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Identification of priority areas for rehabilitation in wastewater systems using ENTROPY, ELECTRE and TOPSIS

Cansu Orhan[a], Mahmut Firat[b,*] and Salih Yilmaz[c]

[a] Vocational School of Technical Sciences, Ardahan University, Ardahan, Turkey
[b] Civil Engineering Department, İnönü University, Malatya, Turkey
[c] Civil Engineering Department, Çankırı Karatekin University, Çankırı, Turkey
*Corresponding author. E-mail: mahmut.firat@inonu.edu.tr

ABSTRACT

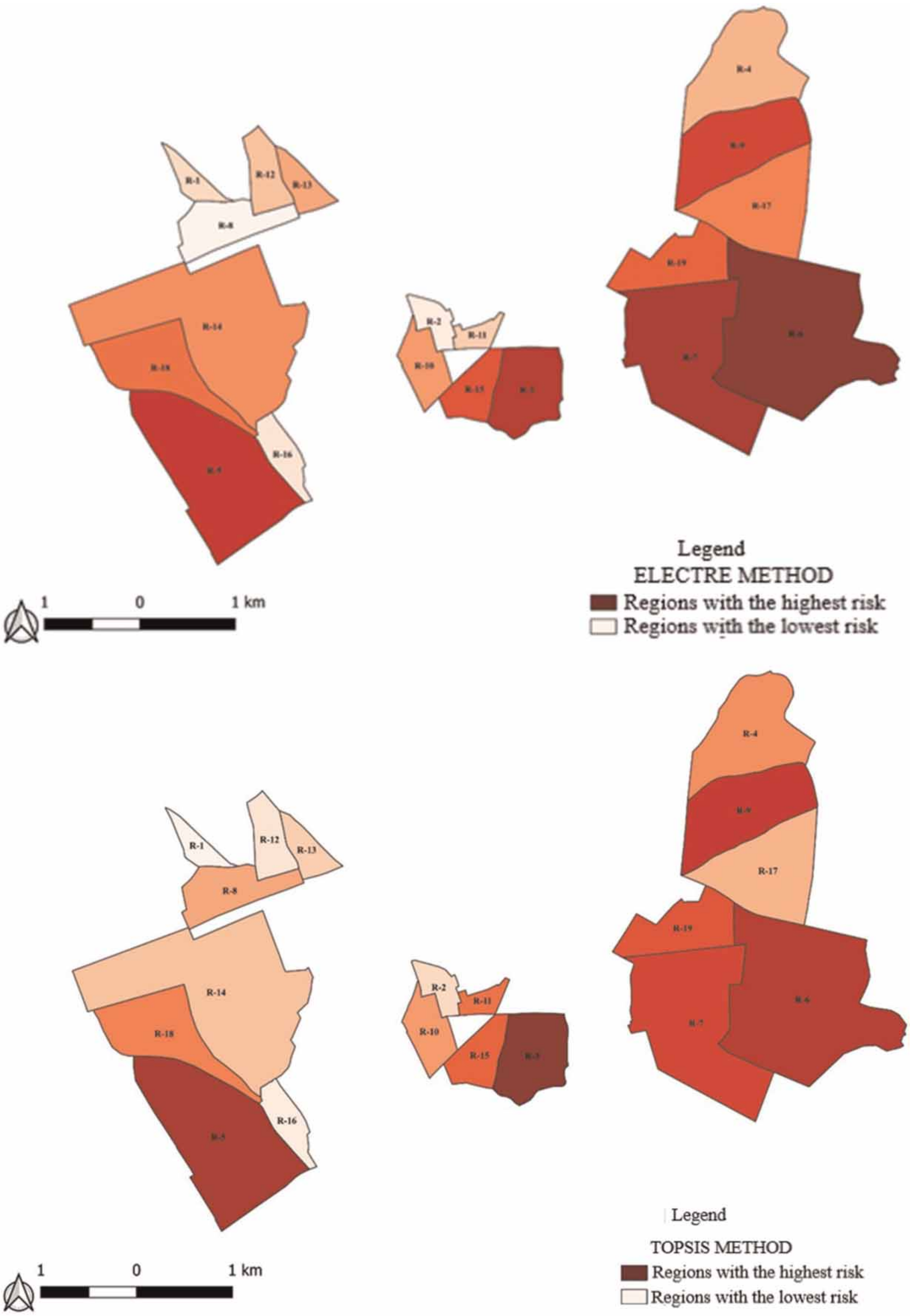
Wastewater system failures cause operating conditions to deteriorate. Therefore, risk factors should be identified and rehabilitation priority should be established by considering all factors. Determining rehabilitation priority areas is very important in terms of public health, service quality and operating cost. The aim of this study, which was carried out in Malatya, Turkey, was to determine rehabilitation priority in wastewater systems by integrating the ENTROPY, ELECTRE and TOPSIS methods. Some 26 physical, hydraulic, operating and cost factors were considered. The factor weightings were determined by the ENTROPY method to define the factors' contributions, based on the field data. Rehabilitation priorities were then determined separately using ELECTRE and TOPSIS, taking the factor weights and field data into consideration. Priority regions in rehabilitation were obtained similar according to both methods. The results obtained will provide a reference for wastewater system management and determination of rehabilitation priorities.

Key words: ENTROPY, multi-criteria decision analysis, pipe rehabilitation, wastewater systems

HIGHLIGHTS

- The priority regions in the rehabilitation of wastewater systems were defined.
- An integrated methodology of ENTROPY, ELECTRE and TOPSIS was proposed.
- The physical, hydraulic, operating and cost factors were considered.
- The data of the factors were obtained according to field measurements.
- The weights of factors were determined by the ENTROPY method based on field data.

