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ORIGINAL RESEARCH PAPER

Contamination depth prediction in sandy soils using fuzzy rule-based expert system

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ABSTRACT

As a result of rainfall in large quantities, the leachate generated under the municipal solid waste (MSW) is increased, which leaks to the groundwater aquifers and pollutes it. Accurate evaluation of leachate leaks levels has long been regarded as a problem in Iraq due to a lack of reliable data and costly measuring costs. This work proposes a novel fuzzy expert system to predict the pollution status of the underground water in sandy soils. The expert system consists of two subsystems; fuzzy logic system and crisp logic system. The expert system is trained using a data set developed by finite element analysis of sandy soil subjected to contamination materials.

KEYWORDS

artificial intelligence, contamination, fuzzy logic, expert system, finite elements analysis, underground water

1. INTRODUCTION

Modern technologies are used to dispose of waste in a better way than it occurred in the past. However, such disposal is not subject to controlled conditions as only developed countries are subject to full environmental protection [1]. Soil contamination is one of the most important issues in environmental engineering that affects human health and living organisms directly and indirectly. Soil contamination is not an absolute concept; it is related to the type of soil used. Generally, any alteration in soil properties and its elements with an unusual increase or decrease in concentration affecting human health, engineering facilities, groundwater, and agricultural land is called soil pollution [2]. Waste is a direct result of different types of human activities, and it was difficult to deal with it over different times and historical periods. The landfill has emerged as the simplest and least economical way to deal with this waste. Waste sites are a serious threat to groundwater resources, either through waste materials coming into contact with groundwater underflow or through leakage from precipitation [3]. Although landfilling is the most general method of solid waste disposal in many countries, it still poses a high hazard of pollution to the soil and groundwater if the site of a landfill is not planned, controlled, and designed exactly [4]. In Iraq, after a period of disorders and international sanctions, many of the infrastructures are neglected, leading to a reduction in the basic and essential services. As a result, waste management is under development, and solid waste management is one of the major problems faced by local administrations. Figure 1 illustrates the unsanitary landfill in Iraq. As a middle-income country, the generation rate in Iraq is between 0.35 and 0.65 kg/capita.day [5]. The percentage of liquid and soluble components in municipal solid waste in Iraq is high since the garbage comprises organic materials such as residual vegetables, fruit, and food. Groundwater is one of the important sources of drinking water in many countries. Therefore, contamination of groundwater due to landfill leachate causes environmental and health concerns [6]. In this paper, an expert system is proposed to predict the depth of contamination materials

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Fig. 1. Unsanitary landfill in AL-Najaf governorate

that can develop after a period of time of dumping waste in sandy soil. The depth that the pollutants can drop is a very important factor because we struggle to make sure that the contamination materials do not reach the underground water and causes pollution. Firstly, the sandy environment was modeled and analyzed using finite element analysis FEA. The FEA data set is used then for the training process and developing logical rules which are necessary for the fuzzy system [7]. The fuzzy system [8] is one part of the developed expert system, while the second part of the system is a crisp logic system. Both the fuzzy and crisp subsystems are forming the expert system, which predicts how much contamination depth could be. Also, it returns intelligent information and takes a smart decision under consideration of soil type and waste components and properties. Remarkably, the expert system works perfectly and gives reasonable decisions. This article presents a new application for the fuzzy logic from a very important aspect of environmental science, which is prediction of a possible pollution in underground water. The importance of the study is that there are no similar works in the literature applying fuzzy rules for a smart expert system that can predict the contamination under waste dumping zones. The proposed smart tool provides health authorities with free valuable assessments to the state of the underground water in dumping sectors depending on the properties ofn the soil and waste conditions.

Section1 in this article is the introduction to the pollution of the ground water problem especially the pollution caused by waste dumping in improper sandy zones with emphasis on the article contribution. Section 2 presents the related works that used fuzzy logic for similar problems. Sections 3 and 4 are about problem definition and the methodology of the experimental data that was collected for the sake of finite element analysis. Section 5 describes the finite element analysis for the contamination of the underground water in sandy soils. Section 6 describes in details the expert system which is based on fuzzy and crisp logic and trained using finite element dataset. Section 7 is the discussion on the efficiency of the expert system to properly predict the contamination depth after a period of time as well as providing other intelligent information. Section 8 provides the conclusions and recommendations for future work while section 9 contains the acknowledgments.

2. RELATED WORKS

Maria Giaoutzi et al., in 2006, developed a fuzzy system logic and Delphi method to take the decision of landfill siting problem and the results are better than using fuzzy logic alone [9]. Garg et al., 2007 revealed that evaluation of methane generation during gas emission from a sanitary landfill could be done by fuzzy composite programming after modeling a set of information with unknown mathematical interrelationships and imprecise data [10]. Ojha et al., in 2007, used fuzzy logic to solve the problem of finding the best site location to be a sanitary landfill [11]. Many criteria should be met for choosing the proper area for solid waste treatment, like the amount of waste, pollution effects, etc. Abdallah et al., in 2011, illustrated that landfill is a system of physical, chemical, and biological components that can be controlled using fuzzy logic to predict the amount of biogases produced and leachate generated. The control system consists of two outputs, biogas and leachate, while the inputs are the amounts of the biological, chemical, and physical elements in the composition [12]. Abdallah M. et al., in 2011, showed that there is no standard procedure for the system of the landfill because it contains numerous processes and site-specific variables. Therefore, they have proposed automated monitoring and expert control for bioreactor landfills based on fuzzy logic [13]. Isalou et al., in 2013, developed an integrated system of fuzzy logic and analytic network process ANP to take the decision of choosing a suitable place to dispose of the municipal solid wastes. This decision becomes complicated when a set of parameters is taken into consideration relating to the human settlements integration. The integrated system of fuzzy logic and ANP can give better results compared to fuzzy logic and ANP individually [14]. Aydi A. et al., in 2013, also conducted the citing problem but in different formulations by combining fuzzy set theory, Weighted Linear Combination (WLC), and analytic hierarchy process (AHP) in a GIS environment [15]. Bagheri et al., in 2017, simulated landfill leachate emission into groundwater using fuzzy logic and neural network modeling methods. They have used experimental data to train the neural network and set rules for fuzzy logic, and they have built efficient models to predict the penetration process [16]. Also, a fuzzy logic system for risk assessment to groundwater contamination was developed for natural gas wells during hydraulic fracturing [17].

3. PROBLEM DEFINITION

In recent years, the contamination of groundwater and soil by petroleum products, leachate waste, and so on, has been one of the world's most critical environmental issues. Applying appropriate methods to clean the polluted areas requires an accurate understanding of the accurate behavior and distribution of such contaminants in subsurface layers. The first step in the direction of environmental protection and cleaning of the undesirable effects of pollution is to determine the extent of the contamination, so it is essential to know how these materials move and accumulate under the surface. Because of the complexity of the equations and the environment in which these problems can be solved, we have developed a numerical model by SEEP/W, and CTRAN/W packages in Geostudio 2012 software. They are used to model pollution emission to simulate the movement of various contaminants in landfill soil in Iraq, to predict the behavior and distribution of landfill pollution to properly understand the distribution of contamination in these soils. The prediction process is essential to control contamination and prevent groundwater pollution. The major objective here is to develop a fuzzy logic system to achieve the prediction process based on prior Finite Element Analysis (FEA) training data which are obtained by the Geostudio package.

