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Waste Manag Res 2002 20: 187
DOI: 10.1177/0734242X0202000210

Waste Manage Res 2002: 20: 187–197
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Waste Management & Research
ISSN 0734–242X

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This study presents a Fuzzy Markov groundwater pollution potential assessment approach to facilitate landfill siting analysis. Landfill siting is constrained by various regulations and is complicated by the uncertainty of groundwater related factors. The conventional static rating method cannot properly depict the potential impact of pollution on a groundwater table because the groundwater table level fluctuates. A Markov chain model is a dynamic model that can be viewed as a hybrid of probability and matrix models. The probability matrix of the Markov chain model is determined based on the groundwater table elevation time series. The probability reflects the likelihood of the groundwater table changing between levels. A fuzzy set method is applied to estimate the degree of pollution potential, and a case study demonstrates the applicability of the proposed approach. The short- and long-term pollution potential information provided by the proposed approach is expected to enhance landfill siting decisions.

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Keywords – Landfill siting, groundwater table, fuzzy set, Markov chain, dynamic system, wmr 485–5

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Received 11 December 2000, accepted in revised form 8 November 2001

Introduction

Despite availability of various alternatives, landfilling remains the most prevalent disposal method for municipal solid waste (MSW) generated in Taiwan, R.O.C. New landfill sites are extremely difficult to obtain because of increased land costs and the NIMBY (Not In My Back Yard) (Lober *et al.* 1994; Ham 1993) consensus from the general public. Landfill siting has thus become a sensitive environmental issue, particularly for a densely populated island such as Taiwan.

Potential groundwater pollution is one of the driving environmental issues for landfill siting. A landfill site must be carefully located to prevent groundwater pollution from leachates. The groundwater table around the landfill site should be as low as possible to reduce the likelihood of leachates being received from a landfill. Therefore, a siting procedure must be developed which considers the groundwater table close to a landfill site.

The impact of pollution on groundwater resources is conventionally evaluated using a weight-ranking method. The US EPA developed the DRASTIC (1985) system for evaluating the general impact of pollution on groundwater resources. This system assigns different rankings to various groundwater table levels. A weight is also assigned for a specific groundwater impact for its relative importance compared with other impacts. The pollution potential impact level can then be determined by multiplying the rank and the weight. Previous studies (e.g., Bolton *et al.* 1990; Hagemeister *et al.* 1996; and Siddiqui *et al.* 1996) have applied this weight-ranking method to assess the potential for groundwater pollution of a landfill. Such a weight-ranking method is useful when groundwater table levels do not fluctuate significantly and also is useful for assessing the worst-case scenario based on the highest groundwater level. However, this weight-ranking method cannot properly evaluate the impact of a dynamic groundwater table for which the water table level does not remain the same all the time.

As generally known, a static model overlooks temporal changes in the surrounding environment, while a stochastic model can simulate a dynamic system. Ünlü (1994) and Hamed *et al.* (1995) applied stochastic methods to simulate the transfer of contaminants in the soil and groundwater. The potential for groundwater pollution depends on the likelihood of leachates contaminating groundwater, of which the water level variation is a dynamic system. A dynamic model is thus more appropriate than a static one in terms of analysing groundwater pollution potential for landfill siting. Markov chain models are dynamic ones that can be viewed as a hybrid of probability and matrix models. Various investigations (Minkoff 1993; Muller *et al.* 1994; Lein 1989) have applied a Markov chain process to analyse dynamic systems. The groundwater table fluctuates and its variation can be expressed by a Markov chain process. The Markov chain approach is capable of analysing a dynamic groundwater table system for the occurrence probabilities of possible groundwater table levels, thereby making it possible to determine the pollution potential in such a dynamic system.

While applying a Markov chain model, the data set analysed is assumed to be stationary. Therefore, a nonstationary data set should be converted into a stationary set before applying the Markov chain model. Takyi *et al.* (1995) and Yapo *et al.* (1993) classified a nonstationary stream flow data using a clustering algorithm to define the range of classifications for transforming into a stationary data set. This study adopts a similar transformation algorithm and applies DRASTIC to define classification ranges (or grades). Besides the stationary requirement, the proper order of the Markov chain must be determined. Various methods are available to determine the order, e.g., Bayes Information Criterion (BIC) (Guttorp 1995) and Akaike's Information Criterion (Tong 1975). This work uses the BIC method because of its practicability, requiring only few parameters to evaluate the order.

The randomness and fuzziness of the uncertainty of a natural hazard make the risk evaluated by a pure probabilistic method unreliable (Chongfu 1996). The fuzzy set approach can effectively deal with imprecise data over an uncertain range (Kaufmann *et al.* 1988). Imprecisely stated decision criteria can be expressed by a fuzzy set. Zadeh (1994) compared the Fuzzy and Boolean methods in geographical modeling and concluded that fuzzy-logic-based modeling is not only informative for decision makers, but also deal more realistically with the gradual transition of land characteristics in agricultural and urban land evaluation processes. Warmerdam (1994) demonstrated that the linear fuzzy membership function is useful for siting and routing hazardous waste operations. Siting decisions are difficult to make based solely on the probability values obtained from the Markov chain model. For instance, two varying table levels with the same probability of occurrence have different pollution potentials because the higher table level generally has a higher pollution potential. Therefore, a fuzzy set approach is applied to process such imprecise information. The probability matrix produced from a Markov chain model is converted into a linear fuzzy set which is effective for landfill siting analysis.