GRAPHICAL ABSTRACT



INTRODUCTION

In urban areas, wastewater systems are important infrastructure elements in terms of human and environmental health. In parallel with increasing population numbers, high-quality infrastructure is increasingly required in accordance with environmental standards. Wastewater systems become inadequate due to damage over time and operating conditions deteriorate as a result (Chughtai & Zayed 2008). Faults and structural defects in these systems can adversely affect human health, as well as increasing the potential for wastewater to pollute the environment and natural water resources. Operating, maintenance and repair costs will also increase where these faults continue (Carriço *et al.* 2012). It is thus important to monitor the system, analyze the factors impairing operating conditions and minimize the effect, determine the most problematic regions, create improvement programs and identify the priority regions, to minimize these problems. Detailed analysis is needed to decide on options such as wastewater line renewal or local repair, reverse slope formation, misuse in existing systems, etc. Models and tools need to be developed for this, to assess system condition and performance within the wastewater rehabilitation program (Inanloo *et al.* 2016; Tscheikner-Gratl *et al.* 2017).

Modeling methods depending on evolving computer technology and including artificial intelligence, statistical models, and multiple criteria decision-making methods, have been proposed and applied recently to establish rehabilitation program and damage analysis in wastewater systems (Ana & Bauwens 2010; Barreto *et al.* 2010; Tagherouit *et al.* 2011; Kabir *et al.* 2014; Hlodversdottir *et al.* 2015; Rokstad & Ugarelli 2015; Inanloo *et al.* 2016; Tscheikner-Gratl *et al.* 2017). Considering the neglect of the relationship between variables and the difficulty of the fuzzy synthetic evaluation method in determining the weights of multiple factors, applied ENTROPY in calculating weight coefficients (Yun *et al.* 2006; Zou *et al.* 2006). In this calculation, ENTROPY takes into account the information in the data belonging to the factors and keeps the data item relationships in balance. As a result, it was clear that ENTROPY produced meaningful results in indicator evaluation. The Elimination and Choice Expressing Reality (ELECTRE) outranking method for multi-criteria analysis is suitable for choosing between options (Haider *et al.* 2015; Alamanos *et al.* 2018). The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is also appropriate for outranking options and solving multi-criteria decision-making problems (Behzadian *et al.* 2012; Li *et al.* 2013). Chughtai & Zayed (2008) emphasized that numerous studies have been carried out on determining wastewater system priority regions, but that there is no standard procedure. They stated that physical, environmental and operational factors should be considered together, and noted that the random selection of pipes for system evaluation is very costly and that priority rehabilitation areas should be defined on the basis of failure rates and structural defects.

Carriço *et al.* (2012) emphasized that structural defects and damage – e.g., collapse, deterioration, flooding, and blockage – are inevitable in infrastructure systems and should be managed in the best way using system data. They also stated that the most appropriate rehabilitation strategy should be developed to manage a system in a long-term and sustainable manner. Taking into account performance and cost, the authors aimed to establish and compare ranking methods for prioritizing maintenance activities in sewer lines.

The analytical hierarchy process (AHP) proposed by Saaty (1980) is a multi-criteria method that is applied widely. In it, the process is applied to choose the most suitable option or to sort them. Ennaouri & Fuamba (2013) applied the AHP method for current condition assessment in combined wastewater systems. All factors affecting deterioration – hydraulic, operational and physical – were considered in developing and appropriate evaluation model for wastewater systems in general. Some 15 factors were determined in total and the AHP method was used to determine their relative superiorities. Rokstad & Ugarelli (2015) emphasized that the most important criterion in deciding on wastewater system rehabilitation is a reliable structural condition assessment. They state that many models have been developed to define the current situation in wastewater systems and most have common characteristics. However, apart from choosing a suitable model, the most suitable variables should also be considered.

Chen *et al.* (2015), using AHP and ENTROPY methods together, aimed to make a classification giving rational results to evaluate groundwater sustainability, using quantitative and qualitative indicators. They state that determining the factor weights, showing the factors' contributions to the evaluation result, is the most important step in such analyses and comprehensive evaluations. Ebrahimian *et al.* (2015) proposed a simple, planned and systematic multi-criteria approach, by applying AHP and fuzzy AHP methods based on decision-makers' and technical personnel's opinions, to select the most suitable construction method in urban stormwater projects. Factors such as technical limits, construction restrictions, environmental and legal factors, land use and traffic were considered, and 7 projects evaluated. Kessili & Benmamar (2016) used the AHP and PROMETHEE II methods together in determining rehabilitation project priorities in wastewater systems. The weight coefficients of the variables were determined by AHP, and the alternatives were ranked with PROMETHEE II. Siefi *et al.* (2017) suggested the best candidate thermal power plant sites using multi-criteria evaluation and geographic information system (GIS) in Kahnuj County, southeast Iran. Each criterion was mapped in the GIS environment.

Anbari *et al.* (2017) emphasized that regions in wastewater systems with high failure rates should be identified and their performance improved. They said that it was important to develop a model for determining risk-prone and priority areas in wastewater system rehabilitation, rather than employing time-consuming and costly processes. Hawari *et al.* (2017) said that evaluation of the current situation in wastewater systems, the fuzzy analytical network process method, can be important, especially for decision-makers, in choosing fault repair or renewal activities. Singh *et al.* (2018) investigated surface water quality using quality indices and explored the application of a multi-objective decision-making method (TOPSIS) in arranging decisions for policy makers on the basis of overall ranking of the sampling locations. They felt that the study had justified the effectiveness of TOPSIS in prioritizing decisions for policy makers in complex scenarios. Lizot *et al.* (2020) presented a six-step, multi-criteria methodology for evaluating water treatment systems, considering relevant economic, social, technical and environmental criteria. The AHP and ELECTRE II methods were combined to weight the criteria and rank the systems. Tabesh *et al.* (2020) used the TOPSIS method to investigate the effectiveness of the reduction policies for the apparent and real losses of non-revenue water. Dortaj *et al.* (2020) applied multi-criteria decision-making methods – e.g., AHP, ANP, TOPSIS and ELECTRE – to select suitable construction sites for subsurface dams. They stated that use of an advanced method like ELECTRE reduced some uncertainties in SSD site selection and that this developed methodology could be used as a basis for more detailed field investigations. On the other hand, various literature studies have been carried out on infrastructure management and rehabilitation, such as water distribution pipe renewal based on seismic risk (Youn *et al.* 2021), risk-based pipe renewal strategies (Salehi *et al.* 2021; Sufian *et al.* 2021), pipe replacement scheduling based on optimization algorithm and modeling methods (Salehi *et al.* 2018; Kerwin & Adey 2020; Wu & Abdul-Nour 2020; Zangeneh-madar *et al.* 2020; Dell'Aira *et al.* 2021; Ghobadi *et al.* 2021).