4. ENVIRONMENT SPECIFICATIONS

The area of study is located in Najaf governorate in the middle of Iraq and south of Baghdad on a rising plateau above the sandy ground west of the river Euphrates, as shown in Fig. 2. A set of laboratory and field tests were achieved in this work for identification, including the sieve analysis test, the standard proctor tests, the minimum density test, sand cone test, and the percentage of Gypsum content according to the ASTM (D 422 -1998), ASTM (D698-1998), ASTM D4254, ASTM (D1556) specifications and Iraqi standard specification (45-1984) respectively. Table 1 summarizes the properties of the soil used in the study. The laboratory permeability test of soils of the area of study was conducted at four densities: 1.28 gm cm^{-3}, 1.42 gm cm^{-3}, 1.59 gm cm^{-3}, and 1.81 gm cm^{-3} to evaluate the effect of density on the permeability. Figure 3 shows the relationship between the coefficient of permeability and densities of sandy soil.

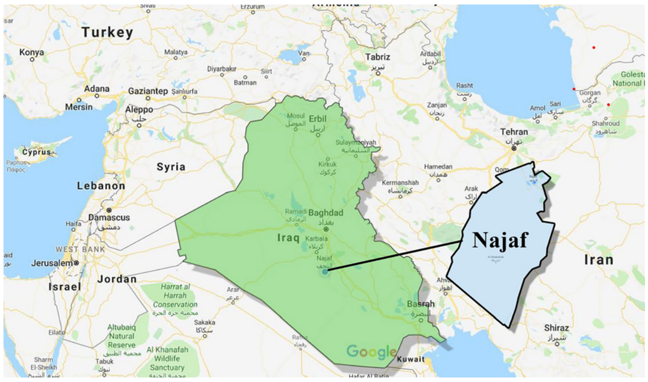

Fig. 2. Location of soil sampling from AlNajaf city in Iraq and the location of collecting samples

5. FINITE ELEMENTS ANALYSIS

The finite element package (GeoStudio 2012) is used for the analysis of the sandy soil. SEEP/W is a finite element software product for the estimation of groundwater leakage and excess issues of pore water pressure dissipation in porous materials.

Table 1. Properties of soil. Adapted from [2], under Creative Commons Attribution 3.0

Characteristics	value
Gravel, %	2.64
Sand, %	94.32
Fine, %	3.04
D10, mm	0.17
D30, mm	0.28
D60, mm	0.9
Cu	5.29
Cc	0.51
Soil Classification System (USCS)	SP
Field density (gm cm^{-3})	1.8142
Field water content %	3.05
Proctor dry density (gm cm^{-3})	1.77
Min.dry density (gm cm^{-3})	1.18
Optimum moisture content (OMC) %	16
Gypsum content %	18.03
Field permeability k (cm s^{-1})	3.2*10^{-2}

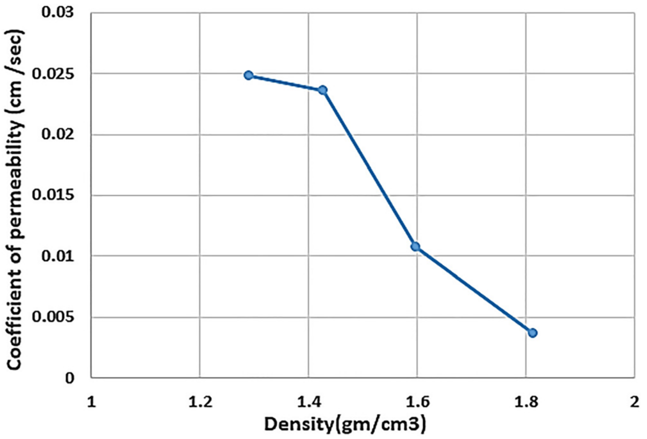

Fig. 3. Coefficient of permeability vs density of soil

In addition to the steady-state saturated flow, SEEP/W can model both saturated and unsaturated flow. This allows the analysis of seep as a function of time and the consideration of processes such as precipitation infiltration. CTRAN/W is a finite element software product used to model the migration of contaminants through porous materials such as sandy soil. CTRAN/W uses SEEP/W flow velocity to calculate the movement of dissolved components in pore water [18]. CTRAN/W and SEEP/W should be used as a couple to analyze the emission of contamination. In order to investigate the emission of pollution in a porous medium such as sandy soil, a model should be constructed in the SEEP/W environment [2]. The value of the diffusion coefficient for leachate is estimated as $1^{*}10^{-9}\,m^2\,s^{-1}$, and the saturated water content of sand is estimated at 0.41 [19]. The permeability ratio (*ky/kx*) for sandy soil is taken as 1 and 0.1 [20], Iraqi municipal solid waste density (C) = 0.45 t m^{-3}. Table 2 shows the information used in numerical modeling.

The numerical data are expressed in Figs 4 and 5, representing relations among inputs and outputs. Where D is the depth of the contamination, C is the concentration of the leachate, K is the permeability coefficient, and k_y/k_x is the permeability ratio. The numerical solutions of the FEA were used to conclude too many logical rules to govern the behavior of the fuzzy subsystems.

Table 2. Information used in numerical modelling. Republished from [2], under Creative Commons Attribution 3.0

Parameter	Value
Water level, m	3
Capillary rise, mm	350
Longitudinal dispersivity, m	2
Transverse dispersivity, m	1
Dry density, gm cm^{-3}	1.77
Length of model, m	15
Width of model, m	5
Diffusion, $m^2\,s^{-1}$	10–9

6. EXPERT SYSTEM

A hybrid expert system presented in this section consists of two subsystems; a crisp logic system and fuzzy logic system. The fuzzy system is used for intellectual estimation of the required time for a contamination material to pollute the groundwater and estimate the penetration depth after a period of time. The crisp logic system provides minimal information but with a high rate of accuracy with respect to the fuzzy system. The proposed expert system can take the following decisions for a specific waste type and soil characteristics:

1. Is the dumping time safe or unsafe, i.e., can a thrown leachate on soil reach the water table for a given time?
2. What types of leachate can be stored in a landfill without causing pollution for underground water?
3. Decide what types of leachates can be stored permanently or temporarily.
4. For specific conditions where the pollutants have not reached the water table yet, the expert system can predict how much time is required for this pollutant to arrive in the underground water.

6.1. Multiple regression

Multiple regression was used to represent numerically the data expressed in Figs 4 and 5 in nonlinear equations. The resulted equations are the basis of the crisp logic system where the user can call for predefined depth and width of contamination equations with a specific range of K, C, and t. The regression model is illustrated by equations (1) and (2), which represent the depth (D) and width (W) of the contamination over time.

$$D = a_o + a_1\,t + a_2\,K + a_3\,C + a_4\,t^2 + a_5\,K^2 + a_6\,C^2 + a_7\,t\,K + a_8\,t\,C + a_9\,K\,C + a_{10}\,t\,K\,C, \quad (1)$$

$$W = b_o + b_1\,t + b_2\,K + b_3\,C + b_4\,t^2 + b_5\,K^2 + b_6\,C^2 + b_7\,t\,K + b_8\,t\,C + b_9\,K\,C + b_{10}\,t\,K\,C, \quad (2)$$

where $a_o, a_1, a_2, a_3, a_4, a_5, a_6, a_7, a_8, a_9$, and a_{10}; $b_o, b_1, b_2, b_3, b_4, b_5, b_6, b_7, b_8, b_9$, and b_{10} are coefficients. For simplicity, equations (1) and (2) can be written as follows

$$D = a_o + a_1\,x_1 + a_2\,x_2 + a_3\,x_3 + a_4\,x_4 + a_5\,x_5 + a_6\,x_6 + a_7\,x_7 + a_8\,x_8 + a_9\,x_9 + a_{10}\,x_{10} \quad (3)$$

$$W = b_o + b_1\,x_1 + b_2\,x_2 + b_3\,x_3 + b_4\,x_4 + b_5\,x_5 + b_6\,x_6 + b_7\,x_7 + b_8\,x_8 + b_9\,x_9 + b_{10}\,x_{10} \quad (4)$$

where

$$x_1 = t,\; x_2 = K,\; x_3 = C,\; x_4 = t^2,\; x_5 = K^2,\; x_6 = C^2,$$
$$x_7 = t\,K,\; x_8 = t\,C,\; x_9 = K\,C,\; x_{10} = t\,K\,C$$

