Therefore, the ranking values of fuzzy appropriate indices for the alternatives were computed based on the method developed in Chang and Chen (1994).

Let F_i $(i = 1,2,\ldots,m)$ be the fuzzy appropriate indices of m alternatives. The maximizing set $M = \{(x, f_m(x)) | x \in R\}$ with

$$f_m(x) = \begin{cases} (x - x_1)/(x_2 - x_1), & x_1 < x \leqslant x_2, \\ 0 & \text{otherwise} \end{cases}$$

and minimizing set $G = = \{(x, f_g(x)) | x \in R\}$ with

$$f_g(x) = \begin{cases} (x - x_2)/(x_1 - x_2), & x_1 \leqslant x < x_2, \\ 0 & \text{otherwise,} \end{cases}$$

where $x_1 = \inf S$, $x_2 = \sup S$, $S = \cup_{t=1,m} \; F_i$, $F_i = \{x | f_{Fi}(x) > 0\}$, for $i = 1,2,\ldots,m$.

Defining the optimistic utility $U_M(F_i)$ and pessimistic utility $U_G(F_i)$ for each appropriate index F_i as

$$U_M(F_i) = \sup(f_{Fi}(x) \wedge f_M(x)) \text{ and} \tag{5}$$

$$U_G(F_i) = 1 - \sup(f_{Fi}(x) \wedge f_G(x)). \tag{6}$$

For $i = 1,2,\ldots,$ where $\wedge$ means min.

Ranking value $U_T(F_i)$ of fuzzy appropriate indices is defined as:

$$U_T(F_i) = \alpha U_M(F_M) + (1 - \alpha) U_G(F_i), \quad 0 \leqslant \alpha \leqslant 1. \tag{7}$$

The value α is an index of rating attitude. It reflects the expert's risk-bearing attitude. Let $B = (c, a, b)$ be a normal triangular fuzzy number. The index of rating attitude of an individual expert is defined as $Y = (a-c)/(b-c)$ (Chang and Chen, 1994). If $Y > 0.5$, it implies that the expert is a risk lover. If $Y < 0.5$, the expert is a risk averter. If $Y = 0.5$, the attitude of expert is neutral to the risk. Thus, the total index of rating attitude, R, with the evaluation data of individuals can is shown as

$$R = \left\{ \sum_{i=1}^{k} \sum_{j=1}^{n} (a_{tj} - c_{tj})/(b_{tj} - c_{tj}) + \sum_{i=1}^{m} \sum_{t=1}^{k} \sum_{j=1}^{n} (o_{itj} - q_{itj})/(p_{itj} - q_{itj}) \right\} \Big/ (kn + mkn). \tag{8}$$

From Eqs. (4), (6) and (8), the ranking values $U_t(F_i)$ can be approximately expressed as

$$U_T(F_i) \cong R[(Z_i - x_1)/x_2 - x_1 - Q_i + Z_i) + (1 - R)[1 - (x_2 - Y_i)/(x_2 - x_1 + Q_i + Y_i)]. \tag{9}$$

Table 7
Fuzzy appropriateness indices for the seven alternatives

Alternatives	Fuzzy appropriateness index
Site 1	(0.45563, 0.55988, 0.65963)
Site 2	(0.3405, 0.42463, 0.51308)
Site 3	(0.34713, 0.43275, 0.52553)
Site 4	(0.53163, 0.41638, 0.49888)
Site 5	(0.35525, 0.4415, 0.53055)
Site 6	(0.34425, 0.434, 0.5311)
Site 7	(0.33525, 0.4235, 0.52023)

Table 8
Ranking values of the different alternatives

Alternatives	Ranking values
Site 1	0.786689
Site 4	0.580556
Site 5	0.371734
Site 3	0.342253
Site 6	0.340457
Site 7	0.310792
Site 2	0.266668

And the ranking values of the fuzzy appropriateness indices for alternatives are presented in Table 8. Site 1 exhibits the highest potential in this site selection process.

