

# Discriminative model of pipeline accidents detection in water supply and distribution systems

V A Zayko, M D Chernosvitov and V I Poluyan

Samara State Technical University, 194, Molodogvardeyskaya st., Samara, 443001,  
Russian Federation

E-mail: kafvv@mail.ru

**Abstract.** The paper deals with the problem of current assessment of emergency conditions and diagnostics of emergency pipelines location in water supply and distribution systems (WSDS) in conditions that allow maintaining the quality of water supply network functioning at a certain target level. The diagnostic process here consists of the following three stages: detection of the fact of the accident, assessment of the quality level of the system operation and search of the emergency area. To solve the problem, the researchers resort to the method of discriminative analysis. This method makes it possible to use information about the values of such controlled parameters as pressure at the network certain points and discharge in the network sections thus assessing if the technical condition under diagnosis belongs to one of the emergency subsets. The method also involves the decision procedure constructed in the multidimensional space of the observed indicators proving the emergency conditions.

## 1. Introduction

The problem of current assessment of emergency conditions and diagnostics of emergency pipelines location in water supply and distribution systems (WSDS) is crucial in choosing control actions that allow maintaining the quality of water supply network functioning at a certain target level [1]. To fulfil the requirement of efficiency in the management of large and complex systems is only possible when automating the process of detection and localization of damaged elements, which require specially developed methods and algorithms for diagnosis [2-4].

## 2. Problem specification

The authors consider WSDS to be complex technical systems. Thus, generally accepted terminology introduced in Papers [5, 6] is used in this paper also when classifying these systems technical conditions. According to the Papers mentioned, any complex technical system can be in good working condition; in poor working condition; in operable condition; in non-operable condition.

These terms cover main technical WSDS conditions, which are characterized by a set of parameter values describing these conditions [7]. The transition of the system from one technical state to another usually occurs as a result of damage (shutdown) or recovery (inclusion) of its individual elements. A system in which all elements function properly is considered to be in good working condition, but in case of damage to one or more elements, the system becomes non-operable. At the same time, a system in poor working condition can be fully operable, i.e. perform its main functions to provide consumers with water at the required level of quality of functioning (RLQ). Thus, WSDS –can be

- in full operable condition with RLQ being not lower than the required design level;

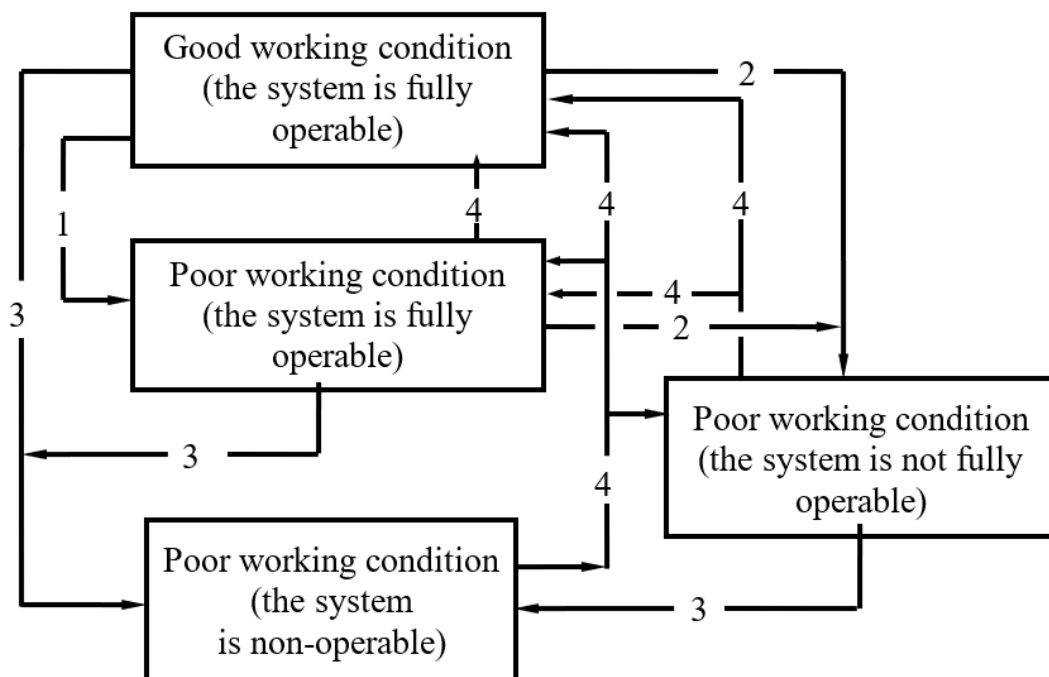


Content from this work may be used under the terms of the [Creative Commons Attribution 3.0 licence](https://creativecommons.org/licenses/by/3.0/). Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