The literature studies show that determining the priority regions in wastewater system rehabilitation is very important in terms of health, operation and cost. Several issues come to the fore in determining wastewater system rehabilitation priority:

(i) selection of the most appropriate methods, integration and requirements,
(ii) determination and integration of variables affecting the problem (taking into account the operational, hydraulic and economic variables rather than just physical factors), and
(iii) realization of the priority ranking.

Therefore, the aim of this study was to determine wastewater system rehabilitation priority using ENTROPY, ELECTRE and TOPSIS together. The most important idea in this study is the determination of weight coefficients using ENTROPY based on the field data.

Rehabilitation priorities were then determined separately using ELECTRE and TOPSIS, by considering the factors' weights and field data.

METHOD

ENTROPY

ENTROPY can be applied in the formation of a decision matrix. In this method, standard normalization is first done using Equation (1), for each decision matrix cell (Zou *et al.* 2006). The ENTROPY value, e_j is calculated using Equation (2).

$$r_{ij} = \frac{x_{ij}}{Makj} \tag{1}$$

$$e_j = -k \sum_{j=1}^{m} p_{ij} \ln(p_{ij}) \tag{2}$$

where i is the decision point, j the parameter, p_{ij} the normalized value (Equation (3)), n the number of decision points, x_{ij} the benefit value, k the ENTROPY coefficient (Equation (4)) and w_j the weights of parameters (Equation (5)). The weight coefficients express the effect level of all variables considered. According to Equation

(5), the weights obtained using ENTROPY should be in the range 0–1, and the sum of their weights should be 1.

$$p_{ij} = \frac{x_{ij}}{\sum_{1}^{j} x_{ij}} \tag{3}$$

$$k = \frac{1}{\ln(n)} \tag{4}$$

$$w_j = \frac{1 - e_j}{\sum_{1}^{m} (1 - e_j)} \tag{5}$$

ELECTRE

ELECTRE is multi-criteria decision-making software that enables the most appropriate ranking to be made by combining a criterion's weight with quantitative and qualitative criteria (Roy 1991; Soner & Önüt 2006).

Creating the decision matrix and normalized decision matrix

The decision matrix (X_{ij}) can be expressed as the initial matrix, containing the alternative data (Equation (6)). A normalized decision matrix (R) is created using Equation (7). The weighted normalized decision matrix (V) given in Equation (8) is obtained by multiplying the elements in the normalized decision matrix and the factor's weight coefficients (Slowinski & Roy 2013).

$$\mathrm{X} = \begin{vmatrix} \mathrm{x}_{11} & \cdots & \mathrm{x}_{1n} \\ \vdots & \cdots & \vdots \\ \mathrm{x}_{1m} & \cdots & \mathrm{x}_{mn} \end{vmatrix} \tag{6}$$

$$\mathrm{R} = \begin{vmatrix} \mathrm{r}_{11} & \cdots & \mathrm{r}_{1n} \\ \vdots & \cdots & \vdots \\ \mathrm{r}_{1m} & \cdots & \mathrm{r}_{mn} \end{vmatrix} \tag{7}$$

$$\mathrm{V} = \mathrm{R} * \mathrm{W} = \begin{vmatrix} \mathrm{v}_{11} & \cdots & \mathrm{v}_{1n} \\ \vdots & \cdots & \vdots \\ \mathrm{v}_{1m} & \cdots & \mathrm{v}_{mn} \end{vmatrix} \tag{8}$$

Determination of the concordance and discordance matrix

The alternatives' factor weights and rankings in the normalized decision matrix (V) are compared to determine the concordant and discordant sets (Adhikary *et al.* 2013). The concordant set elements and the sum of the normalized factor weights are calculated. Moreover, the concordant and discordant matrices are determined (Roy 1991; Adhikary *et al.* 2013; Abdolazimi *et al.* 2015). Formulation of these steps is shown in Figure 3.

Determination of the superiority matrix

First, threshold values of concordance and discordance parameters in decision-making are calculated. Then the superiority of regions is determined by comparing the threshold values of the concordance and discordance parameters (Figure 3) (Roy 1991; Abdolazimi *et al.* 2015). The final superiority matrix (H) is obtained by multiplying each element of the concordance superiority matrix with the discordance superiority matrix (Triantaphyllou 2000). The net distance relationships of the alternatives can be improved by calculating the net concordance (C_{net}) (Equation (9)) and discordance (D_{net}) (Equation (10)) indices for each alternative (Triantaphyllou 2000).

$$C_{net} = \sum_{\substack{q=1 \\ q \neq p}}^{m} C_{pq} - \sum_{\substack{q=1 \\ q \neq p}}^{m} C_{qp} \tag{9}$$

$$D_{net} = \sum_{\substack{q=1 \\ q \neq p}}^{m} D_{pq} - \sum_{\substack{q=1 \\ q \neq p}}^{m} D_{qp} \tag{10}$$

TOPSIS

TOPSIS, a multi-criteria decision-making method, was proposed by Yoon (1980), and developed by Hwang & Yoon (1981). When making a decision using TOPSIS, the alternative should be close to the positive ideal solution point and have Euclidean length from the non-ideal solution point (negative ideal solution) (Lai *et al.* 1994).