4. Discussion

4.1. Advantages and disadvantages of the approach

The methodology followed in this paper differs from the conventional methods of integrating GIS with MCDM for landfill selection because the approach follows two sequential steps rather than a full-integrated scheme. In the first stage, GIS-based analysis of spatial data has been a new specialized process, capable of analyzing complex problem of evaluating various geospatial features for targeting potential areas for siting landfills. While GIS offers unique capacities for automating geospatial analysis for screening all possible sites, data availability can prove to be a limiting factor in its application for selection of a landfill. Landfill selection process can lead to situations in which certain criteria, such as public nuisance, economic factors and impacts on historical markers, may cause increased ambiguities in the decision making process due to lacking sufficient information. The candidate sites obtained in the first stage can be narrowed down using a prescribed MCDM process. Multicriteria evaluation is primarily concerned with how to combine the information from several criteria to form a single index of evaluation. In case of Boolean criteria, the solution usually lies in the union (logical OR) or intersection (logical AND) of conditions. However, for continuous factors in crisp MCDM process, a weighted linear combination is a usual technique (Voogd, 1983). As the criteria are measured at different scales, they are standardized and transformed such that all factor maps are positively correlated with suitability. Establishing factor weights is the most complicated aspect, for which the most commonly used technique is the pair-wise comparison matrix. In response to the vague (fuzzy) conditions, domain experts in the second stage got involved. By including the expert opinion and combining them with the power of fuzzy and MCDA yielded a crystal structure very much dependent of the screening values of data sets. This can be enormously advantageous in solving controversial political debates in the future. The advantage of this method is therefore placed upon the capability to incorporate the knowledge of the domain experts in the uncertain decision making process when there is a lack of crisp information related to certain criteria, such as public nuisance and impact of landfill on historical markers. However, the disadvantage of this method is that the selection of the best candidate site is dependent on the judgments of the domain experts and can be sensitive to changes in the decision weights associated with criteria. In certain situations, two experts may have contradicting judgments about suitability of a candidate site. Hence, it is required to assess the extent of difference or similarity between the two experts in association with decision weights. Where the experts are forced to give ranks to the pre-defined candidate 7 sites, the selections are only made among these (i.e., site 1 is better than all other 6 sites). But some might argue that it may not be the very best ideal case. If the screening process is loosened a little bit may be a candidate site 8 will appear and may be at some criterion it will score more. To respond to this challenge, a field check was done in the early stage and in the middle of this study to ensure that site 1 would also be the approved one at the field eventually.

In this study the decision weights are provided by the decision makers as a triangular fuzzy number and therefore overlap of the triangular fuzzy sets (shown in Fig. 8) is used as a similarity measure between the two experts. The overlap measure indicates the extent to which the two experts agree upon each other for the importance of a particular criterion in the selection of a landfill. The overlap measure for the each of the criteria was estimated

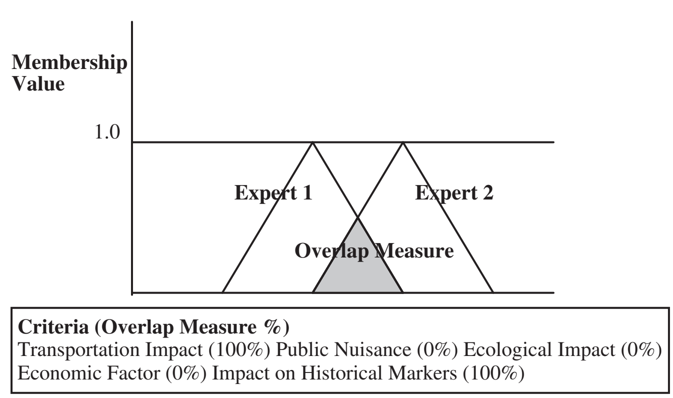

Fig. 8. Illustration of similarity measure between two experts.

mathematically as illustrated in the figure. The values of such overlap measure for the criteria TI and HM are 100% whereas there was no overlap between the weights for the criteria PN, EI and EC indicating that there is a marked difference between the experts in their judgments of the importance of the three criteria (PN, EI and EC) in the selection of a landfill. The discrepancy in the judgment between two experts can have a significant impact on the selection process, which can be minimized by having more experts to provide assessment of the decision criteria weights. The overlap measure can thus provide vital information related to the similarity between the experts involved in the decision making process.

4.2. Sensitivity analysis

In a landfill selection process, it becomes necessary to assess the reliability of the method involved in identification of the best candidate site. A small perturbation in the decision weights may have a significant impact on the rank ordering of the sites and subsequently change the best choice. Therefore, sensitivity analysis using Monte Carlo simulation was performed to determine the probability of changes in rank ordering. Hence, the decision weights were systematically varied to investigate the relative impacts of the weights on the rank ordering of the landfill sites. The weights for the five different criteria provided by the experts as triangular fuzzy set were varied within a range of 20% provided that a latin hypercube sampling of the inputs was used to conduct such a simulation. The results of 100 simulations were shown in Fig. 9. It can be observed that site1 still completely dominate all the other sites despite a certain degree of variations in the decision weights. With the aid of 100 simulation runs, it indicates that the ranks of the seven-candidate sites remained the same as shown in Table 8 except for candidate sites 2 and 7. Candidate site 7 occupied the last rank 49 times out of the 100 simulations replacing site 2, thus demonstrating the fact that site 7 and site 2 perform identically with respect to the decision criteria selected according to the two experts. The fact that the perturbation of the decision weights has a small impact on the ranking of the candidate sites reveals that the degree of domination of the candidate sites is almost independent of changes in the decision weights associated with selected criteria.