- in half-operable condition with RLQ being lower than the required design level but above the maximum permissible RLQ reduction;
- in non-operable condition with RLQ below the maximum permissible level. In this case the system fails.

### 3. Discussion

There is usually a transition period between two technical conditions, which is determined by the duration of the emergency element shutdown. During this period, RLQ might drop below the maximum permissible level. The duration of WSDS operation in this state is determined by regulatory requirements. Figure 1 shows the general scheme of WSDS technical conditions.



**Figure 1.** General scheme of WSDS technical conditions: 1 – failure, in which normal level of the system functioning quality is maintained ; 2 – failure, leading to decline in the level of functioning quality which is still above the minimum allowable; 3 – failure, leading to reduction in the system functioning quality below normal; 4 – failure recovery.

WSDS condition can be fully characterized by  $\mathbf{Z}(t)$  vector, which is a mathematical model of its functioning, that is

$$\mathbf{Z}(t) = \{x_1(t), x_2(t), \dots, x_n(t), y_1(t), y_2(t), \dots, y_m(t)\}, \quad (1)$$

where  $\mathbf{n}$  is the number of parameters describing the mode of WSDS operation,  $\mathbf{m}$  is the number of WSDS elements.

$\mathbf{x}_i(t)$  parameters describing the mode of WSDS operation ( $i=1, \dots, n$ ) take values of physical quantities measured or obtained as a result of the following calculation: pressure at certain particular points of the network, discharge in certain areas, water levels in basins, etc.

The state of each  $j^{\text{th}}$  WSDS element ( $j=1, \dots, m$ ) is described by the function:

$$y_j(t) = \begin{cases} 1, & \text{if the } j^{\text{th}} \text{ element is operable;} \\ 0 & \text{if the } j^{\text{th}} \text{ element fails.} \end{cases}$$

The number of elements  $y_j(t)$  and parameters  $x_i(t)$  is determined at the development stage of the diagnostic system and depends on the complexity and dimension of the system. The points of space between which the vector  $Z(t)$  moves form the conditions motion trajectory

In the process of WSDS functioning all sets of the system conditions can be divided into a number of subsets, characterized by some common feature. When solving the problem of diagnostics of emergency states, it is proposed to use a three-stage diagnostic process. At the first stage it is necessary to detect the fact of the accident which causes RLQ deviation. At the second stage it is assessed if WSDS is operable or non-operable. Then the network emergency site is located. In this three-step approach, all states of the system are divided into three subsets:

- H subset corresponding to WSDS fully operable state;
- C subset corresponding to WSDS damage that reduces the RLQ to the level which is not below the minimum permissible (the state is not fully operable);
- A subset corresponding to WSDS damage that reduces the RLQ below the maximum permissible level (non-operable state).

#### 4. Solution

The following three tasks are solved in the development of the algorithm for diagnostics and control of WSDS in emergency states:

- 1) recognition of the states characterized by damages of network sites as regard to their belonging to subsets A or C;
- 2) detection of damaged area;
- 3) determination of the composition of shut-off and control devices and the order of remedial actions.

Thus, at the first stage of diagnosis, the whole set of states is divided into **H** and  $(A \cup C)$  subsets, at the second stage is divided into **A** and **C** subsets and at the third stage, the site where the accident occurred is located.

After the detection of the damaged section it is necessary to choose such control actions that minimize the damage and prevent WSDS from falling out of subset **C**. In case WSDS condition is beyond the permissible level transfer system it is important to transfer the system in **C** or **H** area using the best trajectory.

According to Papers [8, 9], one of the best methods to determine which of the selected subsets (**A** or **C**) belongs to the recognized state is the method of discriminative analysis.