Creating the decision matrix and normalized decision matrix

The decision matrix is used to represent the relationship between the parameters affecting the target and alternative regions (Lai *et al.* 1994). The normalized decision matrix representing the relative performance of the alternatives is obtained by Equation (11), (Chen & Hwang 1993; Wang & Chang 2007).

$$\mathrm{NDM} = \mathrm{R_{ij}} = \frac{\mathrm{a_{ij}}}{\sqrt{\sum_{k=1}^{m} \mathrm{a_{ij}^2}}} \tag{11}$$

Finding positive and negative ideal solution values

The weighted decision matrix is formed by multiplying each column of the normalized decision matrix by the weights of the variables (García-Cascales & Lamata 2012). Positive ideal (A + ={V1 + ,V2 + …, Vn + }) and negative ideal (A − ={ V1 − , V2 − …, Vn − }) solutions are defined separately for each alternative, based on the weighted decision matrix (Figure 3) (Huang *et al.* 2018).

Calculation of separation criteria

The distance to the positive and negative ideal solutions is calculated using equations given in Figure 3 (Huang *et al.* 2018; Çelikbilek & Tüysüz 2020).

Calculation of proximity degree

The relative proximity of each alternative to the ideal solution is calculated using Equation (12) (Jadidi *et al.* 2010; Huang *et al.* 2018).

$$\mathrm{C_i*} = \frac{\mathrm{S_i^-}}{\mathrm{S_i^-} + \mathrm{S_i*}},\ 0 \le \mathrm{C_i^*} \le 1 \tag{12}$$

C_i^* is the relative optimal proximity. A numerical value of C_i^* indicates absolute closeness to the ideal solution while a zero (0) value indicates absolute closeness to the negative ideal solution (Jadidi *et al.* 2010; Huang *et al.* 2018).

FACTORS AND DATA

The most important step is to provide accurate and systematically measured data. Not only hydraulic variables are effective on pipe malfunctions, but also the network's physical and environmental factors. This enabled evaluation on the basis of hydraulic and financial data, as well as environmental factors (the condition of critical structures, road type, soil, traffic intensity, etc). Wastewater systems have been examined for the factors that are most important in deciding priority regions in wastewater system rehabilitation and some 226 factors were determined (Chughtai & Zayed 2008; Ana & Bauwens 2010; Barreto *et al.* 2010; Carriço *et al.* 2012; Ennaouri & Fuamba 2013; Mounce *et al.* 2014; Ebrahimian *et al.* 2015; Rokstad & Ugarelli 2015; Del Giudice *et al.* 2016; Inanloo *et al.* 2016). The use of so many different parameters in the analysis is very difficult, increasing the complexity and risk of inaccuracy. Instead of using numerous variables to solve problems, factors representing its natural structure and suited to it were preferred (Table 1). Since regular measurement of the data is the most important stage of model development, measurability has been prioritized when determining the factors. Malatya province, in east Turkey, was selected as the area studied (Figure 1). The total length of the wastewater network is 1,229.4 km (MASKI 2018).

The city center was investigated by considering the pipe type, age, lengths and depth, as well as the slope, occupancy rate and population. The pipe cleaning in the network was performed by technical staff. To obtain the data on these factors, detailed analyses of the wastewater projects, and field calibration and CCTV imaging were applied (Figure 2).

Table 1 | Factor description

Factor	Description
Pipe diameter	Diameter of wastewater pipe
Pipe age	Age of wastewater pipe (years)
Pipe material	Material of wastewater pipes (1 = concrete, 2 = plastic)
Pipe depth	Pipe construction depth (m)
Cleaned pipe length	Pipe length of cleaning and CCTV images (m)
Uncleaned pipe length	Uncleaned pipe length (m)
Pipe slope	Slope of the constructed pipe
Reverse slope ratio	Proportion of pipes with reverse slope in the service system
Street slope	Street slope
Minimum distance between manholes	Minimum distance between two manholes (m)
Maximum distance between manholes	Maximum distance between two manholes (m)
Soil thickness above pipe	Sum of asphalt and liner material thickness above pipe
Number of service connections	Number of building connections to main pipe
Number of customers	Number of customers
D < 250 mm	Pipes smaller than 250 mm diameter
Structural fault ratio	Ratio of the number of faults detected by CCTV camera (oil-grease, pipe material integrity, slump condition, gravel, degradation rate/deformation, tree/plant roots, congestion, building connection, faulty manufacture) to pipe length (n/km).
Pipe overload	Capacity exceeded
System type	1 = separate, 2 = combined
Area	Service area
Population	Population in region
Pipe renewal cost	Renewal cost
Number of failures or repairs	Number of failures or repairs
Soil characteristics	Soil type (e.g., highly aggressive, aggressive, moderate)
Traffic intensity	Traffic intensity in street (high, moderate and low)
Road type	Road type
Number of critical customers	Significant water consumers – e.g., hospitals, schools, military or public buildings, etc.
Area	Area served (m^2)

The structural fault ratio was determined by dividing the number of structural faults found between two manholes on the CCTV images by the distance between them. The structural fault types determined from images include oil-grease, pipe material integrity, slump condition, gravel, degradation rate/deformation, tree and plant roots, blockages, building connections, faulty manufacture, etc. Among the problems occurring in wastewater systems, oil and grease are generally associated with the high oil content in restaurant wastewater, and the discharge from major water consumers such as hospitals and military and public institutions can cause insufficient pipe-flow capacity. Pipe material integrity issues and collapse can be expressed as fractures and cracks at junctions, with pipe movement due to loose ground, excess soil cover and pressure, excessive traffic density and freeze-thaw effects. Pipe collapses can also arise from bad workmanship at connections, pipe aging, unsuitable pipe material, and/or washing away of soil around the pipe. Blockages occur in lines where duct cleaning frequency is low and/or too much paper and wet wipes are discarded. Reverse slopes are usually caused by construction faults.

