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Application of the analytical hierarchy process for planning the rehabilitation of water distribution networks

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Abstract

Purpose – This study aims to develop a decision support tool to improve planning for the rehabilitation of water distribution networks (WDN) using the analytical hierarchy process (AHP) method and the urgency level score.

Design/methodology/approach – In this paper the AHP method was used to outclass the indicators having a strong influence on the deterioration of the pipes and the score of the level of urgency is calculated to establish the rehabilitation program (short, medium and long term). The proposed model was tested for the case of the city of Souk-Ahras in Algeria.

Findings – Based on the judgments of twenty-four experts, the relative weights of the three physical, operational and environmental criteria of the pipeline were calculated and found to be equal to 35.40%, 55.60% and 9.00%, respectively. The two indicators, number of failures and pressure, were found to have the highest overall weights. The results of this article can be used to improve decision-making in WDN rehabilitation planning in Algeria.

Research limitations/implications – The main objective of water companies is to provide citizens with good quality drinking water in sufficient quantity. However, over time, WDN age, degrade and deteriorate. This degradation leads to a drop in the performance through the degradation of water quality and an increase in loss rates. WDN rehabilitation is one of the most widely adopted solutions to address these drawbacks.

Originality/value – Application of a hybrid method (AHP- Level of Emergency) for the planning of the rehabilitation of WDN in Algeria.

Keywords Water supply service, Rehabilitation, Decision support, MCDM, Urgency level

Paper type Research paper

Introduction

Adequate access to water and sanitation services is a basic human right across the world (Al-Awar, Abdulrazzak, & Al-Weshah, 2006). Water Supply Service (WSS) managers must provide water with good quality and sufficient quantity and pressure at an affordable price to

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all citizens. This water is transported through water distribution networks (WDN). Over time, WDN age and degrade, resulting in higher rates of water loss, poor water quality and deterioration in the quality of service resulting in an increase in customer complaints. Decision-makers and managers of WSS are continually looking for solutions to improve this situation. One of the most widely adopted solutions worldwide is the rehabilitation of WDN (Rahman, Romali, Sufian, & Seman, 2020) in order to provide, consistently, adequate supply to consumers (Prasad, 2021). Rehabilitation consists of repairing, renewing or replacing critical pipes.

In Algeria, the rate of drinking water losses is around 50% in many cities (Boukhari, Pinto, Abida, Djebbar, & de Miras, 2020). These water losses have a negative impact on the economic viability and technical performance of WSS and constitute a relevant indicator of the inefficiency of WSS providers. These inefficiencies are exacerbated by ageing pipes and hydraulic equipment (valves, suction cups, etc.), poor infrastructure management and the quality of leakage repairs, which are among the most relevant factors for the deterioration of drinking WDN (Farley & Trow, 2003). However, rehabilitation planning by decision-makers and WSS managers needs to take into account qualitative and quantitative data and information on different elements using criteria, subcriteria and indicators that are sometimes conflicting and contradictory. To achieve this objective a documentary research (data collection) and interviews with WDN operation and maintenance managers of the local water company (ADE: *Algérienne Des Eaux*), are carried out to identify and select all pertinent factors that have a direct or indirect impact on the degradation and deterioration of WDN in the city of Souk-Ahras.

Several researchers have studied different aspects of WDN rehabilitation including: (1) planning of rehabilitation, (2) strategies to improve rehabilitation practices (Hajibabaei, Nazif, & Sitzenfrei, 2019), (3) rehabilitation techniques and (4) factors influencing WDN rehabilitation. Due to the complexity of using multiple criteria to solve the rehabilitation problem and the lack of data, researchers have promoted the application of multicriteria decision making methods (MCDMs) as an effective decision support tool. MCDMs are widely used because they have a strong ability to produce sustainable and well-structured solutions to different complex decision problems (Lai, Lundie, & Ashbolt, 2008). In recent years, several researchers have applied MCDMs in water resources management (dos Santos Amorim, Bezerra, Silva, & de Sousa, 2020). The Analytical Hierarchy Process (AHP) is the most applied MCDM method in decision-making studies because it is the simplest and the most flexible in comparison to other MCDM methods (Dos Santos, Neves, Sant'Anna, de Oliveira, & Carvalho, 2019).

In this paper, a decision support tool was developed for the improvement of WDN rehabilitation planning. This is done by taking into account the fact that WDN were influenced by internal factors (length, diameter, depth, type of materials, age, location of the pipe, etc.) as well as external factors (type of soil, presence of groundwater, location of other networks, traffic, etc.). Considering all internal and external factors makes decision making very complex and requires the involvement of actors from different fields (decision makers, managers and engineers and scientists) with extensive professional and academic experience. The aim of this decision support tool is to identify pipes that should be rehabilitated in the short, medium and long term according to their level of urgency. The AHP method was applied for the classification of indicators that have a great influence on the planning of the rehabilitation of drinking WDN. The application of our model in a real case can improve the planning of WDN rehabilitation and will have lasting effects on the functional performance and quality of drinking water services.

The article is organized as follows: after this introduction, a literature review on the application of MCDMs and AHP is presented. Next, a full description of the decision support tool that has been developed in this paper is presented. Then, the main results are presented and discussed, and are followed by the conclusion section.

Literature review

Planning the rehabilitation of WDN

In recent years, several researchers have applied different models and methods for planning the rehabilitation of drinking water networks. For example, genetic algorithm (GA) based on case studies and applying multiobjective optimization models have been introduced for rehabilitation scheduling (Alvisi & Franchini, 2009; Bakri *et al.*, 2015; Elshaboury, Attia, & Marzouk, 2020; Dell'Aira, Cancelliere, Creaco, & Pezzinga, 2021). Tabesh, Delavar, and Delkhah (2010) developed a combined geographic information system (ArcView) and hydraulic simulation software (Epanet) for the planning of pipe rehabilitation in WDN. Francisque *et al.* (2014) developed a decision-making tool based on a risk approach and a hybrid genetic algorithm (HGA), named Water main Replacement Risk-based Model (WARRM) to priorities the rehabilitation of drinking water pipes. Other researchers have used machine learning model (Raspati *et al.*, 2022) while several other researchers have applied at least one of the MCDM methods for planning the rehabilitation of WDN (Scholten, Scheidegger, Reichert, Mauer, & Lienert, 2014; Caetano, Carriço, & Covas, 2022).