Landfill siting generally requires processing significant amounts of spatial information, including environmental, social, economic, and engineering data. Collecting and analysing these spatial data is time consuming and tedious. Thus, a computerised geographical information system (GIS) has operated in recent years to facilitate siting related tasks. Lindquist (1991) demonstrated the feasibility of applying a GIS for a landfill siting problem in Illinois. Our earlier study (Kao *et al.* 1996) integrated a GIS, an expert system, and a network multimedia interface to develop a prototypical network GIS for assisting engineers in siting a landfill. Siddiqui *et al.* (1996) developed a Spatial-AHP system for use with GIS for landfill siting. ArcView (ERSI, 1996a), a GIS, is used in this work to facilitate the processing and interpolation of geo-referenced data.

The Fuzzy Markov approach developed herein is applied to facilitate landfill siting in a case study for the Miaoli Prefecture in central Taiwan, R.O.C. The case study presented herein demonstrates the effectiveness of the proposed approach in assessing the potential pollution impact from a landfill on the groundwater table. The siting decision is analysed and discussed according to the resulting fuzzy set and GIS analyses.

Methodology

Leachate from a landfill may significantly pollute groundwater. The likelihood of such pollution is closely related to the level of potentially affected groundwater tables. The higher the groundwater table the greater the probability for leachate pollution. Because the groundwater table level fluctuates, its temporal and spatial dynamic variation should be evaluated for siting a landfill. This study presents a Markov chain approach for assessing the dynamic variation of the groundwater table. The variation of a groundwater table from one state to the other, i.e., the transition probability, is determined by the previous state. Table 1 lists the various levels of a groundwater table, divided into 7 grades. This division is adopted from DRASTIC (1985). An nxn transition probability matrix is constructed based on various grades of a groundwater table. The transition probabilities p_{ij}'s (Jain, 1992) are expressed as

$$P = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ p_{n1} & p_{n2} & \cdots & p_{nn} \end{bmatrix} \quad (1)$$

Note that

$p_{ij} \geq 0$ *for all i, j*

and that

$$\sum_{j=1}^{n} p_{ij} = 1 \quad \text{for } i = 1,2,3,\cdots,n$$

where P denotes a stochastic matrix and n is the number of groundwater table level grades and is equal to 7 herein. The stochastic matrix denotes the probabilities of the groundwater table grade fluctuating between grades. The transition probabilities of groundwater table grades can be computed according to the Markov chain approach. The associated pollution potential of each grade can be determined from Table 1.

Table 1. Grade division for groundwater table levels

Range (meters)	Rating In DRASTIC	Grade
< 0-1.5	10	1
1.5-4.5	9	2
4.5-9	7	3
9-15	5	4
15-22.5	3	5
22.5-30	2	6
30+	1	7

The primary state probability of groundwater table level grades can be shown as the row matrix listed below:

$$P(0) = [p_1(0) \quad p_2(0) \quad \cdots \quad p_n(0)] \quad (2)$$

If the probability of state i is $p_i(0) = 1$, then other elements of the row matrix equal zero. The first step transition, P(1), can be expressed by the following equation.

$$P(1) = P(0)P \quad (3)$$

And the following transitions can be expressed by a similar formulation, e.g., $P(5) = P(0)P^5$ indicates 5 transitions. If the stochastic matrix is built using an interval of one month, then 5 transitions imply the simulation for 5 months later.

The BIC (Guttor, 1995) is used to determine the order of the Markov chain. The order that maximizes the BIC value, as computed below, is the desired order.

$$\text{BIC} = 2\sum m_{ij} \log P_{ij} - k \log n \quad (4)$$

where m_{ij} denotes the number of transitions that occur from state i to j in the data chain, pij is the probability for the transition from state I to j; k = (d–1)d *L; d is the number of states; L is the order; and n is the number of data entries.

According to the transition probabilities determined for all observation stations, the inverse distance weighted (IDW) function provided by ArcView (ERSI, 1996b) is employed to estimate the transition probability of each unmonitored land cell. The IDW interpolator (ERSI, 1996b) assumes that each input point has a local influence that diminishes with distance. The interpolator assigns a higher weight to the points closer to the processing cell than those farther away. Map layers for transition probabilities are then generated by ArcView for further analyses. However, siting decisions cannot be made directly from the transition probability matrix. Two varied grades with the same transition probability do not have the same pollution potential because the potential of the grade with higher table levels is higher. To resolve this problem, the fuzzy set approach described below is applied.