Equations (3) and (4) are solved by determining the values of the coefficients $[a_o,\ldots,a_{10}]$ and $[b_o,\ldots b_{10}]$ depending on

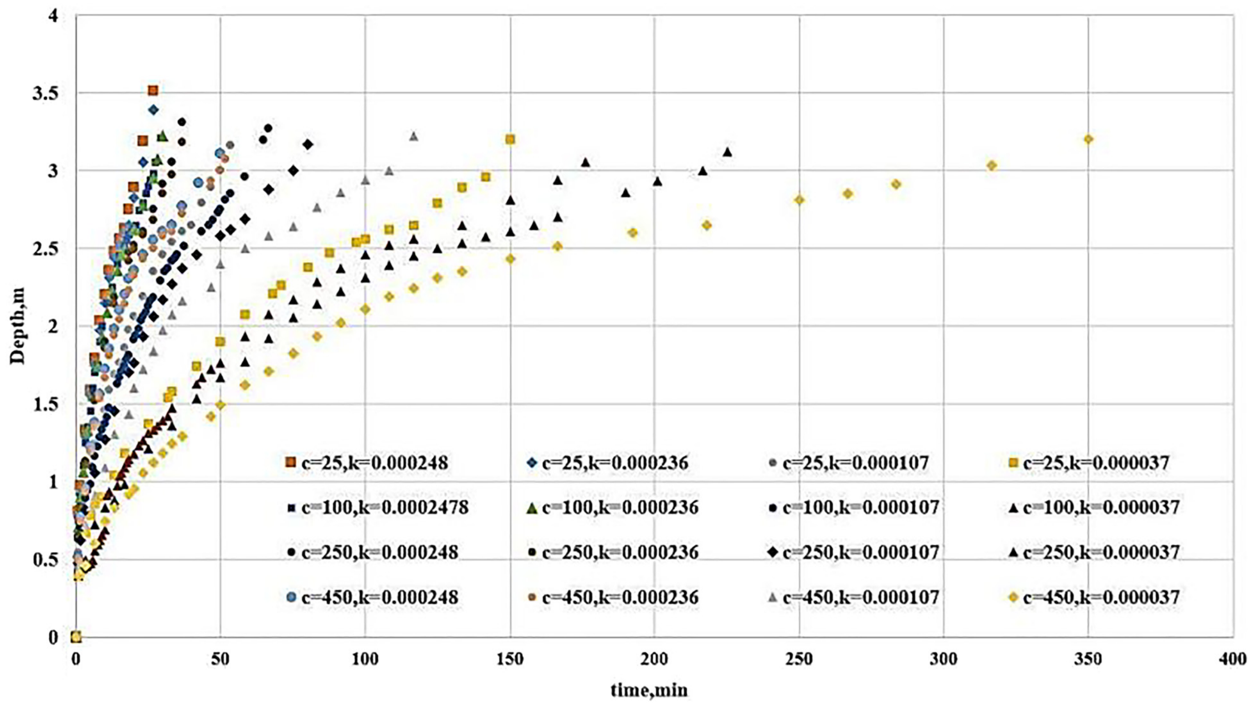

Fig. 4. FEA solution for D for different values of C and K for $k_y/k_x = 1$

the data set in Figs 4 and 5. In other words, equations (3) and (4) express the depth and width of contamination for all the cases in the abovementioned figures by finding a different set of coefficients. Finally, 32 different forms have been estimated for equations (3) and (4) that represent the data in Figs 4 and 5. For each combination of C, K, t, and k_y/k_x there is a specific set of coefficients a, and b. Therefore, for the proposed system, there are 32 different sets of coefficients, meaning 32 different equations that represent the crisp logic phase of the expert system. For instance, Fig. 6 shows the curve of the FEA depth of the penetration in dashed style while the regression curve is represented in

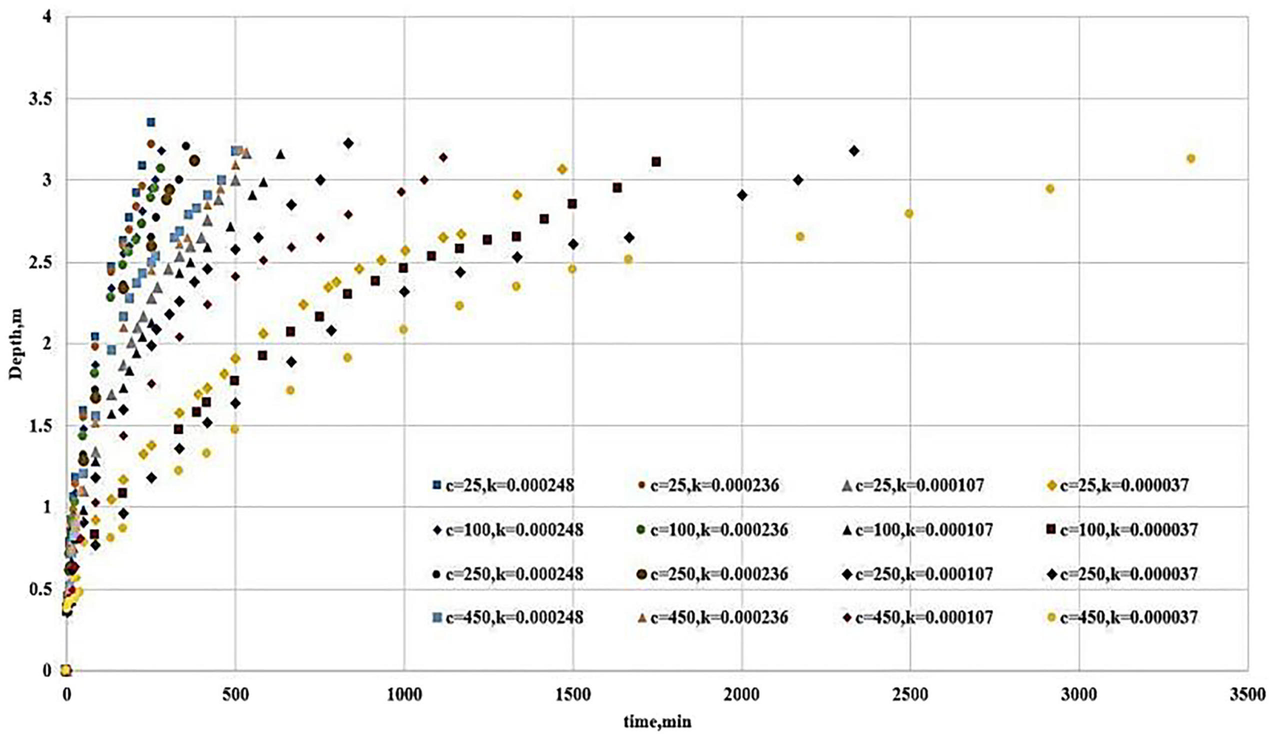

Fig. 5. FEA solution for D for different values of C and K for $k_y/k_x = 0.1$

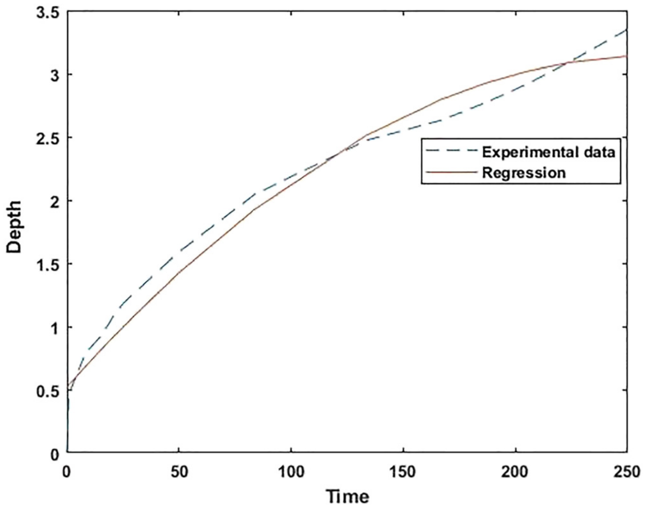

Fig. 6. Real and regression curves of the depth, which is represented in Fig. 4 for $C = 25\,kg\,m^{-3}$, $K = 0.000248\,m\,s^{-1}$, and $0 \leq t \leq 250$

solid for the case $C = 25\,kg\,m^{-3}$, $K = 0.000248\,m\,s^{-1}$, and $0 \leq t \leq 250$.