The physical, operational and hydraulic data in Table 2 were obtained directly from the field-based CCTV images and databases (GIS, SCADA, and failure management system). The customer information, number of

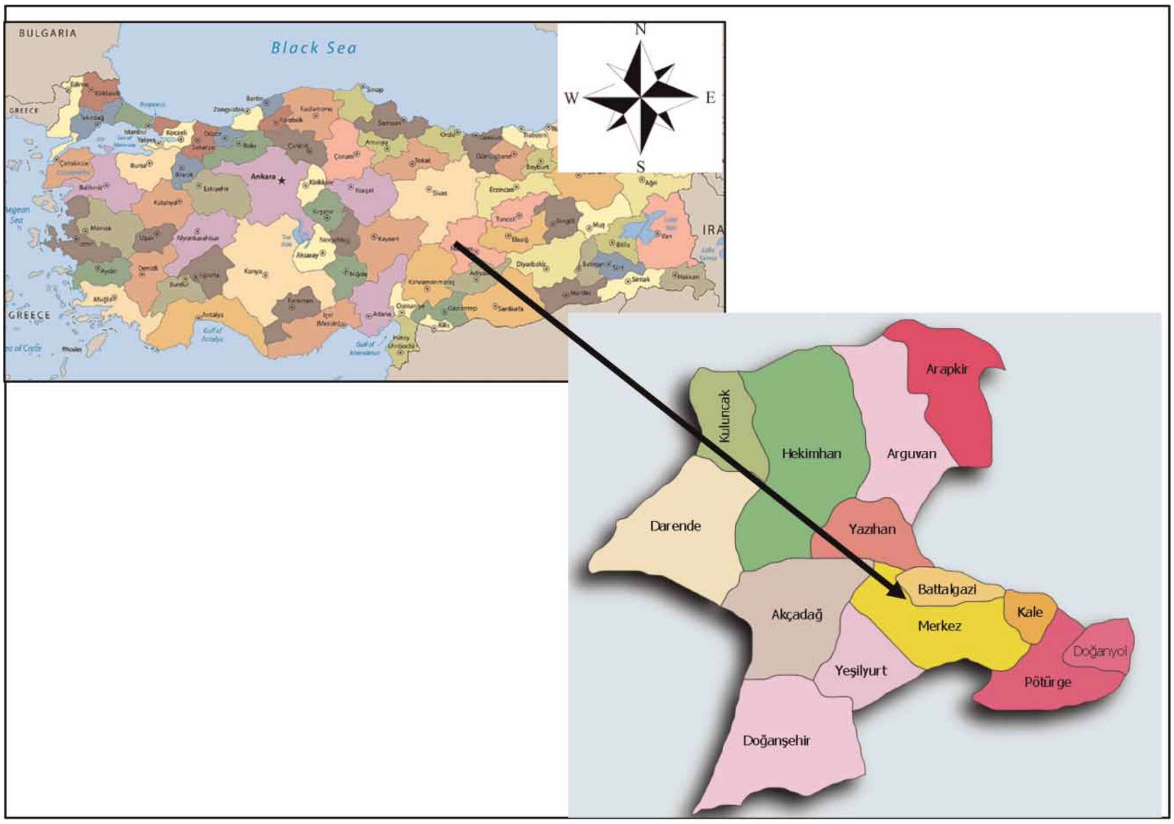


Figure 1 | Study Area (Orhan 2018).

Figure 2 | CCTV images for fault detection (MASKI 2018; Orhan 2018).

Table 2 | Data used in analysis

Region	Pipe diameter	Pipe age	Pipe material	Pipe depth	Cleaned pipe length	Pipe length not cleaned	Pipe slope	Reverse slope ratio	Street slope	Minimum manhole distance	Maximum manhole distance	Soil thickness above pipe	Number of service connections	D < 250 mm
R1	200	21	1	1.953	1,323.25	127.36	0.742	0.730	0.004	1.51	64.87	2.156	183	39
R2	400	20	1	2.103	2,385.01	220.67	1.590	0.047	0.048	1.24	75.5	2.075	184	33
R3	300	16	1	2.517	1,838.63	62.83	0.951	0.078	0.043	1.02	72.41	2.003	180	43
R4	200	25	1	2.138	1,273.61	196.86	2.618	0.212	0.011	1.46	168.73	1.928	137	43
R5	200	25	1	2.097	287.95	59.73	2.677	0.141	0.033	6.4	57.61	2.232	39	13
R6	300	20	1	2.500	470.71	0.10	1.600	0.001	0.131	0.85	58.1	2.703	13	14
R7	200	10	1	2.000	347.54	0.10	0.430	0.001	0.003	27.08	47.18	2.203	38	9
R8	200	10	2	2.000	34.37	0.10	4.000	0.001	0.002	11.76	22.61	2.203	2	2
R9	200	25	1	2.428	881.67	195.63	2.080	0.235	0.010	0.19	59.96	2.478	128	34
R10	200	15	1	2.367	695.90	130.17	2.940	0.250	0.051	2.97	54.29	2.501	103	25
R11	200	15	1	2.730	180.56	31.19	0.650	0.265	0.051	8.5	56.05	2.933	20	8
R12	200	8	1	2.214	2,039.25	33.01	0.480	0.037	0.203	2.88	65.33	1.923	56	47
R13	200	10	1	2.335	586.77	116.79	0.415	0.001	0.013	6.76	62.82	1.920	70	20
R14	200	25	1	2.000	56.12	0.10	0.440	0.001	0.002	19.71	36.41	2.203	6	2
R15	200	25	1	2.020	562.15	55.58	1.420	0.001	0.024	9.84	51.96	2.240	42	16
R16	200	25	1	2.000	534.68	0.10	0.498	0.030	0.002	0.88	58.65	2.203	55	15
R17	200	25	1	2.000	403.50	0.10	0.907	0.001	0.002	1.75	52.65	2.203	59	15
R18	300	15	1	2.383	1,058.60	83.55	2.020	0.229	0.036	0.64	60.18	2.588	45	13
R19	200	13	1	1.870	360.83	1.70	3.285	0.001	0.011	0.81	59.9	2.087	12	12