The membership function μ_A of a fuzzy set A can be expressed as the equation listed below (Klir & Folger 1988).

$$\mu_A(P_i) \longrightarrow [0,1] \quad (6)$$

A membership function expresses the membership degree of each element of a universal set based on a specified range. Larger values denote higher degrees of set membership. Fuzziness of criteria is to decrease the uncertainty to facilitate a decision-making analysis (Wenger & Rong 1987).

Applying the fuzzy set approach initially involves determining an appropriate membership function, given by the transition probability. In the proposed membership function listed below, the membership value of the transition probability of a high groundwater table is set smaller than that for a low table; and vice versa.

$$\mu_A(p_i) = \begin{cases} 1 & p_i \le 0.1*i \\ [(0.1*i+0.1)-p_i]/0.1 \quad where & 0.1*i < p_i \le (0.1*i+0.1) \\ 0 & p_i > (0.1*i+0.1) \end{cases} \quad (7)$$

Fig. 1. illustrates the relationship between membership values and transition probability of each grade. With the above membership function, along with the previously created transition probability maps and the map calculation function provided by ArcView (ERSI 1996b), the membership map for each groundwater table level grade can be generated for further siting analysis.

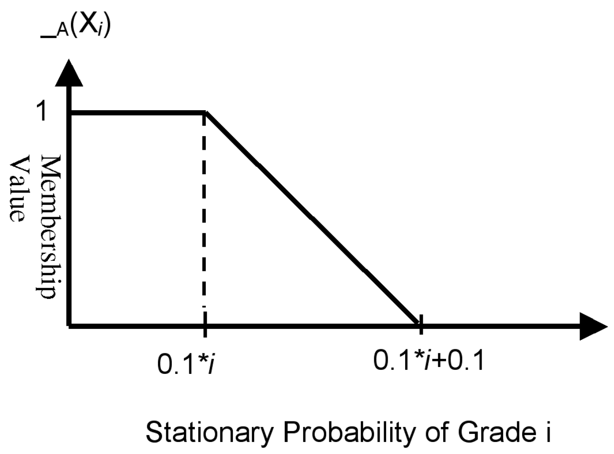

Fig. 1. Membership function and stationary probability of grade i

This study uses scalar cardinality (Klir & Folger 1988) for sorting candidate sites sequentially. The scalar cardinality of a fuzzy set A defined on a finite universal set X is the summation of the membership grades of all the elements of X in A, as computed using the following equation.

$$|A| = \sum_{x \in X} \mu_A\,(Pi) \quad (8)$$

A site with higher scalar cardinality is assumed to be more suitable for constructing a landfill than one with lower scalar cardinality. The ArcView map calculation function is used again to sum up the membership grades of all land elements in each candidate site to obtain the scalar cardinality of each candidate site. Finally, a siting decision is made one the basis of this scalar cardinality map, with the assistance of the GIS.

Case study

The siting area for this study includes three counties of Howlong, Shihwu, and Tong-Shiiau in Miaoli Prefecture in central Taiwan, R.O.C. The study area is approximately 224.7 square kilometers and divided into 89,482 land cells, each cell is 50 m x 50 m. The population density is 402 capita sq^{-1} km. The Taiwan EPA is tentatively planning to construct a regional landfill for the three counties. Various GIS map layers and related information were collected for the study area.

Preliminary screening

Before applying the proposed Fuzzy Markov method to this landfill siting problem, various criteria for environmental, socio-cultural, and engineering/economic factors were adopted to preliminarily screen out areas (Kao *et al.* 1996) obviously inappropriate for landfill construction. This prescreening process can eliminate a significant amount of inappropriate areas within the siting area. Further siting analysis with the proposed method focuses only on the remaining area, thereby saving analysis time. According to the collected criteria, a landfill site must restrain from the following sensitive areas.

Environmental factors:

- Groundwater protection areas;
- Water-sources, water-quality and water-quantity conservation districts;

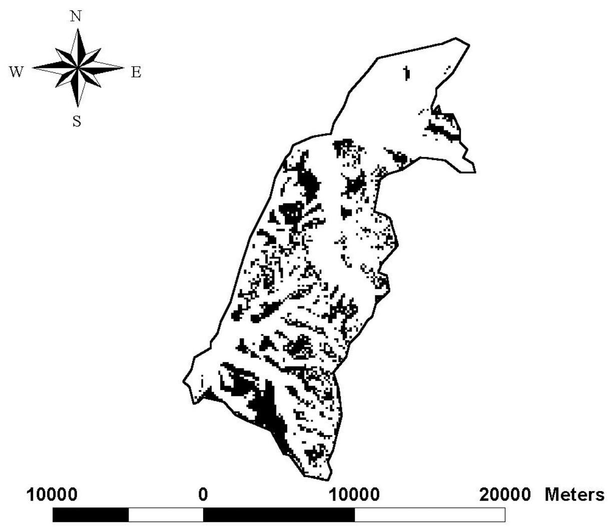

Fig. 2. The areas remained after the preliminary screening stage for the study area

- The buffer zone close to a stream (a 180 m buffer zone was set);
- Natural ecology conservation districts;
- Fault and unstable areas (a 60 m buffer zone was set); and
- The 100-year flood plain.