Multicriteria decision-making (MCDM)

MCDMs are operational research methods used to deal with complex decision problems. MCDMs allow the evaluation of several elements (criteria, subcriteria and alternatives) based on expert judgments to select the best available solutions. MCDMs have been used in several scientific and technical fields such as in energy, transport, industry, civil engineering, engineering, medicine and water resources. According to Hajkowicz and Higgins (2008), there are several MCDM methods, but the most applied in water resources management are techniques for order of preference by similarity to ideal solution (TOPSIS), AHP, elimination and choice translating reality (ELECTRE) and preference ranking and organization method for enrichment evaluation (PROMETHEE) and hybrid methods such as Fuzzy-AHP (FAHP) and AHP-TOPSIS. However, each of these approaches has different characteristics and applications.

Various researchers have applied the different techniques of MCDM to water resources management issues. Santos *et al.* (2016) used a hybrid method by combining AHP with TOPSIS to select the best solutions in drinking water treatment, using four evaluation criteria: financial viability, environmental sustainability, technological performance and social acceptability. Salehi, Jalili Ghazizadeh, and Tabesh (2018) developed a decision-making model called Water Distribution Systems Rehabilitation (WDSR) using a hybrid TOPSIS-Fuzzy method based on technical and nontechnical criteria to plan the rehabilitation of water networks. Ghandi and Roozbahani (2020) developed a decision support tool based on an integrated Fuzzy-PROMETHEE V method to select the best alternatives in the management of drinking water supply by choosing five criteria: reliability of water supply, simplicity of implementation, cost optimization, social satisfaction and quality of drinking water.

Analytical hierarchy process

The AHP method was proposed by Saaty in the 1980s. AHP is one of the most widely used MCDM methods in the field of water management (Hajkowicz & Higgins, 2008). Several researchers have applied the AHP in different sector of water resources management (Dos Santos *et al.*, 2019; Pagano, Giordano, & Vurro, 2021), urban infrastructure management (Fraga, Medellın-Azuara, & Marques, 2017), wastewater management (Igroufa, Benzerra, &

Seghir, 2020), sustainability assessment of water and sanitation services (Boukhari, Djebbar, Amarchi, & Sohani, 2018), reduction of water losses in distribution networks (Zyoud *et al.*, 2016) and water quality assessment (Islam, Sadiq, Rodriguez, & Legay, 2016). Various researchers have applied the AHP method in the case of the rehabilitation of WDN. For example, Kessili & Benmamar (2016) developed a decision support tool based on a combined method of AHP and PROMETHEE II to rank the prioritization of sewer network rehabilitation projects in the city of Algiers (Algeria). The study includes 12 evaluation criteria. The results show that the relative weights of the criteria were: collapse has a major impact on sewer rehabilitation prioritization (0.1849), damage (0.1484), capital expenditure (0.1239), flooding (0.1233), mobility (0.0920), blockage (0.0761), leak (0.0742), rehabilitation technique (0.0630), structural condition of the sewer (0.0426), type of material (0.0299), size of the network (0.0267) and age of the sewer pipes (0.0148). Choi, Han, and Koo (2015) developed a decision method based on a hybrid AHP-ELECTRA approach for the priorization of the rehabilitation of the WDN of the city of Seongnam, Republic of Korea. The authors selected five evaluation criteria. The results of their study were as follows: average pipe age 0.136, pipe aging ratio (≥21 years) 0.216, pipe corrosion 0.209, leak cases 0.341 and safety 0.098. Aschilean, Badea, Giurca, Naghiu, and Iloaie, (2017) applied the AHP method to choose the optimal technology to rehabilitate the pipes of the water distribution systems of the city of Cluj-Napoca, (Romania). The authors used seven decision criteria, which are diameter, pipe length, time required for installation, pipe life, pressure drops, price for pipe replacement and installation conditions.

Materials and methods

Study area and data collection

The city of Souk-Ahras is the capital of the wilaya (Department) of Souk-Ahras, located in the North-East of Algeria. The management of drinking water services (production and distribution) is ensured by the Algerian water company (ADE) since July 2006 (Boukhari, Djebbar, Guedri, & Guebail, 2011). The city of Souk-Ahras is supplied from Ain-Dalia dam and Taoura groundwater. The drinking water supply system is composed of a treatment plant, 18 water tanks with a total storage capacity of 33700 m^3, 55 km of conveyance and 220 km of distribution network (Boukhari & de Miras, 2019). The WDN is composed of different materials (Polyvinyl Chloride (PVC), High-Density Polyethylene (HDPE), cement asbestos (CA), steel and cast iron) and the diameters vary between 63 and 315 mm. The distribution system of the city of Souk-Ahras suffers from several problems, the most notable of which is the lack of continuous service. The causes of this situation lie in the high rate of losses which exceeds 50% (Guebail, Djebbar, Guedri, & Boukhari, 2011; Boukhari *et al.*, 2020).

Methodology of AHP application

As mentioned in several scientific researches, the application of the AHP method is carried out in six main steps (Kilinç, Özdemir, Orhan, & Firat, 2018). The first step of the AHP methodology is to define the main objective related to the problem to be solved. Then, and to achieve the defined goal, the evaluation elements (criteria, subcriteria and alternatives) must be identified. The third step can be illustrated by the creation of the hierarchical structure (a structure with several levels) of its components (Dos Santos *et al.*, 2019). Fourth step is the composition of pairwise comparison matrix for all decision items using standard scoring values taking into account expert judgments. The selected experts were asked to compare the elements with each other according to the scale proposed by Saaty (1980). The last two steps are the calculation of the relative weights of the elements and the verification of the consistency of each comparison matrix. Figure 1 presents the methodology of the AHP application.

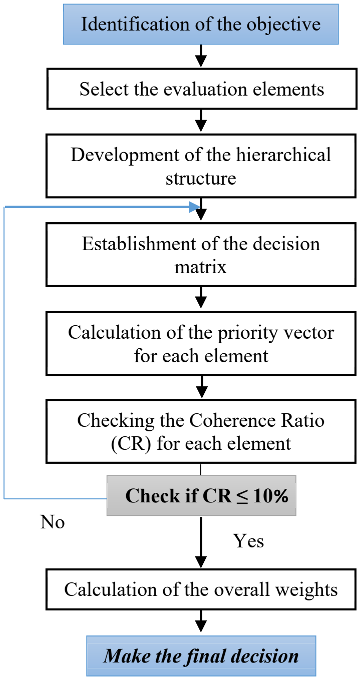

Figure 1.
Methodology for the application of the AHP

This methodology indicates that the elements provide a primary focus for developing decision matrices for each element. However, these matrices help determine the relative weights of each element in the same layer. Then, after calculating the relative weights of each element, the overall weight is determined for each indicator. Finally, based on the final score, the most relevant indicators for WDN rehabilitation planning are determined. The following sections detail the methodology.

(1) Step 1: Identification of the objective

The first step of the AHP is the identification of the problem and the objective of the task at hand being a research or an engineering undertaking.