Its application assumes that the decision whether the diagnosed condition is within one or the other subsets is made directly and is based on the information of the controlled parameters values, that is pressure at the network certain points and discharge in the network sections. The method also involves the decision procedure constructed in the multidimensional space of the observed indicators proving the emergency conditions. Each state in this  $n$ -dimensional space **W** corresponds to a point with coordinates determined by the values of the parameters  $x = \{x_1, x_2, \dots, x_n\}$ .

There is a very simple geometric vector representation showing if the condition under investigation is within one of the subsets described above. In fact, if the representatives of subsets **A** and **C** are known and the corresponding regions  $W_A$  and  $W_C$ , are allocated in space, it is only necessary to find out to which of these regions the condition belongs. If the specified areas are defined in space, it is enough to check whether the investigated state satisfies the conditions that define these areas and then identify which of the conditions corresponds to the emergency state. To describe the area, it is possible build a function that in the case of belonging to the recognized emergency state of the corresponding area takes the maximum value compared to the functions for other areas. Such functions are called discriminative and are formed from the condition that for all states of the components of **A** and **C** subsets the following inequality is satisfied:

$$FA(x) > FC(x). \quad (2)$$

A specific type of discriminative functions  $F_A(x)$  and  $F_C(x)$  is calculated on the basis of a priori information which is a training sample obtained by modeling WSDS emergency states or observing them in real systems, and allowing dividing all states into two subsets, **A** and **C**. At the same time, in the process of forming discriminative functions, it is possible to consider all of them in order to determine the most suitable, i.e. having the best recognition abilities.

Standard programs can be used to calculate discriminative functions describing  $W_A$  and  $W_C$  regions and characterizing the states of subsets **A** and **C**. As a result of these calculations, the discriminative equation is calculated for each subset of **A** and **C** states,

$$F(x) = C_0 + \sum C_i \cdot x_i, \quad (3)$$

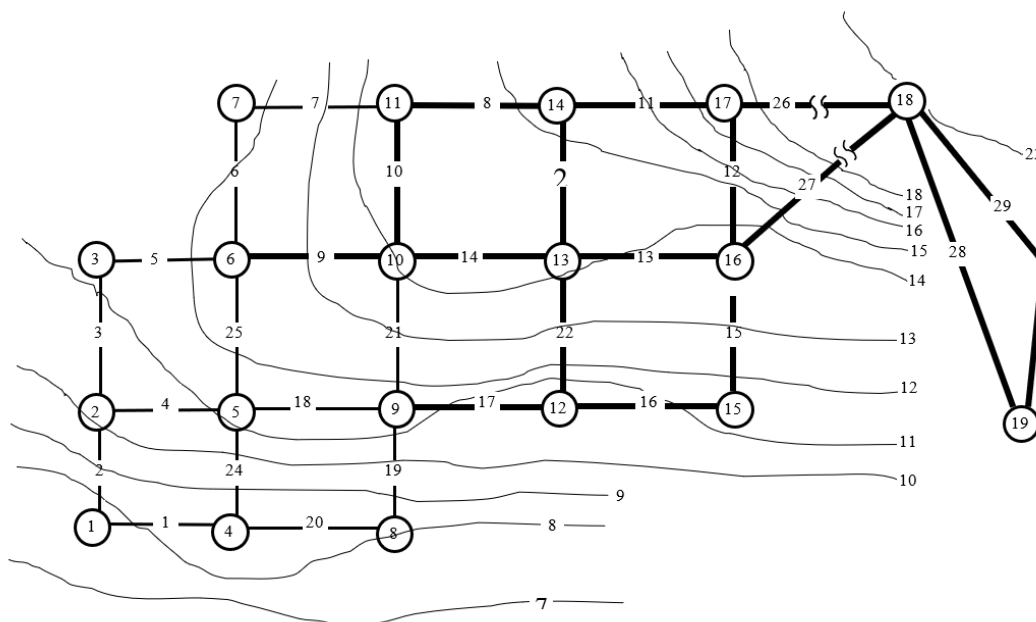
where  $C_0$  is an absolute term of an equation; and  $C_i$  is the coefficient for feature  $x_i = 1, \dots, n$ .