Socio-cultural factors:
- Urban planning areas (a 150 m buffer zone was set);
- Cultural and historic sites (a 305 m buffer zone was set); and
- National parks.

Engineering/economic factors:
- Areas distant from accessible roads (an acceptable distance of 1100 m was set); and
- Land slopes greater than 25%.

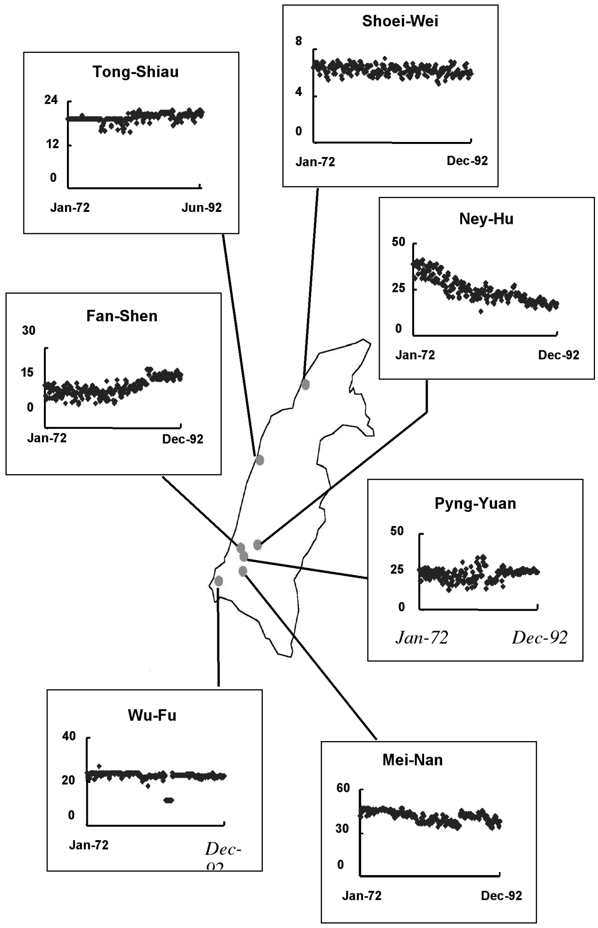

Fig. 3. The location and historical groundwater table plot (unit: meter) of each observation station in the study area

According to the above criteria, various digital map layers were collected or prepared. Map layer analysis functions provided by ArcView (ERSI 1996b) were applied

Table 2. Basic statistical information of groundwater table levels at each observation station

Station	Data		Groundwater table level (meters)					
	From	To	Max.	Min.	Max-Min	Average		
						1986-1987	1991-1992	1972-1992
Shoei-Wei	1972	1992	7.24	5.02	2.22	6.26	6.04	6.22
Tong-Shiau	1972	1992	21.68	15.47	6.21	20.69	20.45	19.48
Ney-Hu	1972	1992	41.02	13.33	27.69	22.50	16.77	24.50
Fan-Sheh	1972	1992	18.05	8.66	9.39	16.47	14.09	14.00
Mei-Nan	1972	1992	47.19	33.09	14.1	39.14	37.54	41.24
Wu-Fu	1972	1992	26.93	11.52	15.41	23.05	22.40	22.40
Pyng-Yuan	1972	1992	34.62	12.95	21.67	24.52	25.29	23.06

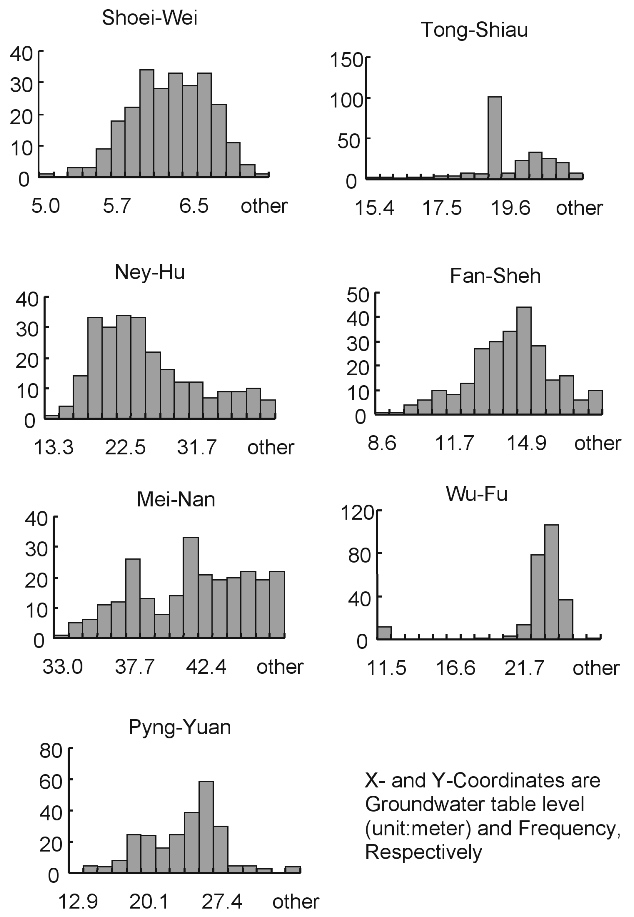

Fig. 4. Groundwater table level histogram of each observation station

to process these digital maps to eliminate areas inappropriate to be a landfill site. Fig. 2. illustrates the areas remaining after this preliminary screening stage by eliminating the sensitive areas listed above.