(2) Step 2: Selection of evaluation items

Before starting the AHP procedures, elements (criteria, subcriteria and indicators) most widely applied in WDN rehabilitation planning should be selected based on the problem of the study area and the opinion of decision-makers and experts.

(3) Step 3: Building the hierarchical structure

The construction of the hierarchical structure involves several levels of assessment. However, the process will divide the complex decision-making into a simple hierarchical structure of all elements of this structure that are divided into independently evaluated layers to facilitate the assessment.

(4) Step 4: Establishing the decision matrices

After the construction of the hierarchical structure, the next step is to establish the decision matrices of all elements for each level. The judgment applied by the experts made it possible to determine the decision matrices for each level of the hierarchical structure. For this purpose, the decision matrices were established by comparing the preference of each element to another element to determine and rank the relative and overall weights. The judgment of these experts was based on the Saaty scale (Table 1).

In this step, a pairwise comparison matrix "A" was defined by the following equation (Eq. (1)):

$$A = (a_{ij})_{nxn} = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1 \end{bmatrix} \tag{1}$$

A is the decision matrix, a_{ij} are the pairwise comparisons between elements i and j for $i,j \in \{1, 2,\ldots, n\}$ and $a_{ii} = 1$ *et* $a_{ij} = 1/a_{ji}$

Where n is the number of each element in the decision matrix.

(5) Step 5: Calculating the priority vector for each element

In this step, priority vectors (relative weights) are calculated for each of the elements (criteria, subcriteria and indicators) in the decision hierarchy. The relative weights are estimated from the comparison matrix (after the expert judgment). Next, it is necessary to check that the sum of all weights should be equal to 1.00. To calculate the relative weights, the following steps should be followed:

- Calculate the sum of each column of the "A" matrix
- Divide each element of matrix "A" by the total of the column, and this will give the normalized matrix "B".
- Calculate the average of each row of matrix "B".

(6) Step 6: Check the consistency ratio (CR) for each element

The calculation of the CR is an important aspect in the application of the AHP method. This step is essential to check the consistency or inconsistency of the decision matrix. According to Saaty, the CR should be equal to or less than 10% (Saaty, 1980). The CR is calculated by comparing a consistency index (CI) with a random index (RI). To check the consistency of the decision matrix, the following steps are required:

- Calculate the eigenvalue λ_{max}

Numerical rate	Definition
1	Equal importance
3	Weak importance of one over another
5	Essential or strong importance
7	Very strong importance
9	Extreme importance
2, 4, 6, 8	Intermediate values between two judgments
Reciprocals of above	If activity i has one of the above nonzero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i

Source(s): (Saaty, 1980)

Table 1. Saaty numerical scale

- Determine the value *RI*
- Calculate *CI*
- Calculate *CR*
- Check *CR*

Next, the important step in calculating the AHP was to assess the consistency of the pairwise comparisons. In this step, the consistency assessment was performed based on the verification of the *CR* (Zyoud *et al.*, 2016). As a general rule, *CR* should not exceed 10% for the decision matrix to be coherent (Saaty, 1980; Şener, Şener, Nas, & Karagüzel, 2010). Otherwise, if the percentage of *CR* is greater than 10%, the level of inconsistency should be improved by gradually reducing or increasing the most incoherent value of the decision matrix (Calizaya, Meixner, Bengtsson, & Berndtsson, 2010). According to Saaty (1980), the coherence of each matrix has been calculated from Eq. (2):

$$CR = \frac{CI}{RI} \tag{2}$$

where *CI* is the consistency index and *RI* is the random index.

- *RI* is given in Table 2.
- As suggested by Saaty (1980), *CI* is calculated using Eq. (3):

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{3}$$

- λ_{max}: the largest eigenvalue of the consistency vector,
- n: the number of elements in each matrix (criteria, subcriteria or indicators).

(7) Step 7: Calculation of overall weights

Once these steps have been completed, the AHP provides a vector of overall weights for the last level by multiplying all the relative weights of each element in all levels.

(8) Step 8: Making the final decision

The final step begins by summing the relative values for each set of elements at all hierarchical levels. These values are combined to establish the overall score for the indicators related to the subcriteria layer.

Results and discussion

This section illustrates the process of applying the AHP methodology to the decision-making problem for the planning of the rehabilitation of the drinking WDN of the city of Souk-Ahras,

Table 2. Random consistency index (*RI*)

n	1	2	3	4	5	6	7	8	9	10	11	12
RI	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49	1.52	1.54

Source(s): (Saaty, 1980)

Algeria. Then, the results of the pairwise comparison for the elements of the three levels are presented. Finally, a rehabilitation program was developed to test the performance of this decision support tool.

Selection of assessment items

The AHP method starts with the identification of the problem and the objective of the project. In our case, the main objective is to rank the indicators that have major influence on the planning of the rehabilitation of drinking WDN. Then, the elements are selected by decision-makers, WSS managers and experts. In conclusion, three decision criteria (physical, operational and pipe environment), seventeen evaluation subcriteria and fifty-six indicators were considered for the decision-making of WDN rehabilitation planning (Table 3).

Developing the hierarchical structure

The hierarchical structure makes it possible to identify the contribution of each element to the final decision. In the case of our study, four levels are considered in the AHP process: the first level is dedicated to the evaluation objective, while the other three levels are assigned to the three elements (criteria, subcriteria and indicators). The hierarchical structure developed in this paper is presented in Figure 2. For the criteria level (*Cr*), three decision criteria are considered: (Cr_1) physical, (Cr_2) operational and (Cr_3) pipeline environment. At the subcriteria level, a total of 17 subcriteria (*SC*) were applied for the evaluation of the upper-level criteria, six subcriteria SC_1–SC_6 were selected for Cr_1 respectively, five subcriteria SC_7–SC_{11} were selected for Cr_2 and six subcriteria SC_{12}–SC_{17} were favored for Cr_3. Then, two to five Indicators (*I*) related to each subcriterion are selected based on scientific literature, expert experience and local conditions. For example, for the subcriterion “Types of materials” (SC_2), the indicators chosen are CA $I_{1.2.1}$, PVC $I_{1.2.2}$, HDPE $I_{1.2.3}$, Steel $I_{1.2.4}$ and Cast Iron $I_{1.2.5,}$ respectively.

Establishing the decision matrix

To establish the decision matrix, twenty-four experts (eight university researchers who have published scientific articles in the field of water management, eight decision-makers from the water resources directorate and eight WSS managers from the Souk-Ahras ADE unit) were selected to carry out the judgment (pair-wise comparison) according to the Saaty comparison scale. These experts were chosen according to their professional and scientific experience; they have wide knowledge in WDN management. For this purpose, decision matrices were developed for three levels:

(1) The M1 matrix represents the evaluation of three decision criteria;

(2) The three matrices M2.1−M2.3 represent the 17 evaluation subcriteria;

(3) The matrices M3.1−M3.17 represent the performance of the 56 Indicators.