5. Conclusions

The increasing generation of MSW in the LRGV is one of the greatest challenges faced by governmental authorities. In order to mitigate the impacts on the environment and public health, a claim, which requires a fast decision-making process regarding the final disposal of the MSW, motivates this study. Research findings show that a SDSS, featuring a well-structured architecture and the computational power, improves the application potential in urban and regional planning, and gives essential support to the decision-maker in the assessment of the waste management problem so that a higher level of understanding can be reached in regard to environmental decisions. In order to gain an all-inclusive perspective, the process of decision-making consisted of a two-stage analysis, beginning with an initial site screening followed by a detailed assessment of the suitability of the candidate sites using a FMCDM approach guided by a panel of experts in the site selection process. The first-stage analysis was successful in preliminary landfill site screening leading to exclude the sensitive areas while retaining sufficient areas for further evaluation at the same time. Within the recovered fuzzy region in the second-stage analysis, MCDM method smoothly incorporated the information provided by two experts leading to fulfill the ranking of the seven

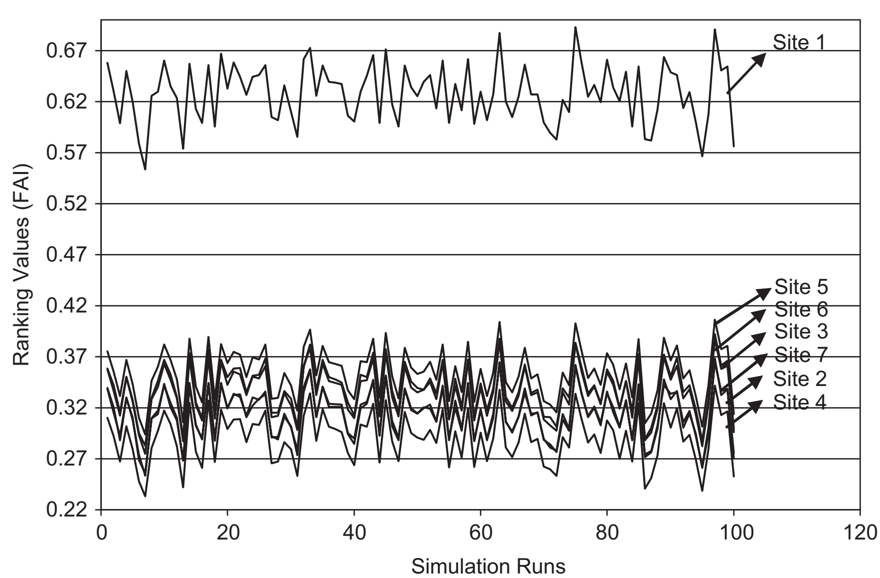

Fig. 9. Monte Carlo simulation showing the changes in ranking values of the candidate sites.

alternatives with respect to five different criteria. All the criteria were eventually aggregated to select the most suitable site in terms of ratings given the fact that fuzzy set theory may aid in justification of the uncertainty in decision-making. In consequence, a SDSS may strengthen the generation and evaluation of alternatives by providing an insight of the problem among the varied objectives and granting essential support to the process of decision-making under uncertainty (Malcezwki, 1999; Sharifi and Van Herwijnen, 2003). With such an effort, it is concluded that "site 1" located near highway 77 closer to Cameron–Willacy boundary is the most suitable site for landfill based on an integrated GIS and FMCDM analysis. A sensitivity analysis was conducted to assess the reliability of the ranking of the candidate sites using a Monte Carlo simulation by changing the decision weights associated with selected criteria. The results indicated that the candidate site 1 still completely dominate the other sites despite variations of the decision weights within a range of 20%. Overall, GIS thus offered the means to identify seven potential landfill sites based on well-defined criteria, which were later ranked according to the preferences provided by two domain experts that were based on their experiences and knowledge of the dynamics of the Lower Rio Grande Valley using FMCDM. FMCDM offered the capacity to incorporate the opinions of the domain experts that can be useful in the future to settle political debate regarding the site selection. Such procedure was eventually proved useful in the case study identifying favorable areas for waste disposal in a fast-growing urban region in south Texas.