Groundwater table levels

Besides eliminating the strictly sensitive groundwater protection areas in the preliminary screening, further siting analysis was performed to evaluate the groundwater pollution impact of a landfill on a selected site and adjacent areas. The groundwater pollution impact is primarily associated with the level (or depth) of the groundwater table. Therefore, the level of the groundwater table must be determined for each land cell in the siting area before applying the proposed method. Seven observation stations operate within the siting area: Shoei-Wei, Tong-Shiau, Ney-Hu, Fan-Sheh, Mei-Nan, Wu-Fu, and Pyng-Yuan. Observed data for the stations were collected. Table 2 lists the available data period and the maximal, minimal, and average groundwater table levels of each observation station. Figs. 3 and 4 illustrate, respectively, the temporal variation and frequency histogram of the groundwater table levels at each station. Figs. 5(a) and 5(b). show the areas with the average groundwater table level below 20 meters for the periods of 1991–1992 and 1972–1992, respectively. The difference between the two sub-figures can be observed and may alter the siting decision, making it difficult to immediately reach a proper landfill siting decision.

Rating method-DRASTIC

Further siting analysis was initially implemented using the DRASTIC index system, as listed in Table 1. Each land cell was rated according to its average groundwater table level. According to Table 2, the differences between the maximum and minimum groundwater table variations of Ney-Hu, Mei-Nan, and Pyng-Yuan observation stations exceed 10 meters. Therefore, their groundwater tables cannot properly be depicted using only the average level to determine their pollution potential rating.

Figs. 6(a)–(d). display the areas with DRASTIC rating below or equal to 1, 2, 3 and 5, respectively. According to this figure, the number of areas with different ratings reduces significantly from rating 3 to 2. DRASTIC divides groundwater table levels into several ranges. Different groundwater table levels would have the same impact, rating, if they are in the same range. For instance, groundwater table levels between 1.5 m to 4.5 m are rated to be 9. If the groundwater table level increases by 1 m from an original level of 1.5 m, then the rating will change to 10; however, the rating remains unchanged if the original level is 4.5 m. Different groundwater table levels with the same rating may thus cause problems. Table 3 summarises the differences between each month by the percentage of

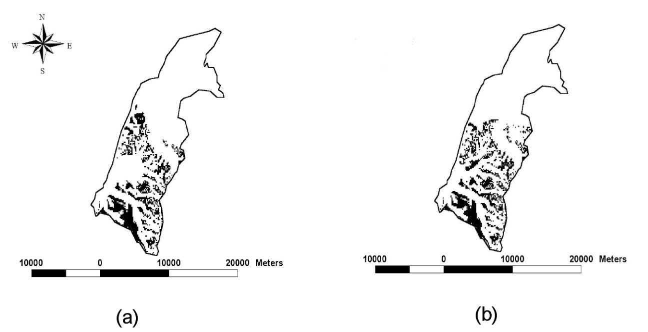

Fig. 5. Preliminary candidate areas with average groundwater table levels under 20 meters: (a)1991-1992; (b) 1972-1992

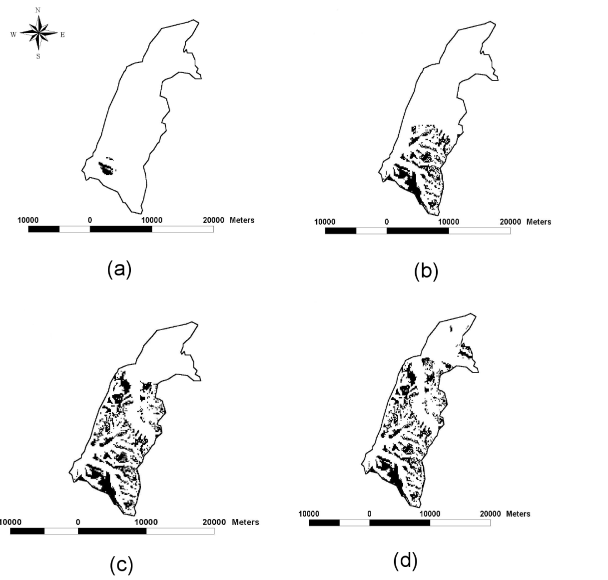

Fig. 6. Areas with DRASTIC rating & ≤ 1, 2, 3, and 5 : (a) rating & ≤ 1; (b) rating & ≤ 2; (c) rating & ≤ 3; (d) rating & ≤ 5

temporal variation for various groundwater table levels. The Ney-Hu, Fan-Shen, Mei-Nan, and Pyng-Yuan observation stations have a greater variation of groundwater table. According to the temporal variation illustrated in Figs. 3 and 4, the likelihood of the rating for the same station being changed is high. A siting decision made based on the rating method may thus be inappropriate.