Figure 7 reveals the flow chart of the expert system where the inputs are depth of the groundwater (*D* level), dumping time (*t*), the concentration of the Leachate (*C*), the permeability of the sandy soil (*K*), and the ratio *ky/kx*. The knowledge base consists of facts which are the set of inputs and outputs of the system, and we apply these facts to the logical rules to get new facts. For the proposed expert system, 134 logical rules were developed based on the FEA. The crisp logic part is defined by a set of (if-then) statements holding a set of specific values of dependent variables *D* and *W*; independent variables *t*, *C*, *K*, and *ky/kx*. The values of *D* and *W* in this part are evaluated using equations (3) and (4). FEA data are more accurate than intellectual estimation but very limited to a specific value of inputs. We have employed this kind of data in the system because it can be extended continuously by adding more data representing solutions for corresponding inputs. If the set of inputs does not match the predefined crisp logic statements, it will be handled to the fuzzy rule-based part of the expert system. Both the crisp logic part and fuzzy logic part are formulated using FEA data for two cases of *ky/kx* values, which are 1 and 0.1.

There are two different fuzzy systems which are expressed in Fig. 7:

1. The First type has inputs consisting of three variables: time of storing, the concentration of the leachate, and permeability of the sandy soil; the output of the system is depth and width of the penetration *D* and *W*. Two systems of this type are employed for k_y/k_x values 1 and 0.1.
2. The second type has the inputs current depth, the concentration of the leachate, and permeability of the soil; the output is the expected time of arrival of contamination in the water table.

6.2. Fuzzy model of the contamination depth

The fuzzy system used in this study consists of three inputs; time, concentration, and permeability, while the output of the system is the depth and width of the penetration *D* and *W*, as shown in Fig. 8. The membership functions used in the fuzzy logic system are of type (trimf) triangular membership functions. Triangular fuzzy numbers are widely employed for the processing and expression of fuzzy information and are