After establishing the decision matrices, the AHP will be applied to calculate the relative weights at each level, and the consistency of the results will be checked.

- Pairwise comparison of criteria

To perform the pairwise comparisons for the three criteria, the judgment results of the 18 experts were listed in a single decision matrix [M1]. Then the AHP process is applied to this matrix.

Criteria	Weight	Sub-criteria	Weight	Indicators	Weight
Physical	*0.354*	*Diameters (mm)*	*0.182*	Φ < 100	0.061
				100 ≤ Φ ≤ 200	0.134
				201 ≤ Φ ≤ 300	0.259
				Φ > 300	0.545
		Types of Materials	*0.265*	CA	0.353
				PVC	0.328
				HDPE	0.155
				Steel	0.111
				Melting	0.053
		Length (m)	*0.089*	Lg < 100 m	0.092
				100 ≤ Lg ≤ 300	0.104
				301 ≤ Lg ≤ 600	0.276
				Lg > 600	0.529
		Age of the pipe (years)	*0.367*	Age < 10	0.098
				10 ≤ Age ≤ 30	0.186
				30 < Age ≤ 50	0.277
				Age > 50	0.439
		Corrosion protection	*0.062*	Internal	0.087
				External	0.274
				No	0.639
		Seals	*0.035*	Glued	0.369
				Bonded with cement	0.354
				Mechanical	0.135
				Thermo fusions	0.096
				Welded	0.047
Operational	*0.556*	*Pressure (bars)*	*0.348*	Pr < 2	0.098
				2 ≤ Pr ≤ 6	0.334
				Pr > 6	0.568
		Velocity (l/s)	*0.120*	V < 0.5	0.060
				0,5 ≤ V ≤ 1.5	0.282
				V > 1.5	0.658
		Failures	*0.325*	0	0.093
				1 ≤ *F* ≤ 3	0.221
				F > 3	0.685
		Drinking water quality	*0.041*	Aggressive	0.260
				Not Aggressive	0.106
				too aggressive	0.633
		Network maintenance	*0.166*	Good	0.106
				Medium	0.260
				Bad	0.633
Pipe environment	*0.090*	*Soil Types*	*0.185*	NonCorrosive Soil	0.333
				Corrosive Soil	0.667
		Laying bed (cm)	*0.265*	Absent	0.589
				Lit ≤ 10	0.252
				Lit > 10	0.159
		Groundwater	*0.074*	Present	0.750
				Absent	0.250
		Pipe depth	*0.099*	Pro < 1	0.633
				1 ≤ Pro ≤ 2	0.260
				Pro > 2	0.106
		Traffic	*0.319*	Main road	0.656
				Secondary route	0.265
				pedestrian crossing	0.080
		Genoa because of other networks	*0.058*	Installation of another network	0.343
				Road works	0.575
				Repair	0.082

Table 3.
The relative weights of the selected elements

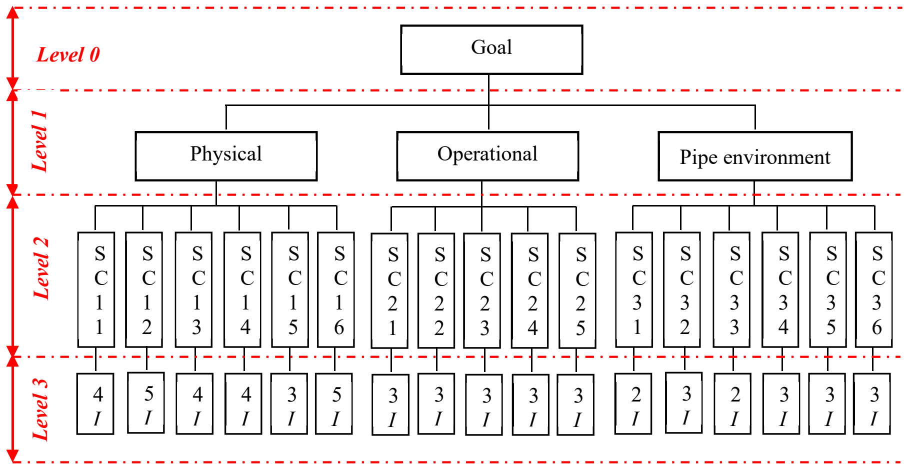

Figure 2. Graphical representation of the proposed hierarchical structure

$$M1 = \begin{bmatrix} 1 & 1/2 & 5 \\ 2 & 1 & 5 \\ 1/5 & 1/5 & 1 \end{bmatrix}$$

Calculating the priority vector

(1) This is done by summing up of each column of the matrix [M1]:

	Cr1	Cr2	Cr3
Cr1	1	0.50	5
Cr2	2.00	1	5
Cr3	0.20	0.2	1
Somme	*3.20*	*1.7*	*11*

(2) Then, divide each element of the matrix [M1] by the total of the column, hence the normalized matrix [B1].

$$B1 = \begin{bmatrix} 0,3125 & 0,2941 & 0,4545 \\ 0,6250 & 0,5882 & 0,4545 \\ 0,0625 & 0,1176 & 0,0909 \end{bmatrix}$$

(3) Finally, get the relative weight vector $\{w_1\}$ by calculating of the average of each row of the matrix [B1]:

$$w_1 = \begin{vmatrix} 0,354 \\ 0,556 \\ 0,090 \end{vmatrix}$$

Verification of the coherence ratio (CR)

(1) Calculating the eigenvalue λ_{max}

To calculate the eigenvalue λ_{max}, the vector $\{C\}$ must first be calculated. It is calculated from Eq. (4):

$$\{C\} = [M1]\,\mathrm{x}\,\{w_1\} \tag{4}$$

$$\{C\} = \begin{bmatrix} 1 & 1/2 & 5 \\ 2 & 1 & 5 \\ 1/5 & 1/5 & 1 \end{bmatrix} \mathrm{x} \begin{vmatrix} 0,354 \\ 0,556 \\ 0,090 \end{vmatrix} = \begin{vmatrix} 1,083 \\ 1,715 \\ 0,272 \end{vmatrix}$$

The calculation of the eigenvector $\{\lambda\}$ is performed by Eq. (5):

$$\{\lambda\} = \{C\}/\{w_1\} \tag{5}$$

$$\{\lambda\} = \begin{vmatrix} 1,083 \\ 1,715 \\ 0,272 \end{vmatrix} \Big/ \begin{vmatrix} 0,354 \\ 0,556 \\ 0,090 \end{vmatrix} = \begin{vmatrix} 3,06 \\ 3,09 \\ 3,01 \end{vmatrix}$$

λ_{max} is the large value of the vector $\{\lambda\}$

$\lambda_{max} = 3.09$.