Precipitation is the major source of groundwater recharge. Since rainfall in each month generally varies, monthly data are therefore analysed for seasonal groundwater table variation. Monthly grade maps are generated based on the DRASTIC rating method. For example, Fig. 7 illustrates a set of such monthly maps for DRASTIC rating below 3. For the map of October, its candidate area is obviously less than those of maps in other months because its groundwater table is significantly higher than others and thus its associated pollution potential is also higher. While overlaying and comparing Fig. 7 with Fig. 6(c), the candidate areas of both figures are obviously different. The original rating method can only provide static or worst-case information and high pollution potential areas due to temporal variation cannot be detected and eliminated.

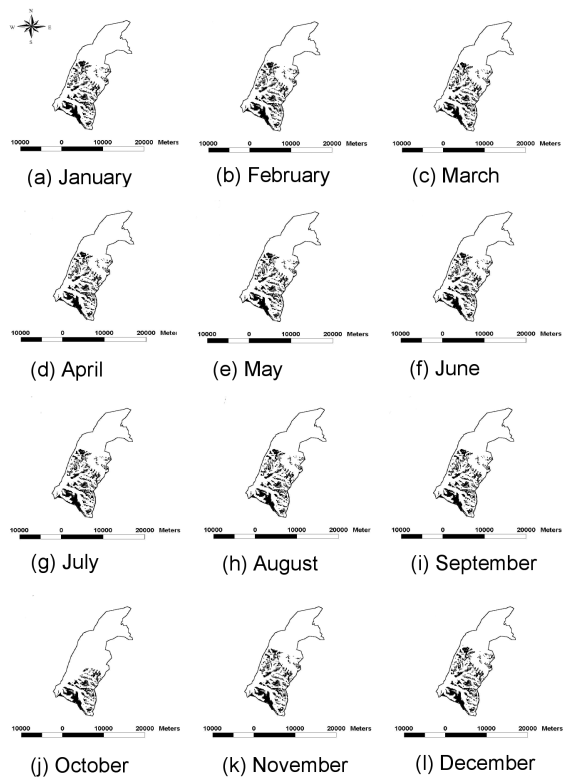

Fig. 7. Areas with DRASTIC rating < 3 for each month

Table 3. Temporal variation of groundwater table at each observation station

Observation	Percentage of difference groundwater table (%)						
Stations	0–0.1 m	0.1–0.5m	0.5–1 m	1–3 m	3–5 m	5–10 m	>10 m
Shoei-Wei	24	59	15	2			
Tong-Shiau	41	30	10	17	2		
Ney-Hu	5	18	14	43	12	7	1
Fan-Shen	9	24	22	37	7	1	
Mei-Nan	6	23	21	37	12	1	
Wu-Fu	37	34	15	12	1	0	1
Pyng-Yuan	4	21	20	32	13	6	4

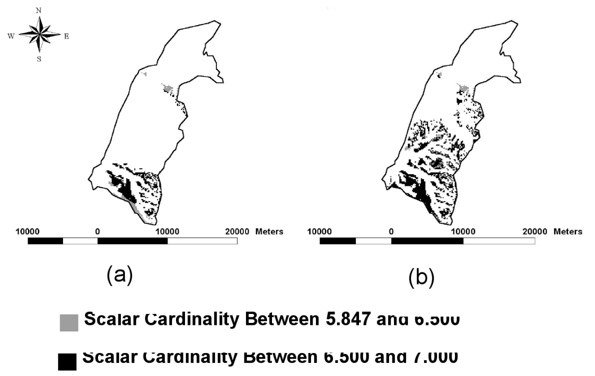

Fig. 8. Candidate areas obtained by using the proposed Fuzzy Markov approach: (a) first step; (b) after-30-years

Fuzzy Markov approach

Data of seven available observation stations in the study area, as listed in Table 2, are used to construct the stochastic matrix for the Markov analysis. A stochastic matrix was established for the seven groundwater table grades, as listed in Table 1, for each observation station. The BIC method is applied to determine the order of the Markov chain. Table 4 lists the BIC values of the varied orders for each observation station, where the one for the first-order is the maximum for all stations. The first order is therefore used herein for Markov chain analysis. According to the transition probabilities determined for all observation stations, the IDW function provided by ArcView (ERSI 1996b) was used to estimate the transition probability of each unmonitored land cell. Seven transition probability GIS maps were then created by ArcView, and subsequently the proposed Fuzzy Markov model was applied. According to the proposed membership function $\mu_A(X)$, candidate areas with acceptable transition probabilities were identified.