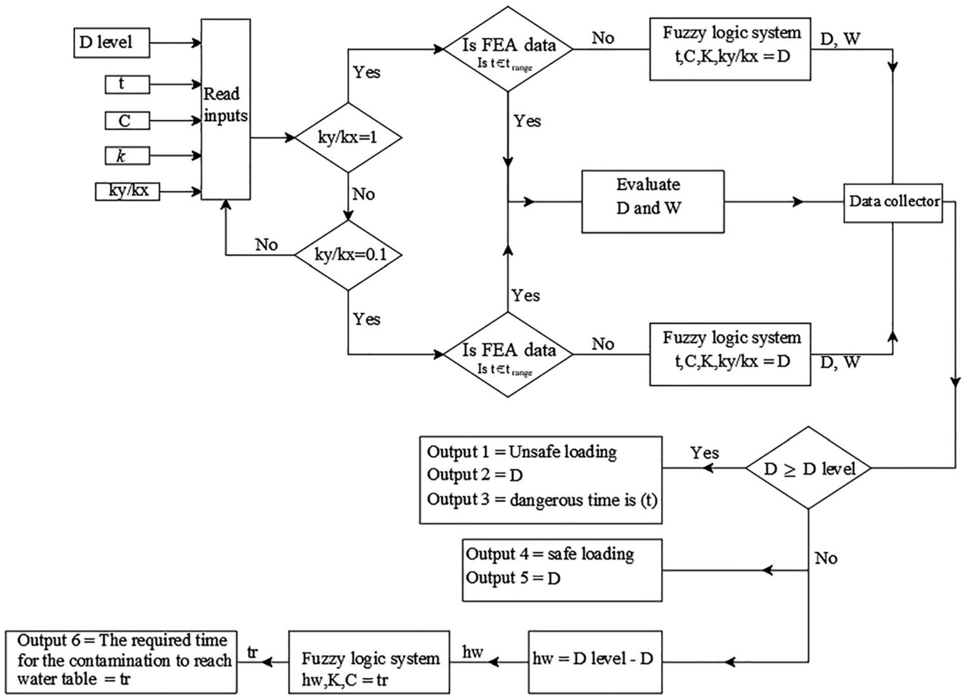

Fig. 7. Flow chart of the expert system

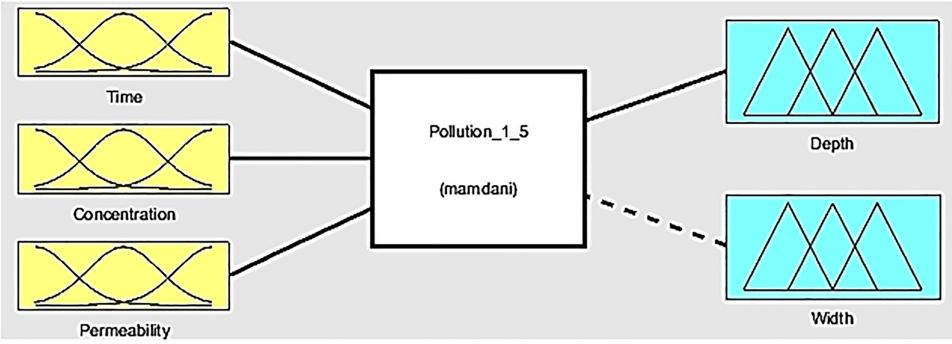

Fig. 8. Fuzzy model to predict the contamination depth

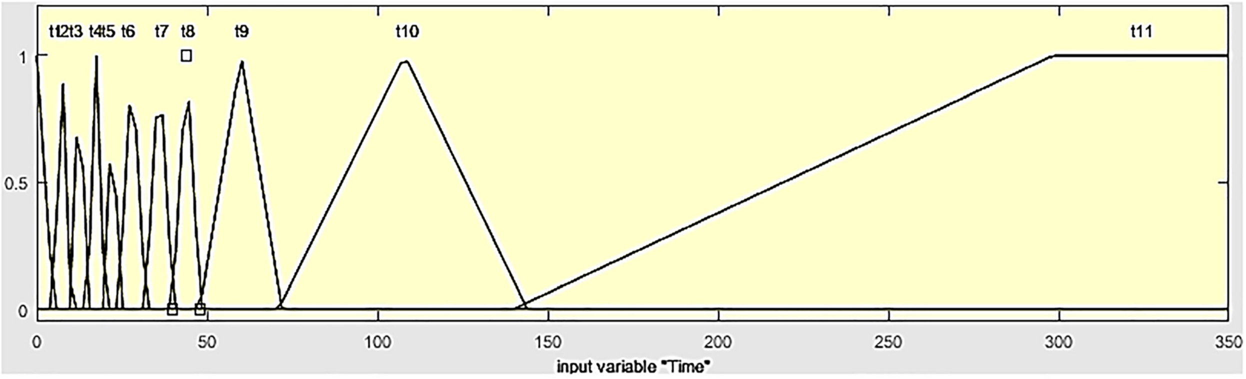

Fig. 9. Membership functions of the input time for $k_y/k_x = 1$

suitable for small or accurate data sets. These methods were successfully used by scholars to assess contamination [21]. In the case of $k_y/k_x = 1$, the membership functions of the inputs are represented in Figs 9–11, while the membership functions of the output D and W are illustrated in Fig. 12. The membership functions of the input t are proportional to the elapsed time distribution of the training data. Figure 13 shows the numbers and time distribution of the points in Fig. 4; for instance, there are 232 points that have a time range [0, 24] seconds, 81 points between [24, 48] seconds, etc. Consequently, the time levels used in this study are 11-time levels; five membership functions for [0, 24] seconds, three membership functions for [24, 48] seconds, one membership function for [48, 72] seconds, one membership function for [72, 144] seconds, and one membership function for [144, 350] seconds. The membership functions of the input concentration are four functions representing $C_1 = 25$ kg m^{-3}, $C_2 = 100$ kg m^{-3}, $C_3 = 250$ kg m^{-3}, and $C_4 = 450$ kg m^{-3}.

Figure 9 shows that the time variable is divided into 11 membership functions; $t1$ to $t11$, C variable has four membership functions $C1$–$C4$ as shown in Fig. 10. Also, the K variable divided into 3 containing three membership functions $K1$–$K3$ as shown in Fig. 11, while the output depth available has nine membership functions revealed in Fig. 12.