(2) Determine the value of the random index (*RI*)

From Table 2, for $n = 3 \rightarrow RI = 0.58$.

(3) Calculate the coherence index (*CI*)

$$CI = \frac{\lambda_{max} - n}{n - 1} = 0,045$$

(4) Calculate *CR*

$$CR = \frac{CI}{RI} = 0,776$$

(5) Check *CR*

The CR value for this matrix is 0.776 (7.76%), which is less than 10%. Therefore, the matrix is considered to be consistent.

The results of the calculation of the relative weights of the criteria matrix [M1] are shown in Figure 3, the criterion "operational" plays the most important role with a relative weight of 55.6% followed by the criterion "physical" (35.4%), and the criterion "pipe environment" (9.0%). In general, operational and physical criteria such as the high age of pipes, repair of leaks and decrease in high operating pressure of WDN have a great influence on failures of drinking water pipes.

- Pairwise comparison of the subcriteria

The process of pairwise comparison of the sub-criteria matrices ([M2.1], [M2.2] and [M2.3]) is carried out in the same way as the pairwise comparison of the criteria matrix [M1]. [M2.1], [M2.2] and [M2.3] represent the three pairwise comparison matrices for all 17 subcriteria. The consistency check is performed in the same way as for the criteria matrix.

$$M2.1 = \begin{bmatrix} 1 & 1/5 & 4 & 1/3 & 4 & 6 \\ 5 & 1 & 3 & 1/2 & 3 & 5 \\ 1/4 & 1/3 & 1 & 1/4 & 2 & 3 \\ 3 & 2 & 4 & 1 & 5 & 9 \\ 1/4 & 1/3 & 1/2 & 1/5 & 1 & 2 \\ 1/6 & 1/5 & 1/3 & 1/9 & 1/2 & 1 \end{bmatrix} \{w_{2.1}\} = \begin{vmatrix} 0,182 \\ 0,265 \\ 0,089 \\ 0,367 \\ 0,062 \\ 0,035 \end{vmatrix}$$

CR = 9.84% < 10% → consistency is verified.

The subcriteria, age of the pipe (36.7%), types of materials (26.5%) and diameters (18.2%), have the highest relative weights for the "physical" criterion and the type of joints is the lowest subcriterion with 3.5%.

$$M2.2 = \begin{bmatrix} 1 & 5 & 1 & 7 & 2 \\ 1/5 & 1 & 1/3 & 6 & 1/2 \\ 1 & 3 & 1 & 5 & 3 \\ 1/7 & 1/6 & 1/5 & 1 & 1/5 \\ 1/2 & 2 & 1/3 & 5 & 1 \end{bmatrix} \{w_{2.2}\} = \begin{vmatrix} 0,348 \\ 0,120 \\ 0,325 \\ 0,041 \\ 0,166 \end{vmatrix}$$

CR = 9.99% < 10% → consistency is verified.

Pressure (34.8%) and the number of failures (32.5%) are the two subcriteria that have high influence on the criterion "Operation". According to experts' judgments and for the case of Souk-Ahras city, the subcriterion "water quality" does not have a great effect on the functioning of the WDN.

$$M2.3 = \begin{bmatrix} 1 & 1 & 3 & 2 & 1/3 & 4 \\ 1 & 1 & 2 & 3 & 1 & 9 \\ 1/3 & 1/2 & 1 & 1/3 & 1/5 & 2 \\ 1/2 & 1/3 & 3 & 1 & 1/4 & 1 \\ 3 & 1 & 5 & 4 & 1 & 3 \\ 1/4 & 1/9 & 1/2 & 1 & 1/3 & 1 \end{bmatrix} \{w_{2.3}\} = \begin{vmatrix} 0,185 \\ 0,265 \\ 0,074 \\ 0,099 \\ 0,319 \\ 0,058 \end{vmatrix}$$

CR = 8.83% < 10% → consistency is verified.

The subcriteria, type of traffic (31.9%), laying bed (26.5%) and type of soil (18.5%), play an important role in the criterion "pipeline environment".

- Pairwise comparison of indicators

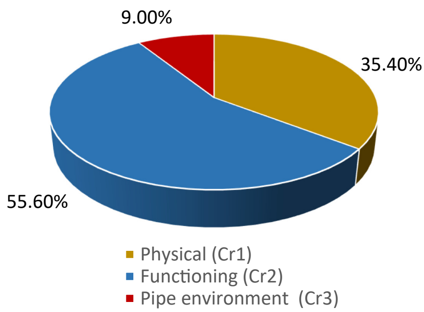

Figure 3. Assignment of relative weights at the criteria level

The relative weights of the indicators are calculated in relation to the matrices M3.1 – M3.17. The pairwise comparison process for the Indicator layer is the same as for the criteria and subcriteria. For this purpose, the priority vectors are calculated in the same way as for the other levels.

$$M3.1 = \begin{bmatrix} 1 & 1/3 & 1/4 & 1/7 \\ 3 & 1 & 1/3 & 1/4 \\ 4 & 3 & 1 & 1/3 \\ 7 & 4 & 3 & 1 \end{bmatrix} \quad w_{3.1} = \begin{vmatrix} 0,062 \\ 0,134 \\ 0,259 \\ 0,545 \end{vmatrix}$$

CR = 7,31% < 10% → Consistency is verified

$$M3.2 = \begin{bmatrix} 1 & 2 & 2 & 3 & 5 \\ 1/2 & 1 & 3 & 4 & 7 \\ 1/2 & 1/3 & 1 & 2 & 3 \\ 1/3 & 1/4 & 1/2 & 1 & 2 \\ 1/5 & 1/7 & 1/3 & 1/2 & 1 \end{bmatrix} \quad w_{3.2} = \begin{vmatrix} 0,353 \\ 0,328 \\ 0,155 \\ 0,111 \\ 0,053 \end{vmatrix}$$

CR = 9,82% < 10% → Consistency is verified

$$M3.3 = \begin{bmatrix} 1 & 1 & 1/4 & 1/5 \\ 1 & 1 & 1/3 & 1/4 \\ 4 & 3 & 1 & 1/3 \\ 5 & 4 & 3 & 1 \end{bmatrix} \quad w_{3.3} = \begin{vmatrix} 0,092 \\ 0,104 \\ 0,276 \\ 0,528 \end{vmatrix}$$

CR = 8,17% < 10% → Consistency is verified

$$M3.4 = \begin{bmatrix} 1 & 1/3 & 1/3 & 1/3 \\ 3 & 1 & 1/2 & 1/3 \\ 3 & 2 & 1 & 1/2 \\ 3 & 3 & 2 & 1 \end{bmatrix} \quad w_{3.4} = \begin{vmatrix} 0,098 \\ 0,186 \\ 0,277 \\ 0,439 \end{vmatrix}$$