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References

Akash, B.A., Mamlook, R., Mohsen, M.S., 1999. Multi-criteria selection of electric power plants using analytical hierarchy process. Electric Power Systems Research 52, 29–35.

Allanach, W.C., 1992. Regional landfill planning and siting. Public Works, December, 48–50.

Altrock, C.V., Krause, B., 1994. Multi-criteria decision-making in German automotive industry using fuzzy logic. Fuzzy Sets and System 63, 375–380.

American Planning Association, 2002. Growing Smart—Legislative Guidebook: Model Statutes for Planning and the Management of Change. APA's Planners Book Service, 〈http://www.planning.org/guidebook/Login.asp〉 (access:September 2003).

Anderson, R.F., Greenberg, M.R., 1982. Hazardous waste facility siting: a role for planners. Journal of the American Planning Association 48, 204–218.

Baas, S.M., Kwakernaak, H., 1997. Rating and ranking of multiple aspect alternative using fuzzy sets. Automatica 13, 47–58.

Baban, S.M.J., Flannagan, J., 1998. Developing and implementing GIS-assisted constraints criteria for planning landfill sites in the UK. Planning Practice and Research 13, 139–151.

Chan, F.T.S., Chan, M.H., Tang, N.K.H., 2000. Evaluation methodologies for technology selection. Journal of Materials Processing Technology 107, 330–337.

Charnpratheep, K., Zhou, Q., Garner, B., 1997. Preliminary landfill site screening using fuzzy geographic information systems. Waste Management and Research 15, 197–215.

Chen, S.M., 1996. Evaluating weapon systems using fuzzy arithmetic operations. Fuzzy Sets and Systems 77, 265–276.

Cheng, C.H., 1997. Evaluating naval tactical systems by fuzzy AHP based on the grade value of membership function. European Journal of Operational Research 96, 343–350.

Chiadamrong, N., 1999. An integrated fuzzy multi-criteria decision making method for manufacturing strategies selection. Computers and Industrial Engineering 37, 433–436.

Choi, D.Y., Oh, K.W., 2000. ASA and its application to multicriteria decision making. Fuzzy Sets and Systems 114, 89–102.

Del Valle, F., 2005. Both sides confident at landfill hearing. Valley Morning Star. Retrieved from 〈http://www.valleystar.com/archives〉.

Dikshit, A.K., Padmavathi, T., Das, R.K., 2000. Locating potential landfill sites using geographic information systems. Journal of Environmental Systems 28, 43–54.

Fanti, M.P., Maione, B., Naso, D., Turchiano, B., 1998. Genetic multi-criteria approach to flexible line scheduling. International Journal of Approximate Reasoning 19, 5–21.

Hauser, D., Tadikamalla, P., 1996. The analytic hierarchy process in an uncertain environment: a simulation approach. European Journal of Operational Research 91, 27–37.

Jensen, J.R., Christensen, E.J., 1986. Solid and hazardous waste disposal site selection using digital geographic information system techniques. The Science of the Total Environment 56, 265–276.

Kaiser, E., Godschalk, D., Chapin Jr., S.F., 1995. Urban Land Use Planning. University of Illinois, Urbana, IL, 493pp.

Kao, J., Lin, H., Chen, W., 1997. Network geographic information system for landfill siting. Waste Management and Research 15, 239–253.

Karsak, E.E., Tolga, E., 2001. Fuzzy multi-criteria decision-making procedure for evaluating advanced manufacturing system investments. International Journal of Production Economics 69, 49–64.

Kaufmann, A., Gupta, M.M., 1988. Fuzzy Mathematical Models in Engineering and Management Science. Elsevier, Amsterdam, Netherlands.

Keir, A.W., Doucett, J.A., Oliveri, T., 1993. Landfill siting using GIS technology: the case of the Peel Landfill site search. In: Proceedings of the Canadian Conference on GIS-1993, Ottawa, Canada, pp. 13–24.

Klostermann, R.E., 1999. The "what if?" collaborative planning support system. Environment and Planning. B, Planning and Design 26, 393–408.

Kuo, R.J., Chi, S.C., Kao, S.S., 2002. A decision support system for selecting convenience store location through integration of fuzzy AHP and artificial neural network, Computers in Industry, in press.

Labib, A.W., O'Connor, R.F., Williams, G.B., 1998. Effective maintenance system using the analytic hierarchy process. Integrated Manufacturing Systems 9, 87–98.