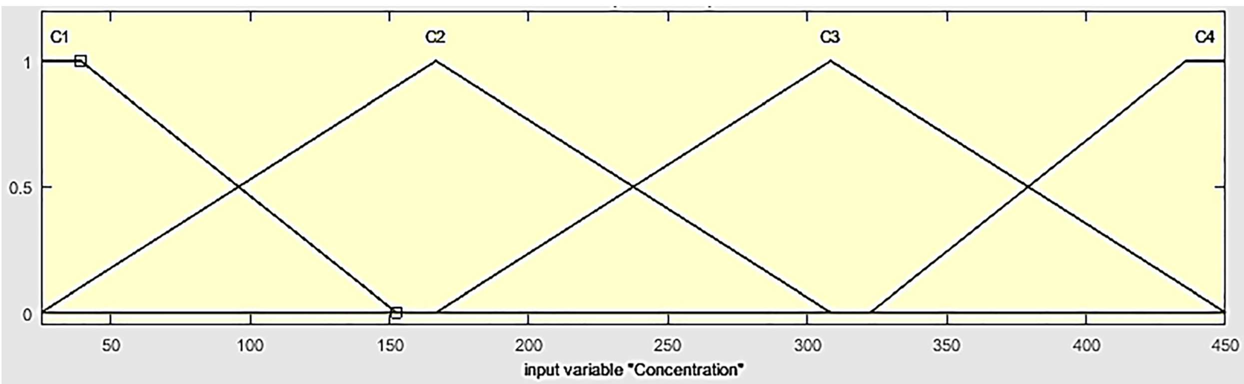

Fig. 10. Membership functions of the input concentration for $k_y/k_x = 1$

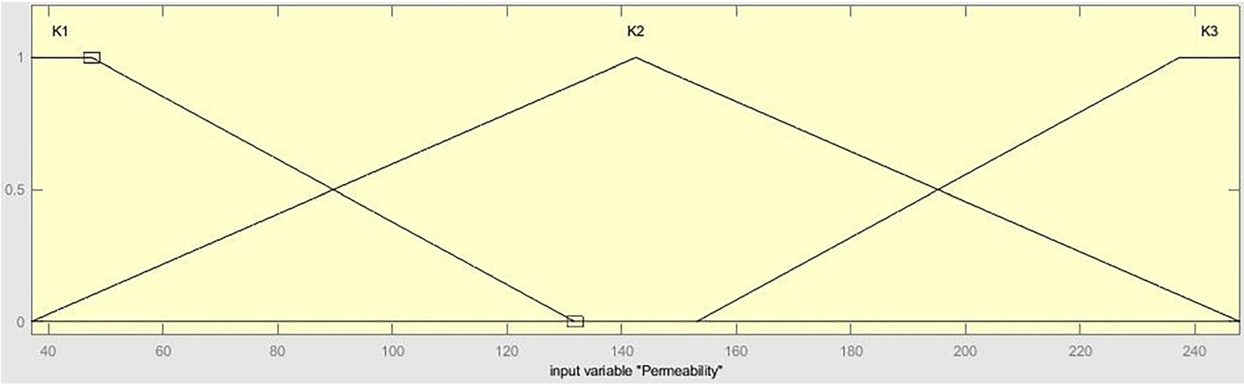

Fig. 11. Membership functions of the input permeability for $k_y/k_x = 1$

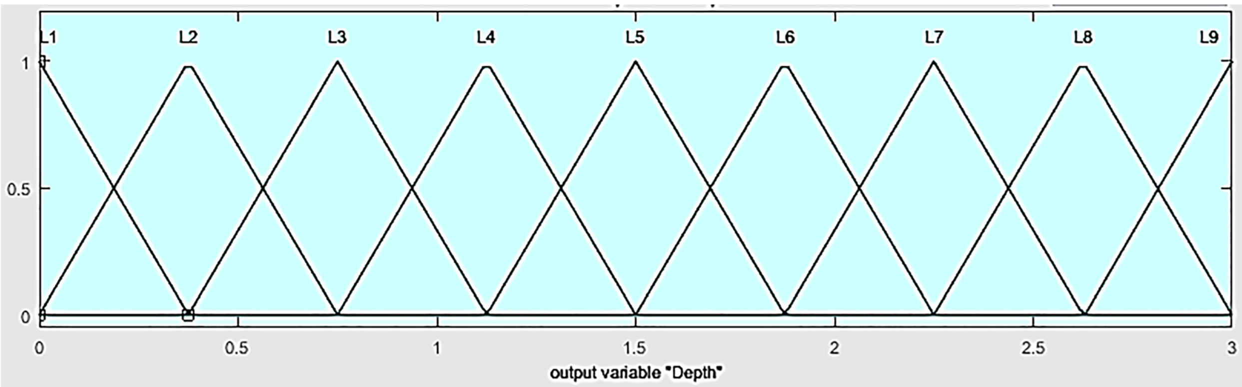

Fig. 12. Membership functions of the output D for $k_y/k_x = 1$

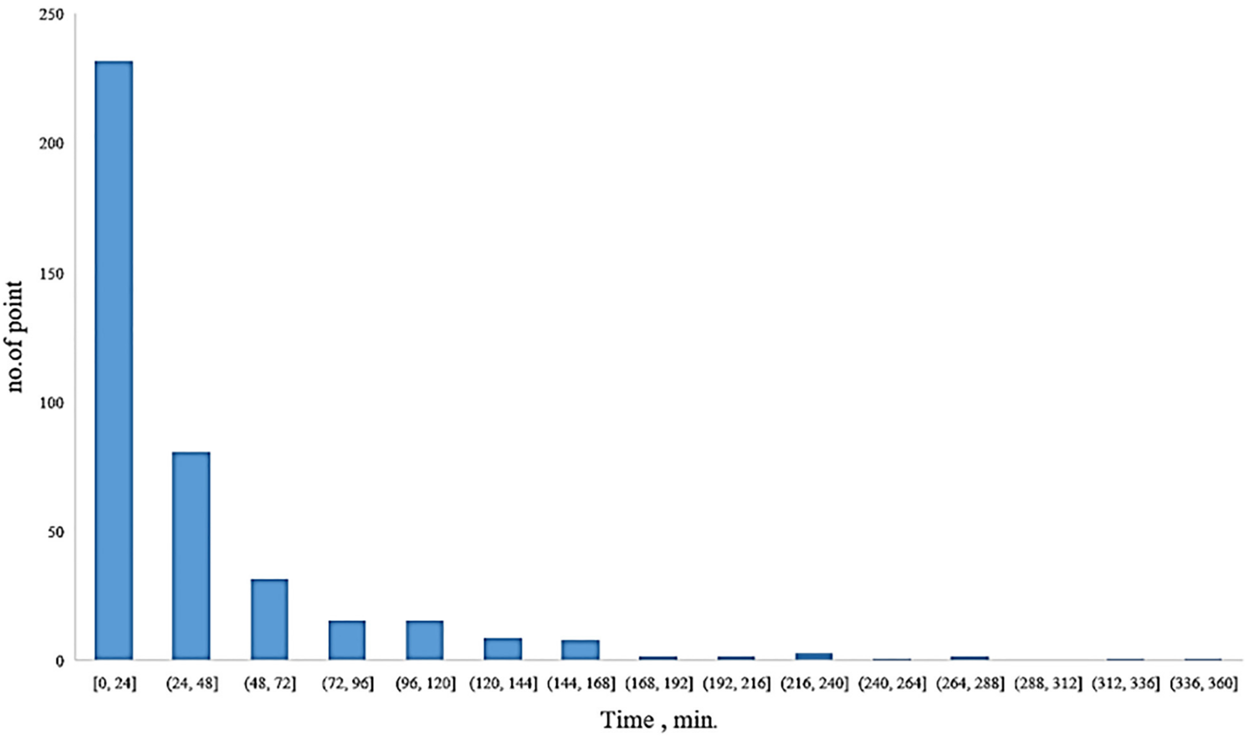

Fig. 13. Time-distribution of the training data for $k_y/k_x = 1$

Table 3. Examples of the fuzzy rules

Rule	Statement
1	If (Time is t1) and (Concentration is C1) and (Permeability is K3) then (Depth is L3)
2	If (Time is t8) and (Concentration is C1) and (Permeability is K3) then (Depth is L9)
3	If (Time is t6) and (Concentration is C2) and (Permeability is K3) then (Depth is L9)
4	If (Time is t3) and (Concentration is C3) and (Permeability is K3) then (Depth is L6)

Thus, all the membership functions are not equally distributed. The fuzzy rule was driven in this work depending on Figs 4 and 5, while Table 3 shows four examples out of the 134 logical rules, and each rule has the same weight in the system.

The membership functions of the input permeability are chosen to be three, representing $K1 = 0.000037$ m s^{-1}, $K2 = 0.000107$ m s^{-1}, and $K3 = 0.000248$ m s^{-1}, while the output variable of D and W consists of nine equally distributed membership functions. In the case of $k_y/k_x = 1$, the resulting surface representing the relationship between time and concentration vs. depth of the penetration is shown in Fig. 14, while the relationship between time and permeability vs. depth is illustrated by the surface in Fig. 15.

In the case of $k_y/k_x = 0.1$, the training data representing D and W for different cases of K and C is represented by Fig. 5, with a dramatic change in time distribution with respect to the training data in Fig. 4. The elapsed time for all cases of penetration ranges from 0 to 3,510 s, where numbers and time-distribution of the points in Fig. 5 are represented in Fig. 16. The input time variable is divided into ten levels represented by ten membership functions shown in Fig. 17. Four membership functions are set for [0, 270] seconds, three membership functions for [270, 540] seconds, one membership function for [540, 810] seconds, one membership function for [810, 1080] seconds, and one membership