CR = 7,39% < 10% → Consistency is verified

$$M3.5 = \begin{bmatrix} 1 & 1/4 & 1/6 \\ 4 & 1 & 1/3 \\ 6 & 3 & 1 \end{bmatrix} \quad w_{3.5} = \begin{vmatrix} 0,087 \\ 0,274 \\ 0,639 \end{vmatrix}$$

CR = 8,65% < 10% → Consistency is verified

$$M3.6 = \begin{bmatrix} 1 & 1 & 3 & 5 & 7 \\ 1 & 1 & 3 & 4 & 7 \\ 1/3 & 1/3 & 1 & 2 & 3 \\ 1/5 & 1/4 & 1/2 & 1 & 2 \\ 1/7 & 1/7 & 1/3 & 1/2 & 1 \end{bmatrix} \quad w_{3.6} = \begin{vmatrix} 0,369 \\ 0,354 \\ 0,135 \\ 0,096 \\ 0,046 \end{vmatrix}$$

CR = 8,54% < 10% → Consistency is verified

$$M3.7 = \begin{bmatrix} 1 & 1/4 & 1/5 \\ 4 & 1 & 1/2 \\ 5 & 2 & 1 \end{bmatrix} \quad w_{3.7} = \begin{vmatrix} 0,098 \\ 0,334 \\ 0,568 \end{vmatrix}$$

CR = 3,50% < 10% → Consistency is verified

$$M3.8 = \begin{bmatrix} 1 & 1/6 & 1/9 \\ 6 & 1 & 1/3 \\ 9 & 3 & 1 \end{bmatrix} \quad w_{3.8} = \begin{vmatrix} 0,060 \\ 0,282 \\ 0,658 \end{vmatrix}$$

CR = 8,84% < 10% → Consistency is verified

$$M3.9 = \begin{bmatrix} 1 & 1/3 & 1/6 \\ 3 & 1 & 1/4 \\ 6 & 4 & 1 \end{bmatrix} \quad w_{3.9} = \begin{vmatrix} 0,094 \\ 0,221 \\ 0,685 \end{vmatrix}$$

CR = 9,43% < 10% → Consistency is verified

$$M3.10 = \begin{bmatrix} 1 & 3 & 1/3 \\ 1/3 & 1 & 1/5 \\ 3 & 5 & 1 \end{bmatrix} \quad w_{3.10} = \begin{vmatrix} 0,261 \\ 0,106 \\ 0,633 \end{vmatrix}$$

CR = 6,20% < 10% → Consistency is verified

$$M3.11 = \begin{bmatrix} 1 & 1/3 & 1/5 \\ 3 & 1 & 1/3 \\ 5 & 3 & 1 \end{bmatrix} \quad w_{3.11} = \begin{vmatrix} 0,106 \\ 0,261 \\ 0,633 \end{vmatrix}$$

CR = 6,20% < 10% → Consistency is verified

$$M3.12 = \begin{bmatrix} 1 & 1/2 \\ 2 & 1 \end{bmatrix} \quad w_{3.12} = \begin{vmatrix} 0,333 \\ 0,667 \end{vmatrix}$$

CR = 0% < 10% → Consistency is verified

$$M3.13 = \begin{bmatrix} 1 & 3 & 3 \\ 1/3 & 1 & 2 \\ 1/3 & 1/2 & 1 \end{bmatrix} \quad w_{3.13} = \begin{vmatrix} 0,589 \\ 0,252 \\ 0,159 \end{vmatrix}$$

CR = 8,13% < 10% → Consistency is verified

$$M3.14 = \begin{bmatrix} 1 & 3 \\ 1/3 & 1 \end{bmatrix} \quad w_{3.14} = \begin{vmatrix} 0,750 \\ 0,250 \end{vmatrix}$$

CR = 0% < 10% → Consistency is verified

$$M3.15 = \begin{bmatrix} 1 & 3 & 5 \\ 1/3 & 1 & 3 \\ 1/5 & 1/3 & 1 \end{bmatrix} \quad w_{3.15} = \begin{vmatrix} 0,633 \\ 0,261 \\ 0,106 \end{vmatrix}$$

CR = 6,20% < 10% → Consistency is verified

$$M3.16 = \begin{bmatrix} 1 & 3 & 7 \\ 1/3 & 1 & 4 \\ 1/7 & 1/4 & 1 \end{bmatrix} \quad w_{3.16} = \begin{vmatrix} 0,656 \\ 0,265 \\ 0,079 \end{vmatrix}$$

CR = 5,37% < 10% → Consistency is verified

$$M3.17 = \begin{bmatrix} 1 & 1/2 & 5 \\ 2 & 1 & 6 \\ 1/5 & 1/6 & 1 \end{bmatrix} \quad w_{3.17} = \begin{vmatrix} 0,343 \\ 0,575 \\ 0,082 \end{vmatrix}$$

CR = 4,16% < 10% → Consistency is verified

The "diameter over 300mm" indicator has the highest weight for the subcriterion (diameters) with a rate of 54.5%. The results of all the other indicators are presented in Table 3.

Calculation of global weights

The overall weight of the indicators is calculated by multiplying its local priority vector by the corresponding local weight of the criterion and subcriteria. The overall indicator weights are synthesized to establish the overall priorities for the selection of indicators that have a high influence on the malfunctioning of drinking water pipes. The results of the global indicator weights are shown in Figure 4.

According to Figure 4, the global weights of the indicators, which have a great influence on the rehabilitation of WDN, are the number of failures exceeding 3 leaks in the same place (I.2.3.3) and the pressure, which exceeds 6 bars (I.2.1.3), and if age of the pipe is over 50 (I.1.4.4) with the following respective percentages 12.38%, 10.98% and 5.70%.

Calculating of the level of urgency

Before a final decision is made, the urgency level must be calculated to enable the classification of pipes that are to be rehabilitated in the short, medium and long term. To perform this task, the model has to be applied to a real case with real data. The 1700 dwelling district, city of Souk-Ahras, was chosen due to the high number of leakage repairs in recent years. The distribution network of the 1700 dwelling district has a length of 12860 m. It includes 90 pipes of different materials (Figure 5) and diameters (Figure 6).

The pipes diameters range from 40 to 300 mm. Lengths material types and diameters are reported in the table below. HDPE is the most used material, with a percentage of 40.41% of the total network length followed by PVC with a percentage of 39.64%.