Fig. 8 displays the candidate cells selected after the first step and after-30-year transitions. The former represents the short-term effect, while the latter represents the long term (or steady state) effect. From the figure, the scalar cardinality of short-term groundwater pollution potential (Fig. 8(a)) was lower than that of long term potential (Fig. 8(b)). The first step transition eliminates 1634 cells whose membership values equal zero. Among the selected candidate cells, 277 cells have the best scalar cardinality of 7 and the minimal scalar cardinality is 5.850. For the long-term transition, 696 cells are eliminated. Among the selected candidate cells,1681 candidate cells have the best scalar cardinality of 7 and the minimal scalar cardinality is 5.847. These results imply that the probability of groundwater pollution potential will decrease in the long term. Cells close to the Tong-Shiau, Wu-Fu, and Shoei-Wei observation stations, as shown in Fig. 8(a), are eliminated by the first step transition because of their significant groundwater table variation. These cells may not be eliminated by a static approach. For instance, according to Table 2, the average groundwater table level of the Wu-Fu and Pyng-Yuan stations is close to 22.5 m, the upper limit of DRASTIC rating=2. With the DRASTIC approach, the area close to the stations may not be eliminated if the DRASTIC rating limit is set to be ≤ 2 (Fig. 6(b).). However, according to Table 3, the groundwater table of the two stations varies between rating=2 and rating=3. Consequently, the appropriateness of their adjacent areas for landfilling may be uncertain. The proposed Fuzzy Markov process allows effective elimination of inappropriate adjacent areas, as shown in Fig. 8(a) for the first step transition, because the process is based on the transition probability instead of the average level.

Comparing Fig. 8(b) with Fig. 6(c) reveals that the area near the Tong-Shiau observation stations was eliminated by the proposed Fuzzy Markov process but chosen by the DRASTIC rating being set to be 7. The average level of the groundwater table around Shin-Pu station is approximately 8 m and therefore its DRASTIC rating is 7. The Fuzzy Markov approach examines the probability of groundwater table transition. Since the groundwater table of Tong-Shiau does not obviously change, the likelihood of a transfer to a lower groundwater table level is small and thus is still considered an area of high leachate pollution potential in both the short and the long terms.

This study has proposed a Fuzzy Markov process to examine the probability of groundwater table transition.

Table 4. The BIC value for each observation station

Observation Station	BIC Value			
	1st order	2nd order	3rd order	4th order
Ney-Hu	-792.68	-6698.64	-33412.50	-11805.61
Fan-Shen	-346.60	-1279.57	-5592.02	-4150.41
Wu-Fu	-369.93	-1490.01	-6731.39	-6640.66
Pyng-Yuan	-851.21	-7210.49	-37487.22	-11805.61

NOTE: All data for stations of Shoei-Wei, Tong-Shiau, and Mei-Nan are classified into the same grade

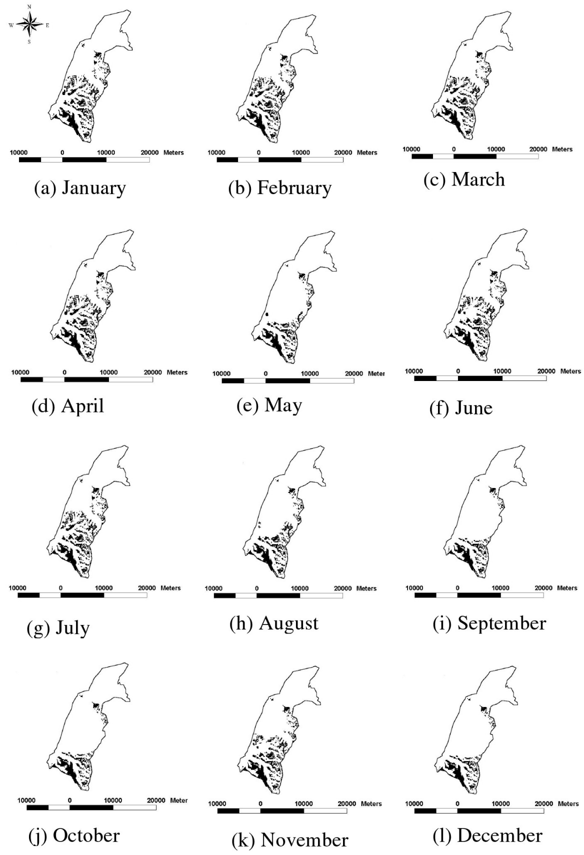

Fig. 9. Areas selected by the short-term (first-step) Fuzzy Markov approach for data in each month