The following sequence is observed when calculating discriminative functions:

1. A training sample is formed by modeling accidents at individual sites, later they are divided into two subsets, that is **A** and **C**.
2. Discriminative functions are calculated.
3. There performed a recognition of emergency states of the training sample with the assessment of the quality of the decision rule.

As a result of classification according to the value of RLQ, all states are divided into two subsets, **A** and **C**. Each set forms the corresponding tables of features, e.g. piezometric heads in WSDS units. Each row of the table corresponds to a specific state that characterizes the damage on one of the network sections. The values of the controlled parameters are arranged in columns, and each parameter has its own column.

When calculating discriminative functions, it is necessary to take into account that the quality of recognition of emergency states largely depends on the composition and number of characteristics which are taken into account. The most useful are those that are insensitive to changes in the conditions of functioning within each of the subsets and change dramatically in the transition from one subset to another. Since the number of possible combinations of features is enormous, the search for a combination that allows more efficient and reliable carrying out the process of recognition of emergency states can be performed by successive changes in the initially selected combination, known as the "basic" option. It is also important to take into account measuring devices which are already parts of WSDS and consider them also as the "basic" option.



**Figure 2.** Design model of water supply network.

In order to analyze the effectiveness of recognition of emergency states with the help of the obtained discriminative functions, it is necessary to perform control recognition of emergency states of the examination sample also obtained by modeling. As a result of this control recognition, all variants of combinations of features are evaluated and the most effective combination is selected.

To illustrate the method described, let us consider the water supply network shown in Figure 2. All the initial information necessary for the formation of the training sample is obtained by means of accidents mathematical modeling by data processing machine. Table 1 shows the value of piezometric heads only for five units of the water supply network. In the process of preliminary analysis these five units were the most informative in terms of the process of diagnosing emergency conditions. As a result of classification, all states are divided into two subsets **A** and **C** according to their RLQ. Each row of the table corresponds to a certain state that characterizes the damage on one of the network sections. The values of the controlled parameters are arranged in columns, and each parameter has its own column.

**Table 1.** Emergency sited and their controlled characteristics.

The number of emergency site	Controlled characteristic (pressure), m					Belonging to the technical condition
	X <sub>1</sub>	X <sub>6</sub>	X <sub>9</sub>	X <sub>14</sub>	X <sub>15</sub>	
1	11.13	27.01	28.38	35.99	37.95	C
2	11.44	27.2	28.91	36.27	38.26	C
3	15.55	26.64	28.98	36.10	38.15	C
4	14.79	26.19	27.98	35.57	37.59	C
5	17.04	24.88	28.35	35.42	37.61	C
6	19.39	21.84	26.60	33.55	35.95	C
7	18.98	21.46	25.33	31.82	34.63	C
8	17.20	19.41	21.98	26.26	30.81	A
9	15.49	20.52	23.09	30.48	32.99	A
10	18.16	20.98	23.02	29.63	32.71	C
11	15.99	18.54	19.45	19.87	25.49	A
12	14.45	16.84	17.00	19.37	19.00	A
13	13.67	15.86	16.18	20.80	22.30	A
14	14.31	15.97	17.06	24.73	27.53	A
15	14.42	17.93	16.28	22.85	16.00	A
16	14.12	18.94	15.31	25.95	22.18	A
17	13.66	19.90	14.16	28.49	28.86	A
18	14.59	22.90	22.49	32.76	34.60	C
19	13.62	23.76	21.87	32.29	34.47	C
20	12.50	24.91	24.93	34.07	35.94	C
21	16.44	21.29	18.74	30.25	32.11	C
22	17.22	21.48	20.27	28.35	28.99	A
23	16.58	19.43	20.15	22.81	27.56	A
24	15.31	25.52	26.43	34.78	36.73	C
25	17.54	23.14	26.08	34.10	36.27	C
26	14.77	17.22	17.53	19.36	20.08	A
27	14.94	17.53	17.69	20.50	19.94	A

Four combinations of features were considered for the presented network:  $S_1 = \{x_6, x_{14}\}$  – baseline,  $S_2 = \{x_1, x_6, x_{14}\}$ ,  $S_3 = \{x_6, x_9, x_{14}\}$  and  $S_4 = \{x_6, x_{14}, x_{15}\}$ . After calculations, discriminative functions  $FA(x)$  and  $FC(x)$ , were obtained for each combination of features. They are presented in Table 2.