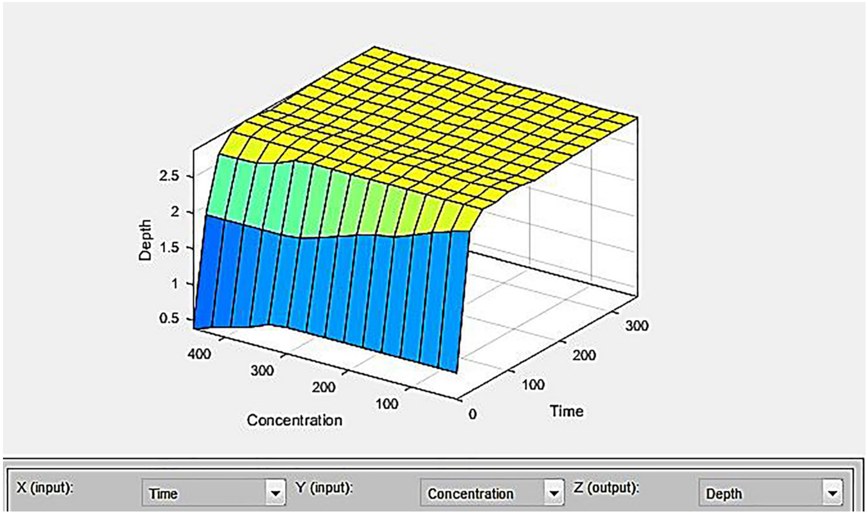

Fig. 14. Surface time-concentration vs. depth for $k_y/k_x = 1$

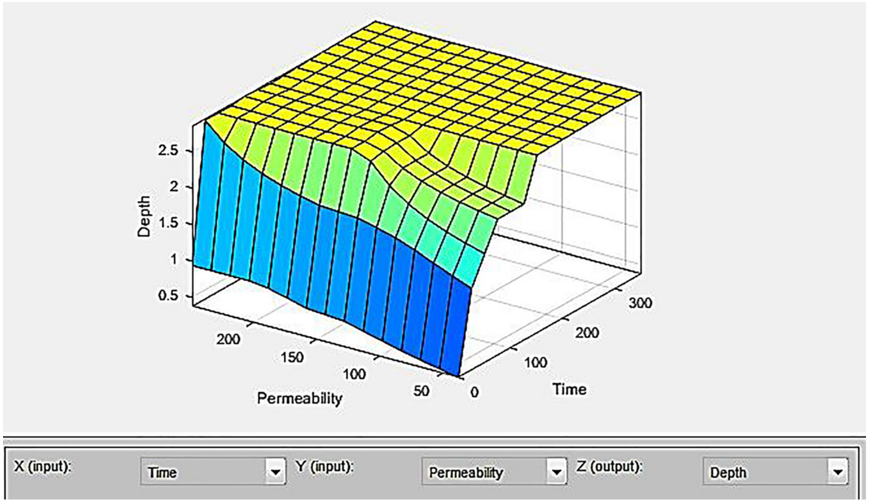

Fig. 15. Surface time-permeability vs depth for $k_y/k_x = 1$

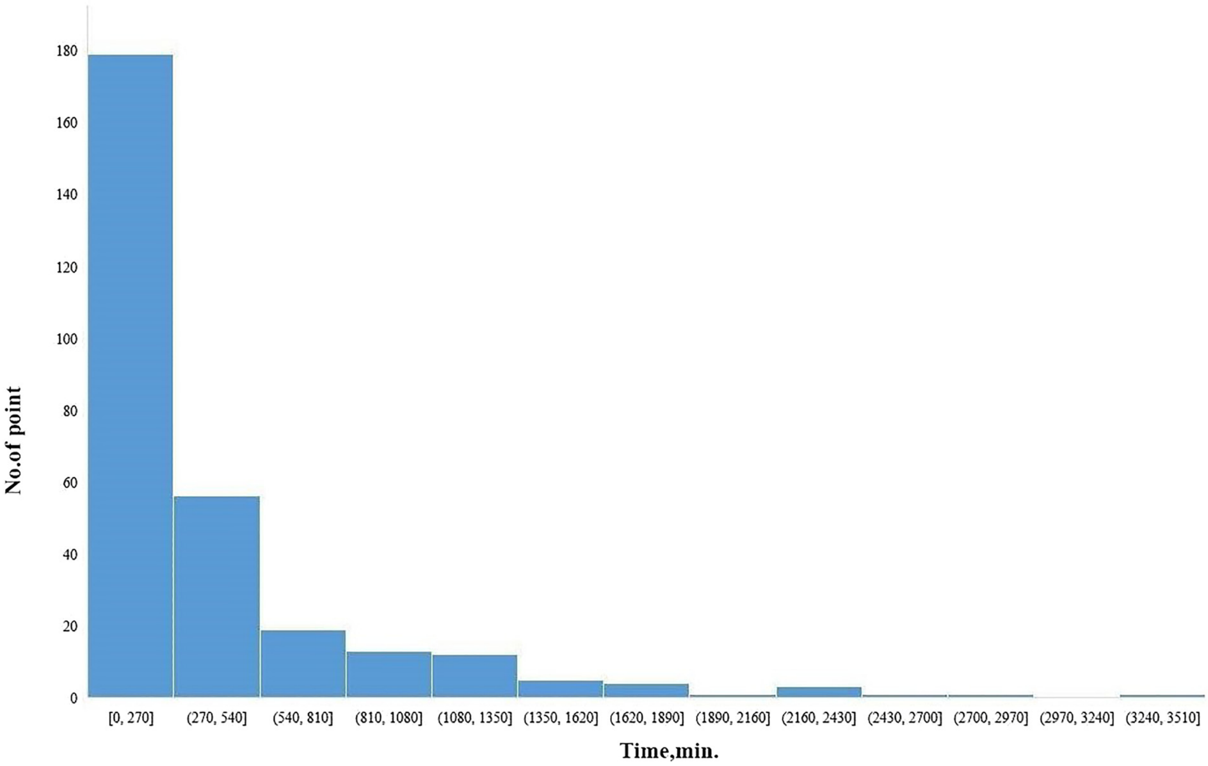

Fig. 16. Time-distribution of the training data for $k_y/k_x = 0.1$

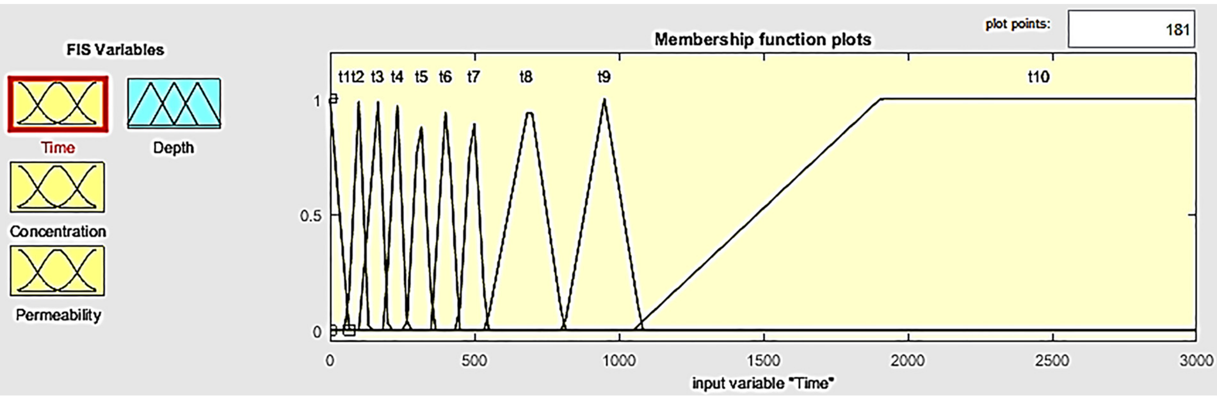

Fig. 17. Membership functions of the input time for $k_y/k_x = 0.1$

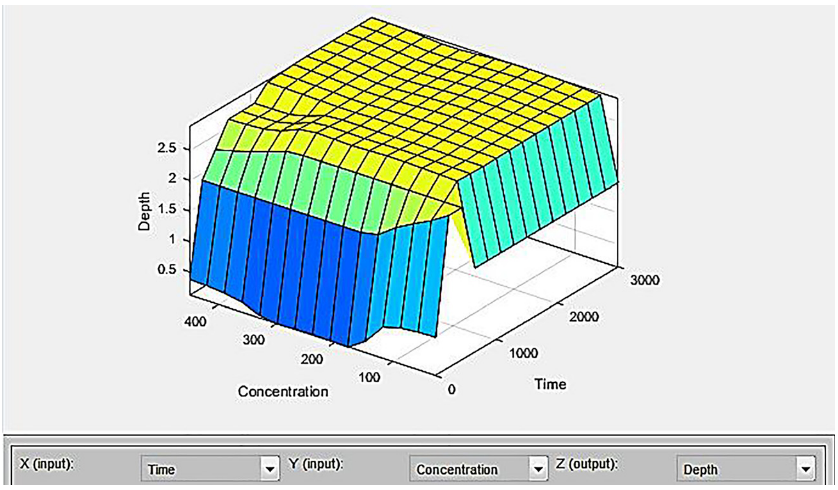

Fig. 18. Surface time-concentration vs. depth for $k_y/k_x = 0.1$

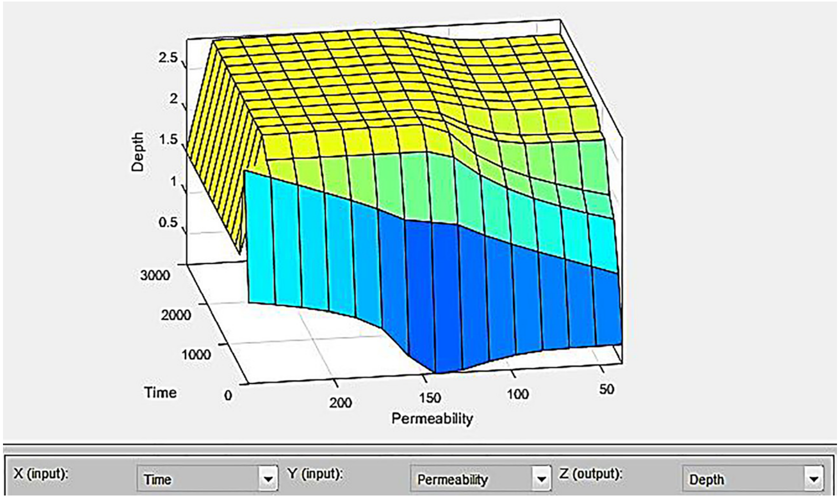

Fig. 19. Surface time-permeability vs. depth for $k_y/k_x = 0.1$

function for [1080, 3000] seconds. The membership functions for the concentration and permeability inputs variables are chosen as the same as what is used in Figs 10 and 11, respectively. The resulted surface representing the relationship between time and concentration vs. depth of the penetration is shown in Fig. 18, while the relationship between time and permeability vs. depth is illustrated by the surface in Fig. 19. The intellectual estimation of the depth of penetration includes the specific values of the inputs in the training set as well as the intermediate values among them.

The logical rules of the fuzzy systems for $k_y/k_x = 1$ and $k_y/k_x = 0.1$ are listed in rule assignment, where these rules are applied to other facts represented by values of concentration, permeability, and time to produce another fact represented by the depth of the penetration.