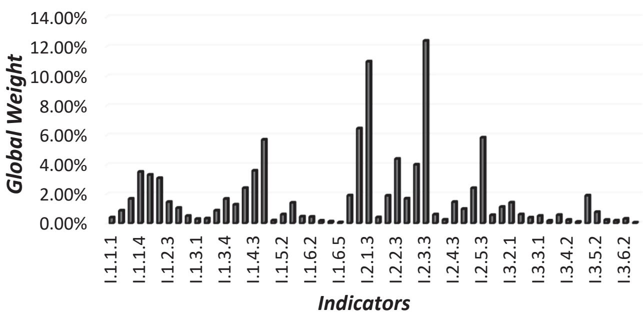

Figure 4.
Overall weights of indicators

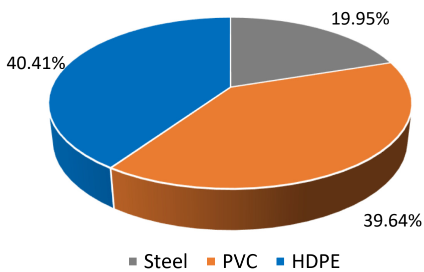

Figure 5.
Types of materials

After calculating the overall weight of each indicator using the AHP method, it is necessary to rank and map the sections in order of importance (priority order) for the planning of the rehabilitation of the WNDs. This task produce a table containing the results related to each pipe in our case study by adding up all values of selected indicators (Appendix 1).

The urgency level attached to each pipe is then calculated (Figure 7). The values of the urgency level obtained ranged from 0.1261 to 0.4816. Subsequently, the pipes were grouped into four classes of urgency levels:

(1) 1st level: urgency level > 0.3000

(2) 2nd level: 0.2300 < urgency level ≤ 0.3000

(3) 3rd level: 0.1500 < urgency level ≤ 0.2300

(4) 4th level: urgency level ≤ 0.1500

The final step is to classify the pipes according to the four-time groups (e.g. the first level equals T1), this will allow building a rehabilitation program. As a result of this step: 14 pipes need rehabilitation before 5 years (T1), 31 pipes between 5 – 10 years (T2), 36 pipes between 10 – 15 years (T3) and 9 pipes after 15 years (T4). The results obtained are illustrated in Figure 8.

The scheme for establishing the rehabilitation program is shown in Figure 9, with:

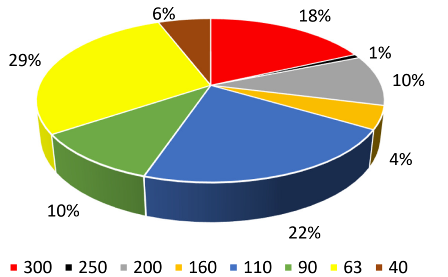

Figure 6.
Different pipe diameters

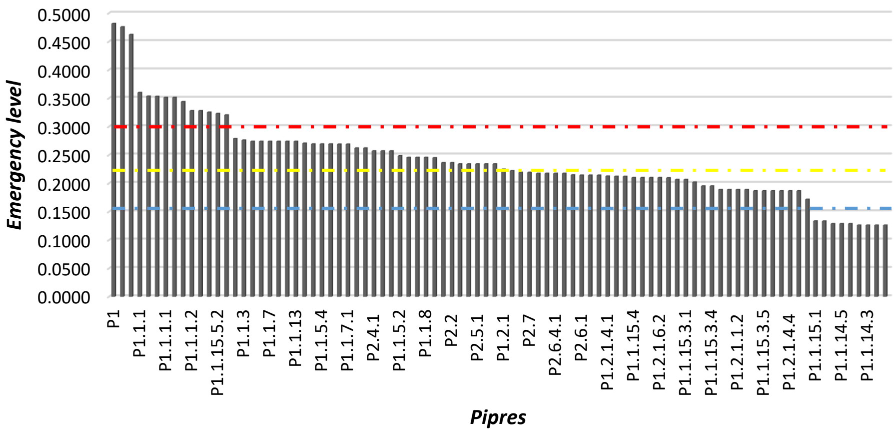

Figure 7.
Variation of the urgency level

- In the first period ($T1 \leq 5$ years): the length of the pipes to be changed is 3394 m. In this period, the steel pipes will be replaced by cast iron and the PVC by HDPE. Additionally, a pressure regulator will be installed to decrease the pressure in this sector;
- Second period ($5 < T2 \leq 10$ years): in this period, 3501 m of PVC pipes will be changed to HDPE;
- Third period ($10 < T3 \leq 15$ years): in the third stage, 4854 m of pipe will be rehabilitated;
- Fourth period ($T4 > 15$ years): in the last phase, 1111 m of pipe will be targeted for rehabilitation.

Conclusions and recommendations

In this article, a decision support tool has been developed based on a hybrid method that integrates the AHP and the calculation of the level of urgency to establish a rehabilitation