**Table 2.** Discriminative equations for different combinations.

Variants of features combination	Discriminative equation
S <sub>1</sub>	$F_A(x) = -34.298 + 2.231x_6 + 1.256x_{14}$ $F_C(x) = -64.918 + 2.660x_6 + 2.092x_{14}$
S <sub>2</sub>	$F_A(x) = -103.908 + 6.569x_1 + 4.807x_6 + 1.082x_{14}$ $F_C(x) = -149.264 + 7.225x_1 + 5.495x_6 + 1.836x_{14}$
S <sub>3</sub>	$F_A(x) = -34.941 + 2.037x_6 + 0.425x_9 + 1.136x_{14}$ $F_C(x) = -66.525 + 2.354x_6 + 0.673x_9 + 1.838x_{14}$
S <sub>4</sub>	$F_A(x) = -34.942 + 2.236x_6 + 0.877x_{14} + 0.416x_{15}$ $F_C(x) = -66.809 + 2.668x_6 + 1.387x_{14} + 0.712x_{15}$

The recognition results for each discriminative equation of the training sample show that  $F_A(x)$  и  $F_C(x)$  lead to fewer errors for S<sub>2</sub> combination of features, with two states in each of the subsets. Here, combinations S<sub>1</sub> and S<sub>3</sub> incorrectly recognize emergency states in Sections 9 and 22, and combinations S<sub>2</sub> and S<sub>4</sub> incorrectly recognize emergency states in Sections 8 and 22. In order to increase the reliability of recognition and reduce the number of errors, it is possible to use a combination of discriminative functions obtained for S<sub>1</sub> and S<sub>2</sub>. This will eliminate errors for Sections 8 and 9. Thus, for the recognition of emergency conditions at the second stage of diagnosis, a combination of S<sub>2</sub> = {x<sub>1</sub>, x<sub>6</sub>, x<sub>14</sub>} is accepted. Control and measuring devices (e.g. pressure sensors) should be placed in Sections 1, 6 and 14, respectively.

## 5. Conclusions

The researchers recommend performing three diagnostics stages of emergency conditions in the water supply network in centralized systems of water distribution. At the first stage, it is necessary to detect the fact of the accident. At the second stage, this condition is referred to a subset A or C. At the third stage, the location of the emergency site is determined.

To solve the problem of the second stage, discriminative functions are effectively used. These functions make it possible to classify the observed emergency state quite accurately. The method presented in the paper is based on the existence of the fact of a sharp change in pressure and discharge in the network sections in the event of an accident, so they are recommended to be used as the main indicators characterizing WSDS condition.

## References

- [1] Zayko V A 2015 Diagnostic problems of emergency conditions in water supply and distribution systems *Scientific review* 15 136-142
- [2] Hajebi S, Temate S, Barrett S, Clarke A and Clarke S 2014 *Water distribution network sectorisation using structural graph partitioning and multi objective optimization: 16th Conference on Water Distribution System Analysis (WDSA)*
- [3] Sophocleous S, Savica D, Kapelan Z, Shen Y and Sage P 2016 A graph-based analytical technique for the improvement of water network model calibration *Procedia Engineering January 2016* p 27-35
- [4] Primin O G, Bortkevich V S, Mirkis V S, Kantor L I and Vinarskiy S L 2014 On developing water supply plans for Russian cities *Water delivery and sanitary engineering* 7 24-33
- [5] *A methodology for selecting indicators to assess the reliability of complex technical systems* 1977 (Moscow: Publishing house of standards)
- [6] GOST 27.002-83 1983 *Reliability in technology. Terms and definitions.* (Moscow)

- [7] Galperin E M 1999 Terms and definitions in water supply *Water delivery and sanitary engineering* 12 23
- [8] Kim J and Muller Ch W 1989 *Factor, discriminant and cluster analysis* (Moscow: Finance and statistics)
- [9] Kendall M J and Stuart A 1976 *Multivariate statistical analysis and time series* (Moscow: Science)