(*Continued.*)

Table 2 | Continued

Region	Structural fault ratio	Pipe overload	System type	*Area*	*Population*	*Pipe renewal cost*	*Number of failures or repairs*	*Soil characteristic*	*Traffic intensity*	Road type	Number of customers	Number of critical customers
R1	14.79	0.40	2	272,031.00	3,442	686,069.16	52	1	2	1	229	3
R2	7.71	0.40	2	836,126.93	4,264	1,255,937.76	34	1	3	2	323	7
R3	18.73	0.50	2	493,044.78	3,047	916,503.72	43	1	2	2	282	5
R4	14.85	0.50	1	322,162.50	1,803	708,766.54	28	2	3	1	264	2
R5	6.32	0.30	1	74,967.52	1,401	167,581.76	21	2	3	2	182	1
R6	18.46	0.70	2	98,698.37	540	226,882.22	8	2	2	1	97	2
R7	1.73	0.40	1	23,413.53	978	167,514.28	16	2	3	1	88	2
R8	5.82	0.50	1	2,905.85	554	16,566.34	7	2	2	1	43	1
R9	12.08	0.70	1	166,880.15	2,590	519,258.60	50	1	2	1	150	2
R10	17.66	0.70	1	105,319.64	1,970	398,165.74	15	1	3	1	170	2
R11	5.19	0.60	1	25,071.15	406	102,063.50	17	2	2	1	20	1
R12	17.22	0.50	2	607,234.70	3,410	998,829.32	45	2	3	2	230	1
R13	4.44	0.60	1	201,315.16	736	339,115.92	14	2	2	1	110	2
R14	8.91	0.50	1	7,483.02	102	27,049.84	4	1	1	1	19	1
R15	6.94	0.60	1	58,012.82	278	297,745.86	23	1	1	1	71	1
R16	3.44	0.80	1	36,783.45	494	257,715.76	9	1	2	1	113	1
R17	40.18	0.80	1	47,367.47	364	194,487.00	19	1	2	1	88	1
R18	11.52	0.70	1	178,618.91	2,889	550,516.30	25	2	3	2	134	2
R19	6.14	0.60	2	36,002.60	195	174,739.46	9	2	2	2	32	1

critical customers and population were obtained from MASKI's customer management system (Table 2) (MASKI 2018; Orhan 2018).

Data including verbal information such as traffic density, soil characteristics, pipe material type, and system type were converted into numerical data while being processed into the decision matrix For example, the traffic volume was classified as low, medium or high, classified as 1, 2 and 3, respectively, while soil characteristics were classified as low-, medium- and high-motion and also numbered 1, 2 and 3, respectively. Two different pipe materials, generally concrete and corrugated metal – 1 and 2, respectively – were used. as well as two network types, separate and combined lines, also 1 and 2.

Analysis and discussion

In this study, criteria such as suitability, applicability, comparability and data measurability were considered in determining factors that might affect the problem. The factors' weight coefficients were determined on the basis of the field data. Often the weight coefficients of variables are determined by scoring or expert opinion but, in this study, they were calculated using quantitative methods and real field data. Some 50,000 fault reports were analyzed for failure and structural defect data. Increasing the number of regions could raise problems in accessing accurate and reliable data, with negative impact on the results.

In this study, a MATLAB-based model was developed to evaluate the sewer pipes and prioritize rehabilitation. The factor weights were determined using ENTROPY. On the basis of these weight coefficients and field data, wastewater pipes can be prioritized according to risk using ELECTRE and TOPSIS. A flow chart for determining rehabilitation priority regions is given Figure 3.

Determination of weight coefficients

The factor weight coefficients are used to determine regional performance and the rehabilitation priority zones, and it is important to calculate them correctly. ENTROPY was used and the results are shown in Table 3.

The highest weight coefficient calculated was for the inverse slope ratio (0.1238) based on results obtained using ENTROPY (Table 4). Reverse slopes cause water to pond in the pipe and overflow from building connections or manholes, especially when water accumulation is excessive. This poses significant structural, environmental, technical and economic problems, and the risk of increase in failures and maintenance-repair costs rises. On the other hand, weight coefficients for pipe and street slope were calculated as 0.0980 and 0.0994, respectively.

These results show that it is important to choose the most suitable slope during design and lay the pipes with the most appropriate slope during construction. Incorrect pipe slope calculation or incorrect construction due to poor workmanship are major factors that can cause line failure under normal operating conditions.

The results in Table 4 indicate that it would be better to evaluate the structural failure rate (0.075) and uncleaned line length (0.0877) together. These two factors' weight coefficients have the highest values after the slope factor. Normal operating conditions are disrupted in systems where cleaning is not done, and structural defects are not detected and repaired. Other important factors causing wastewater line blockages include construction and workmanship defects, and faulty building connections.

The weight coefficient for service connections is significant at 0.0492. As the number of service connections increases, the frequency of failures and thus the cost of maintenance and repair also increases. The minimum distance between manholes also has a high weight coefficient. As the distance increases, clogging will become more difficult to remove and maintenance costs increase. These evaluations show that the calculated weight coefficients are meaningful and consistent with the nature of the problems.

Priority ranking of regions

After calculating the factor weight coefficients, priority rehabilitation areas were determined using ELECTRE and TOPSIS, and their results compared. Decision matrices, normalized decision matrices and weighted normalized decision matrices were calculated using the decision support software developed. The rehabilitation priority rankings according to ELECTRE and TOPSIS are shown in Figure 4(a) and 4(b). Proximity degrees were calculated according to the ideal solutions and rehabilitation priorities determined (Figure 4).