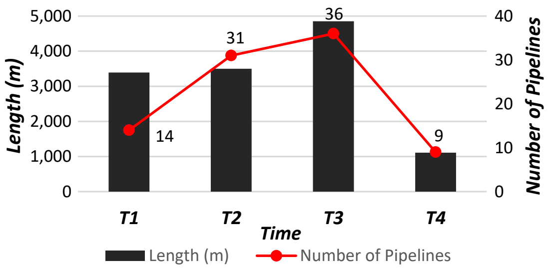

Figure 8.
Histogram of pipes to be rehabilitated versus time

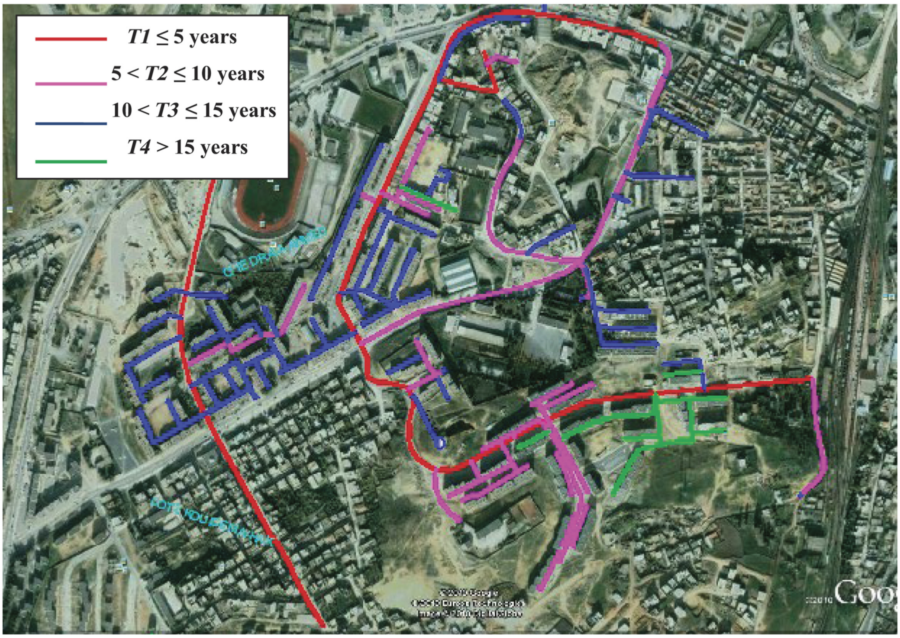

Figure 9.
Graphical interpretation of a rehabilitation program

program for WDN. The AHP method was used to prioritize the indicators having a strong influence on the dysfunctioning of the WDN. On the other hand, the calculation of the level of urgency was applied to classify the pipes to be rehabilitated. When developing the model, three criteria, physical, operational and pipeline environment, were taken into account. The decision matrices were calculated based on the opinions of 18 experts. A decomposition of the problem into a hierarchical structure of elements was necessary. In the case of this study, four levels are considered in the AHP process: the first level is dedicated to the evaluation objective, while the other three levels are assigned to the three elements: criteria, subcriteria and indicators.

According to the results of this model, it is considered with high risk of new damage and failures in the existing WDN pipes with high ages and high pressures. Before a final decision is taken, the level of urgency must be calculated to allow the classification of pipelines to be rehabilitated in the short, medium and long term. The model developed was applied to the district of 1700 housing units in the city of Souk-Ahras. The study area was chosen because of its high number of leak repairs in recent years.

The authors believe that the reliability of the model developed in this study could be further enhanced by adding other criteria and subcriteria such as economy, budget constraints and water revenue ratios and by application or comparing with other methods, for example, fuzzy-AHP.

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Appendix 1
Example of the calculation of the emergency level

Pipes	Diameters	Types of materials	Length	Age	Corrosion protection	Seals	Pressure	Velocity	Failures	Drinking water quality	Network maintenance	Soil types	Laying bed	Water table	Pipe depth	Traffic	Genoa on account of other networks	Sum
P1	300	Steel	915	40	No	Welded	7	2	4	Not aggressive	Bad	No corrosive	Absent	Absent	0.8	Main road	Road works	
	0.0167	0.0105	0.0167	0.0359	0.0140	0.0006	0.1098	0.0440	0.1238	0.0024	0.0584	0.0056	0.0141	0.0017	0.0056	0.0189	0.0030	0.4816
P1.1	300	Steel	1215	40	No	Welded	6.9	2	6	Not aggressive	Bad	No corrosive	Absent	Absent	0.8	Main road	Repair	
	0.0167	0.0105	0.0167	0.0359	0.0140	0.0006	0.1098	0.0440	0.1238	0.0024	0.0584	0.0056	0.0141	0.0017	0.0023	0.0189	0.0004	0.4757
P1.1.1	63	PVC	180	40	No	Glued	6.9	1	2	Not aggressive	Bad	No corrosive	≤10	Absent	0.8	Main road	Repair	
	0.0039	0.0308	0.0033	0.0359	0.0140	0.0046	0.1098	0.0188	0.0400	0.0024	0.0584	0.0056	0.0060	0.0017	0.0056	0.0189	0.0004	0.3601
P1.1.1.1	63	PVC	123	40	No	Glued	6.9	1	1	Not aggressive	Bad	No corrosive	≤10	Absent	0.8	Secondary road	Road works	
	0.0039	0.0308	0.0033	0.0359	0.0140	0.004	0.1098	0.0188	0.0400	0.0024	0.0584	0.0056	0.0060	0.0017	0.0056	0.0076	0.0030	0.3515
P1.1.1.2	63	PVC	54	40	No	Glued	6.9	1	0	Not aggressive	Bad	No corrosive	≤10	Absent	0.8	Secondary road	Road works	
	0.0039	0.0308	0.0029	0.0359	0.0140	0.0046	0.1098	0.0188	0.0169	0.0024	0.0584	0.0056	0.0060	0.0017	0.0056	0.0076	0.0030	0.3280
P1.1.2	110	PVC	90	40	No	Glued	6.9	1	1	Not aggressive	Bad	No corrosive	≤10	Absent	0.8	Secondary road	Repair	
	0.0087	0.0308	0.0029	0.0359	0.0140	0.0046	0.1098	0.0188	0.0400	0.0024	0.0584	0.0056	0.0060	0.0017	0.0056	0.0076	0.0004	0.3532
P1.1.2.1	110	PVC	132	40	No	Glued	6.9	1	1	Not aggressive	Bad	No corrosive	≤10	Absent	0.8	Secondary road	Repair	
	0.0087	0.0308	0.0033	0.0359	0.0140	0.0046	0.1098	0.0188	0.0400	0.0024	0.0584	0.0056	0.0060	0.0017	0.0056	0.0076	0.0004	0.3536
P1.1.2.2	90	PVC	50	40	No	Glued	6.9	1	0	Not aggressive	Bad	No corrosive	≤10	Absent	0.8	Secondary road	Repair	
	0.0039	0.0308	0.0029	0.0359	0.0140	0.0046	0.1098	0.0188	0.0169	0.0024	0.0584	0.0056	0.0060	0.0017	0.0056	0.0076	0.0004	0.3254
P1.1.2.3	63	PVC	80	40	No	Glued	6.9	1	0	Not aggressive	Bad	No corrosive	≤10	Absent	0.8	Secondary road	Road works	
	0.0039	0.0308	0.0029	0.0359	0.0140	0.0046	0.1098	0.0188	0.0169	0.0024	0.0584	0.0056	0.0060	0.0017	0.0056	0.0076	0.0030	0.3280
P1.1.2.4	63	PVC	120	40	No	Glued	6.9	1	1	Not aggressive	Bad	No corrosive	≤10	Absent	0.8	Secondary road	Road works	
	0.0039	0.0308	0.0033	0.0359	0.0140	0.0046	0.1098	0.0188	0.0400	0.0024	0.0584	0.0056	0.0060	0.0017	0.0056	0.0076	0.0030	0.3515

Appendix 2
List of abbreviations

Abbreviations	Definition
ADE	*Algérienne Des Eaux* (Algerian water company)
AC	Asbestos Cement
AHP	Analytical Hierarchy Process
CI	Consistency Index
CR	Consistency Ratio
ELECTRE	Elimination and Choice Translating Reality
FAHP	Fuzzy-AHP
GA	Genetic Algorithm
HDPE	High Density Polyethylene
HGA	Hybrid Genetic Algorithm
MCDM	Multicriteria Decision Making
PROMETHEE	Preference Ranking and Organization Method for Enrichment Evaluation
PVC	Polyvinyl Chloride
RI	Consistency Index
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
WDN	Water Distribution Network
WSS	Water Supply Service

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