Lee, S.J., Lim, S.I., Ahn, B.S., 1998. Service restoration of primary distribution systems based on fuzzy evaluation of multi-criteria. IEEE Transactions on Power Systems 13, 1156–1163.

Levary, R.R., Ke, W., 1998. A simulation approach for handling uncertainty in the analytic hierarchy process. European Journal of Operational Research 106 (1), 116–122.

Lin, H.Y., Kao, J.J., 1999. Enhanced spatial model for landfill siting analysis. Journal of Environmental Engineering, ASCE 125 (9), 845–851.

Longley, P.A., Barnsley, M.J., Donnay, J.P., 2001. Remote sensing and urban analysis: a research agenda. In: Donnay, J.P., Barnsley, M.J., Longley, P.A. (Eds.), Remote Sensing and Urban Analysis. Taylor & Francis, London, pp. 245–258.

Lower Rio Grande Valley Development Council (LRGVDC), 2002. Regional Solid Waste Management Plan Amendment 2002–2020, June 30, 2003.

McIntyre, C., Parfitt, M.K., 1998. Decision support system for residential land development site selection process. Journal of Architect Engineering ASCE 4 (4), 125–131.

Malcezwki, J., 1999. Spatial multicriteria decision analysis. In: Thill, J.C. (Ed.), Spatial Multicriteria Decision Making and Analysis. Ashgate Publishing, Hamshire.

Nagar, B.B., Mizra, U.K., 2002. Hydrogeological environmental assessment of sanitary landfill project at Jammu City, India. Green Journal 17 (8), 223–245.

O'Leary, P.R., Canter, L., Robinson, W.D., 1986. Land disposal. In: Robinson, W.D. (Ed.), The Solid Waste Handbook: A Practical Guide. Wiley, NY, USA p. 271.

O'Meara, M., 1999. Reinventing cities for people and the planet. Washington, DC, Worldwatch Institute, 68pp. 〈http://www.worldwatch.org/pubs/paper/147/〉 (Access: September 2003).

Pierson, E., 2004. Valley could run out of landfill space in coming decades, reports say. The Brownsville Herald.

Paek, J.H., Lee, Y.W., Napier, T.R., 1992. Selection of design/build proposal using fuzzylogic system. Journal of Construction Engineering and Management 118, 303–317.

Saaty, T.L., 1980. The Analytic Hierarchy Process. McGraw-Hill, New York.

Sener, B., Suzen, L., Doyuran, V., 2006. Landfill site selection by using geographic information systems. Environmental Geology 49, 376–388.

Siddiqui, M.Z., Everett, J.W., Vieux, B.E., 1996. Landfill siting using geographical information systems: a demonstration. Journal of Environmental Engineering, ASCE 122 (6), 515–523.

Sharifi, A., Van Herwijnen, M., 2003. Spatial Decision Support System. ITC, Esnchede, p. 64.

Tagaris, E., Sotiropolou, R.E., Pilinis, C., Halvadakis, C.P., 2003. A methodology to estimate odors around landfill sites: the use of methane as an odor index and its utility in landfill siting. Journal of the Air and Waste Management Association 53 (5), 629–634.

Tang, M.T., Tzeng, G.H., Wang, S.W., 1999. A hierarchy fuzzy MCDM method for studying electronic marketing strategies in the information service industry. Journal of International Information Management 8 (1), 1–22.

Teng, J.Y., Tzeng, G.H., 1996. Fuzzy multicriteria ranking of urban transportation investment alternatives. Transportation Planning Technology 20 (1), 15–31.

TSHA Online, The Handbook of Texas Online—Rio Grande Valley. Available at 〈http://www.tsha.utexas.edu/handbook/online/articles/view/RR/ryr1.html〉, accessed on September 12, 2003.

US Department of Agriculture, 1977. Soil Survey of Cameron County Texas. Soil Conservation Service.

US Department of Agriculture, 1982. Soil Survey of Willacy County Texas. Soil Conservation Service.

Voogd, H., 1983. Multi-criteria Evaluations for Urban and Regional Planning. Princeton University, NJ, USA.

Yu, W.D., Skibniewski, M.J., 1999. Quantitative constructability analysis with a neuro-fuzzy knowledge-based multi-criterion decision support system. Automation in Construction 8 (5), 553–565.

Zeiss, C., Lefsrud, L., 1995. Analytical framework for facility waste siting. Journal of Urban Planning and Development, ASCE 121 (4), 115–145.

Zadeh, L.A., 1965. Fuzzy sets. Information and Control 8, 338–353.