The priority rankings show that the first 5 region groups determined using ELECTRE and TOPSIS are similar – ELECTRE showing R-6, R-7, R-3, R-5 and R-9, while TOPSIS shows R-3, R-5, R-6, R-9 and R-7. In general, the density of faults is higher in these regions than elsewhere, as are the numbers of connections, which are thought

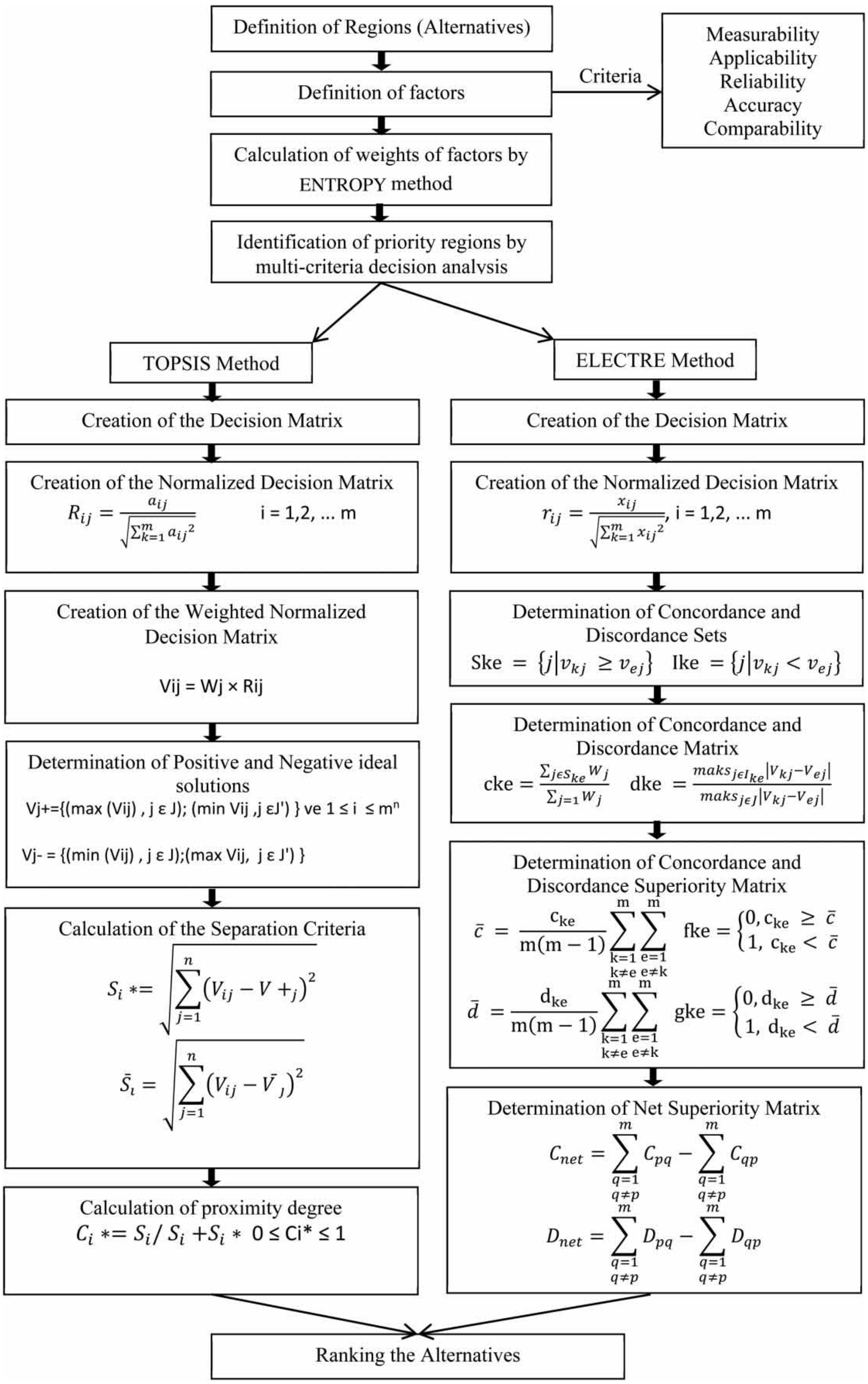


Figure 3 | Flow chart for determining rehabilitation priority regions.

to be significant in pipe failure rates. The regions also have high operating cost levels, particularly because the proportion of pipes with diameters less than 250 mm – i.e., with a high risk of clogging – is generally high.

The rankings show many similar results in this study, as well as differences in rankings (Figure 4). The TOPSIS prioritization determined that some middle-ranking regions – e.g., R-8 and R-11 – are in the lowest ranks according to ELECTRE. Equally, in the ELECTRE prioritization, some middle-ranking regions – e.g., R-1, R-12, R-13 – are in the lowest ranks according to TOPSIS. These differences arise from the methods' working principles.

Table 3 | Weight coefficients determined using ENTROPY

Factor	Weight	Factor	Weight
Pipe diameter	0.0036	Number of customers	0.0310
Pipe age	0.0083	D < 250 mm	0.0317
Pipe material	0.0026	Soil thickness above pipe	0.0010
Pipe depth	0.0008	Pipe overload	0.0043
Cleaned pipe length	0.0457	System type	0.0083
Pipe length not cleaned	0.0877	Area	0.0824
Pipe slope	0.0980	Population	0.0509
Reverse slope ratio	0.1238	Pipe renewal cost	0.0452
Street slope	0.0994	Number of failures or repairs	0.0280
Structural fault ratio	0.0750	Soil characteristic	0.0078
Minimum distance between manholes	0.0596	Traffic intensity	0.0060
Maximum distance between manholes	0.0110	Road type	0.0083
Number of service connections	0.0492	Number of critical customers	0.0310

Table 4 | Priority ranking of regions

	Regions	
Ranking	ELECTRE	TOPSIS
1	R6	R3
2	R7	R5
3	R3	R6
4	R5	R9
5	R9	R7

In ELECTRE, alternative pairs are selected, and binary comparisons and sequencing accord with the compliance and conflict matrices created from the comparisons. In TOPSIS, in the weighted normalized decision matrix, the column gives the maximum positive ideal and the minimum negative ideal for each variable, ranked according to the situation where the alternatives are closest to the positive ideal and furthest from the negative one.