Short-and long-term impacts on the environment are both essential for landfill siting. A static approach such as the DRASTIC method cannot properly depict the dynamic changes in groundwater table and the pollution potential. The proposed Fuzzy Markov process can provide decision makers with both the short- and long-term potential pollution impacts. For instance, according to Figs. 8(a). and 8(b), the area close to the Ney-Hu station may be acceptable for being a landfill site in the long term, but it is less desirable in the short term. From Table 2, the average groundwater table levels of the Tong-Shiau and Wu-Fu stations range between 19.48 m and 23.05 m. With the static approach, the DRASTIC ratings for both stations are identical, rating=3. Therefore, as illustrated in Fig. 6(c), the areas close to both stations are selected by the static approach. However, the selection would be different with the proposed Fuzzy Markov method. The monthly variations in the groundwater table of both stations are beneath 3 m (around 98%), as listed in Table 3. In terms of the long-term result illustrated in Fig. 8(b), the areas adjacent to the Wu-Fu station are selected, while areas around the Tong-shiau station are excluded because its groundwater table variations are different, as shown in Figs. 3 and 4. For the Wu-Fu station, the variation of average groundwater table is insignificant, although it exists an unusual peak of 11.25 m in 1984. For the Tong-Shiau station, the variation of groundwater table is obvious that indicates a higher pollution potential, thus excluding areas around the Tong-Shiau station. This case study demonstrates that the Fuzzy Markov method can improve the static approach and screen out areas with high groundwater pollution potential. The use of short- and long-term information is believed to be able to significantly improve landfill siting decision.

To examine the monthly pollution potential variation, data in the same month are grouped together, and the Fuzzy Markov approach was then applied to each monthly data set for the first-step and after-30-year transitions. Figs. 9 and 10 illustrate monthly results for the short-term and long-term transitions, respectively. For the short-term

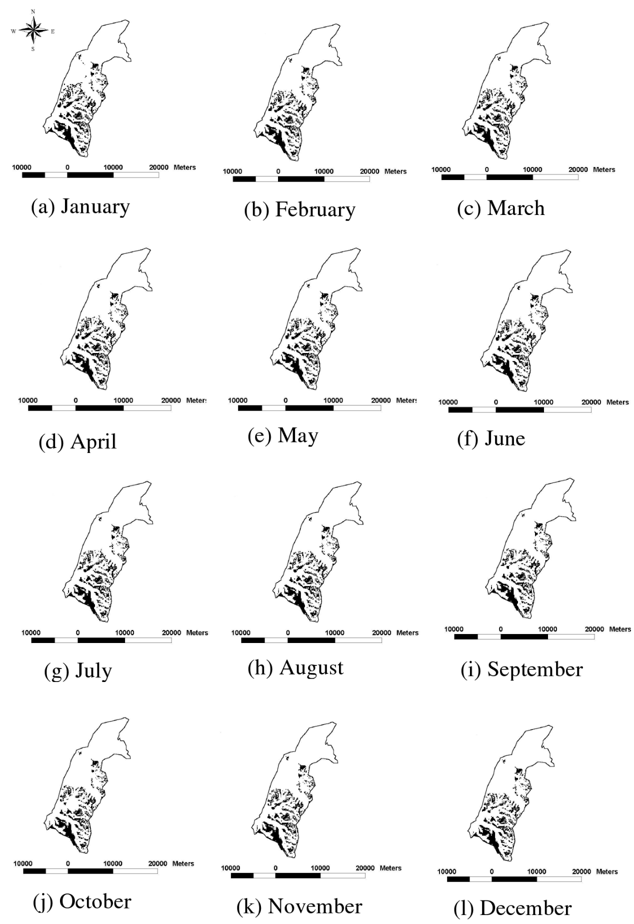

Fig. 10. Areas selected by the long-term (after-30-year) Fuzzy Markov approach for data in each month

result, critical months such as October, September, and December can easily be identified. However, for the long-term transition, critical months are less obvious, although October is still the most critical one. The identification of critical months is useful during the design stage of a landfill site. A landfill designed based on critical monthly situations is believed to have less pollution potential than that based on an overall condition.

Conclusions

Landfill siting analysis should assess leachate pollution potential for groundwater resources. A groundwater table is a dynamic system and frequently changes due to variations in precipitation, topography, geology, soil type, and the up- and down-stream groundwater table levels. Evaluation of groundwater pollution potential based on the average groundwater table level with a static rating method is therefore inappropriate. To overcome this difficulty, this work proposes a Fuzzy Markov approach. This approach estimates the transition probability of a physical system, and the Fuzzy set approach makes it possible to reach a siting decision based on the stochastic matrix obtained from the Markov chain approach. With the proposed approach, the temporal and spatial variation of groundwater table levels can be assessed to provide appropriate short- and long- term information for landfill siting analysis.

Several issues may be worthy of further exploration. Some of them were suggested by the anonymous referees. The multiple liners of a landfill may locally block the recharge from precipitation into the groundwater table and the local recharge pattern may thus be altered by a landfill and may decrease the local groundwater table and increase adjacent water tables. However, this effect applies all candidate sites and is currently assumed not to be significant enough to merit altering the final siting decision. The soil type was not evaluated in this siting analysis. However, different soils have different hydraulic conductivities and attenuation properties and thus have different contamination potentials. Furthermore, the sensitive and uncertainty analyses of such a dynamic approach may be implemented if no clearly superior site can be identified. In case these issues had any possible significant effect on the final decision for a specific siting problem, it should require a further evaluation.

Acknowledgements

The authors would like to thank the National Science Council of the Republic of China for providing partial financial support of this research under Grant No. NSC–87–2211–E-009–007. Valuable comments and suggestions from anonymous referees on revising the manuscript and providing ideas for future researches are also greatly appreciated.

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