Table 4. Comparative statistical results

	h_{FEA}	h_{Fuzzy}	h_w
$t = 5^*$ min. $C = 25^*$ kg m^{-3} $k = 0.000248^*$ m s^{-1}	1.59	1.88	0.89
$t = 12.5$ min. $C = 100$ kg m^{-3} $k = 0.000236$ m s^{-1}	2.23	2.16	0.42
$t = 17.5^*$ min. $C = 100^*$ kg m^{-3} $k = 0.000107^*$ m s^{-1}	1.78	1.63	0.87
$t = 4.17$ min. $C = 50$ kg m^{-3} $k = 0.000101$ m s^{-1}	1.62	1.6	1.03
$t = 125^*$ min. $C = 250^*$ kg m^{-3} $k = 0.000037^*$ m s^{-1}	2.5	2.25	0.15
$t = 11.67$ min. $C = 25$ kg m^{-3} $k = 0.000236$ m s^{-1}	2.31	2.15	0.34
$t = 116.67^*$ min. $C = 450^*$ kg m^{-3} $k = 0.000037^*$ m s^{-1}	2.24	2.2500	0.41
$t = 11.7$ min. $C = 50$ kg m^{-3} $k = 0.000101$ m s^{-1}	1.42	1.3185	1.23
$t = 36.66^*$ min. $C = 450^*$ kg m^{-3} $k = 0.000107^*$ m s^{-1}	2.16	1.99	0.49
$t = 10$ min. $C = 75$ kg m^{-3} $k = 0.000205$ m s^{-1}	2.13	1.96	0.52

7. DISCUSSION

We have employed 10 cases of comparison between FEA results and the results from the fuzzy logic system with 50% of cases chosen to be from training data and 50% out of training data; Table 4 shows the comparative results. For the specified set of inputs, (hFEA) is the depth of penetration given by FEA package while (hFuzzy) is the estimated depth using the fuzzy system. The difference between the current depth given by FEA and the depth of underground water is denoted by hw.

The (*) refers to training data used to develop fuzzy rules.

We note that the error in the result is very acceptable for the data of training and data out of training. The fuzzy system can predict the current depth of the contamination perfectly compared with the depth, which is calculated by FEA. As a result, this is a verification for the fuzzy systems to be acceptable and reliable for further steps. Figure 20 clarified comparison between calculated depth by FEA and Fuzzy logic on different values of concentration.

Figures 21 and 22 reveal two different cases of examination of the proposed expert system; the source code was written in MATLAB 2016b version. In the first examination, the inputs were chosen in ranges located in the database of the crisp logic system. While in the second examination, the set of inputs was chosen out of ranges of the crisp logic. Thus, the system had transferred the inputs to the fuzzy logic systems so as to be solved by intellectual estimation.

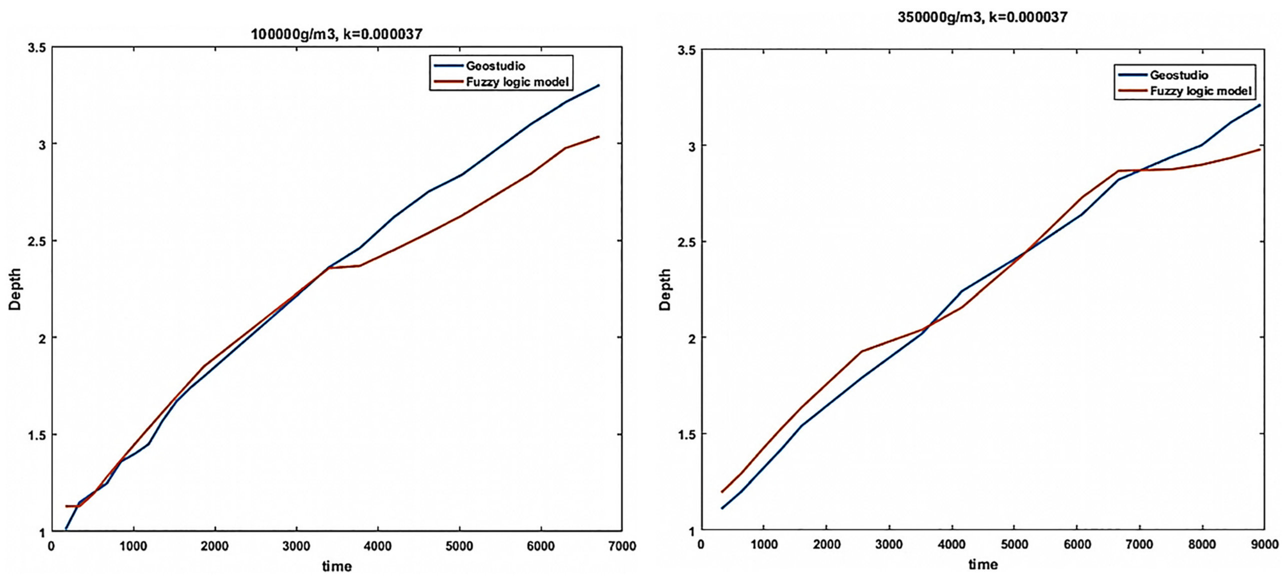

Fig. 20. Comparison between calculated depth by FEA and Fuzzy logic on different values of concentration

```
Command Window
Enter the level of the ground water:  2.65
Enter the time of dumping:  22.5
Enter the concentration of the leachate:  100000
Enter the permeability coefficient of the soil:  0.000107
Enter the permeability choose only 0.1 or 1:  1
%%%%%%%%%%%%%%%%%%%%
FEA data founded
Depth of the penteration=  1.9844
Width of the penteration=  3.5486
safe dumping
The remaining time for the leachate to arrive to groundwater is:  24.7445
fx >>
```

Fig. 21. Examination of the hybrid expert system (1)

```
Command Window
Enter the level of the ground water:  2.65
Enter the time of dumping:  17.8
Enter the concentration of the leachate:  50000
Enter the permeability coefficient of the soil:  0.000101
Enter the permeability choose only 0.1 or 1:  1
%%%%%%%%%%%%%%%%%%%%
Fuzzy system calculations
Depth of the penteration=  1.5719
safe dumping
The remaining time for the leachate to arrive to groundwater is:  29.8227
fx >>
```

Fig. 22. Examination of the hybrid expert system (2)

8. CONCLUSION

The fuzzy logic has proven its activity and reliability by its good intellectual estimation for the contamination prediction problem. This excellent performance can be seen when reasonable solutions correspond to intermediate values of inputs that are not found in the training data. Also, using a triangular membership function in the intellectual variables of the fuzzy system returns more accurate outputs than if the Gaussian membership function is used. The explanation for this behavior is that for contamination penetration problem, the overlap between membership functions should be as minimum as possible. This minimum overlapping can be obtained by using a triangular membership function, while the Gaussian function causes uncontrolled overlapping. The error percentage between the intellectual estimation of the fuzzy system and the training data is about 0.5–15%. This variation in error among given inputs is due to FEA training data, which is unpredictable and error-prone between independent runs. These independent runs are responsible for generating logical rules. For the fuzzy logic part, the membership function of contamination penetration problem, it is found that the main variables should be divided into at least ten levels instead of the usual division (low, medium, high, etc.): the more variable levels, the more accurate results. The hybrid expert system is better than a pure rule-based fuzzy system and pure, crisp logic system because the limited ranges of inputs of the crisp logic system give more accurate outputs than the rule-based system. This can be utilized for the calculations of dangerous cases. The expert system, with its two parts, crisp logic and fuzzy logic, has proven its activity and reliability by its good intellectual estimation. This excellent performance can be seen when the expert system has returned reasonable solutions corresponding to intermediate values of inputs that are not found in the training data.

As for future work, we recommend employing artificial neural networks to be trained by the set of finite element data. A comparison can be performed between using fuzzy rules and neural networks on the efficiency of the expert system.

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