In a decision-making problem with more than one variable, the variables can be contradictory – i.e., when changing from one alternative to another, the values of some variables increase, while decreases in others increases the problem's complexity. Some variables may, therefore, be better for the alternative region studied and some bad. Since the methods' working principles differ and each problem has different variable and alternative features, sequencing must be determined using more than one method to obtain the optimal solution.

CONCLUSIONS

In this study, priority areas in wastewater system rehabilitation were determined by multiple criteria decision-making methods. Criteria such as suitability, applicability, comparability and data measurability were considered in determining the relevant variables. Some 26 factors were considered and their weights calculated using ENTROPY. The highest calculated coefficient was 0.1238 for the inverse slope ratio. Reverse slopes cause water to pond in the pipe and overflow from building connections or manholes, especially when excessive water accumulates, posing significant structural, environmental, technical and economic problems. On the other hand, the coefficients for pipe and street slope were 0.0980 and 0.0994, respectively. The results show that it would be best to evaluate the structural failure rate (0.075) and length of uncleaned line (0.0877) together; these factors' weight coefficients are the highest after the slope factor.

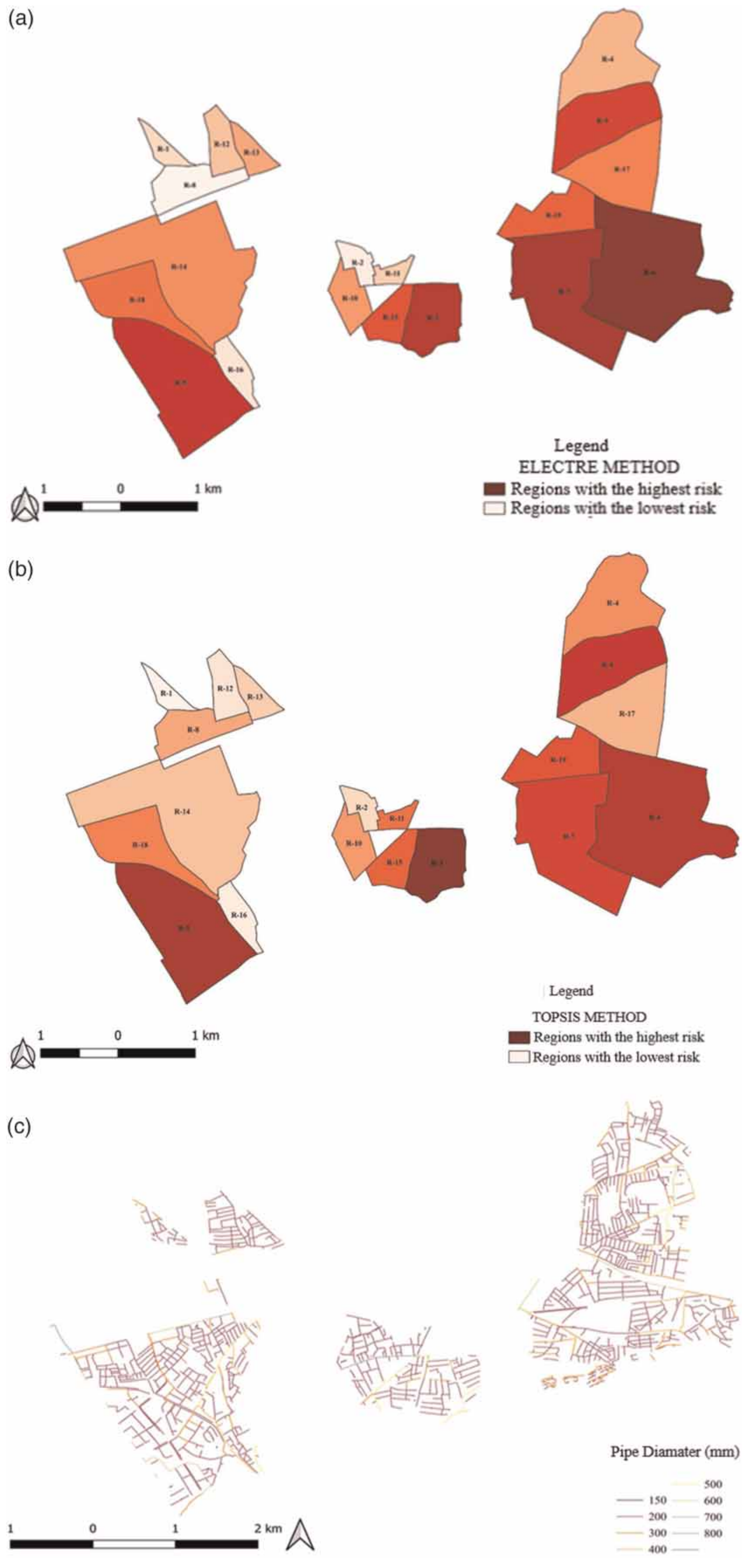


Figure 4 | (a) rehabilitation priority ranking determined using ELECTRE, and (b) using TOPSIS; (c) pipe-diameter distribution in the regions.

The coefficients obtained using ENTROPY represented the nature of the problem and were used, in the next stage, to determine rehabilitation priority regions. This was done using ELECTRE and TOPSIS, based on the weights and field data, and the top 5 regions determined by the two are similar. Fault numbers are generally higher in these regions than elsewhere and the numbers of connections, which are thought to be affect failure rates significantly, are also high.

The lessons learned in determining weights and defining priority regions are:

(i) variable selection – ensuring that data are available, accurate and updated regularly;
(ii) data verification or testing in the GIS database on the basis of CCTV images; and
(iii) determining weight coefficients using field data.

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CONFLICTS OF INTERESTS

The authors have no conflicts of interest to declare.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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