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Research paper

Municipal Water Supply Systems of Giving-Distributive Complex Reliability with Branched Networks

Valeriy Novokhatniy[1], Oleksandr Matyash[2*], Sergiy Kostenko[3]

[1]Poltava National Technical Yuri Kondratyuk University, Ukraine
[2]Poltava National Technical Yuri Kondratyuk University, Ukraine
[3]Poltava National Technical Yuri Kondratyuk University, Ukraine
**Corresponding Author E-Mail: Matyash19831010@Gmail.Com*

Abstract

The basics of the reliability theory of small settlements water supply systems were considered. Methods of the reliability calculation of the supply-distribution complex structures were reviewed: pumping stations, water pipes and branched network. The mathematical reliability model of the water supply technological process to the most distant consumers were constructed according to the water supply selected directions. The real possibility of water supply reliability calculation on an actual example was shown and a graphical representation of the results was performed.

Keywords: *faultlessness, reliability, reparability, water supply systems.*

1. Introduction

The main function of the water supply system is the supply of water to consumers in the necessary quantity under the required pressure. If the water consumers are the population, then the quality of this water should comply with DSTU 7525: 2014 Drinking water [1]. For practical purposes, the presence of these conditions is not enough. It is necessary to be sure that the water supply system will operate without unacceptable frequency and duration of water supply breaks, pressure reductions or water quality deterioration. This confidence will appear when the necessary reliability of the water supply system is provided.

The reliability of water supply as a technological process depends on the reliability of the water supply structures. To assess the water supply reliability of individual water consumers can only be done after the reliability calculation of individual water supply structures, which lie on the water supply way. Such opportunity is shown on the example of the small settlement water supply system in this paper. The performed reliability calculations allow answering two questions - how often will the water supply breaks occur and how long the consumer water supply will resume.

2. Problem Definition

The founders of the water supply systems reliability in the former Soviet Union were M.M. Abramov [2] and Yu.O. Ilyin [3]. In Ukraine, the question of the water supply structures reliability is developed by P.D. Horuzhii [4], V.G. Novokhatniy [5], O.A. Tkachuk [6], O.V. Matiash [7 … 9], I.S. Usenko [10], S.O. Kostenko [11] and others. Foreign scholars such as F. Bouchart, N. Daun, I. Goulter, K.E. Lansey, Y.C. Su, Y.K. Tung [12], L.W. Mays [13], U. Shamir [14], P.K. Swamee [15] and others should be mentioned as well. A considerable number of scientific papers on the water supply systems and structures reliability indicate the significance of the issue. However, in these works, reliability calculations, which operate with the probabilities of such random events as refusals, prevail. Such calculations do not answer the actual consumer questions, namely – how often will breaks in water supply happen and how long will they last? Author`s research answer these questions, but so far only for settlements with branched networks.

3. Purpose and Tasks of the Research

The purpose of the article is to present a method of the water supply reliability calculation on the example of a small settlement and quantitative indicators in real units of time.

4. Principles and Methods of Reliability Calculation

Reliability is the property of the water supply system to supply water to consumers with preservation in time:
– water supply and pressure;
– water quality;
– permissible frequency of breaks in water supply;
– acceptable time for water supply restoration.

Reliability includes faultlessness, repairability, durability and maintainability. **Faultlessness** is the ability of the system to perform the required functions within a given time interval. The water consumer formulates the requirements for the frequency of water supply breaks that need to be performed. **Repairability** is

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the property of the system to be adapted to recover a workable state. The consumer formulates the requirements for the duration of the breaks in water supply that must be performed. **Durability** is the ability of the system to perform the required functions before moving to the limit state. The durability of water supply structures and networks is analyzed.

Readiness is a property that combines faultlessness and repairability. In this case, the concept of failure and restoration of an element or structure are decisive. **Failure** is an event that results in the loss of capacity of a water supply structure or its element. In the technological process of water supply, the failure of the structure can cause a water supply break or a decrease in the supplied water value. **Failure criterion** is a characteristic or characteristics combination of violation of the water supply structure or its element working state. But it is necessary to take into account the consequences of the failure for the consumer.

Faultlessness indicators are the **probability of faultlessness operation** – the probability that the failure of a structure or element will not occur during a given time; **the parameter of the failure flow** – the mathematical expectation ratio of the number of failures to work for a small period of time; **the mean operating time to failure** – the average operation time of the building or element after repair until the next failure.

Repairability indicators are **the recovery probability** – the probability that the recovery time of the working state will not exceed the prescribed value; **the average time for the work capacity restoration** of the structure or its element.

A methodology [16] for choosing key reliability indicators were developed in the reliability theory. The basis of such choice are the dominant factors and consequences that arise in case of failure. Only two are the dominant factors in assessing the consequences of the water supply system failure: **the danger** in water supply break and **the duration** of the break, and therefore all water consumers should be divided into two groups. **The first group** is production with a continuous technological process, where **the danger** of a water supply break is dominant, as it can cause death of people or ecological catastrophe. All other consumers should be classified to **the second group**, where **the duration** of the water supply break is dominant, which leads to ordinary material or moral losses. This group also includes centralized water supply systems of settlements, which are divided into three following categories.

The first category – cities with the number of **inhabitants N ≥ 50000** – allow for water supply breaks no more than 3 hours per day and not more often than one time per 3 months. This norm was adopted in the United Kingdom in 1985.

The second category – cities with a population of **10,000 ≤ N <50000** – water supply breaks are allowed not more than 6 hours per day and no more than 2 times per month. This is determined by the "Code of Service" [17].

The third category – settlements with the number of inhabitants N<10 000 – water supply breaks are allowed not more than 24 hours (similar to DBN [18]) and no more than 2 times a month [17]).

For a quantitative measure of the water supply systems failure of the first group it is reasonable to take the probability of failure ***Q(t)*** during the time ***t***. Opposite probability ***P (t) = 1 - Q(t)*** is the probability of faultlessness operation

$$P(t) = P\{t \geq t_i\} \quad (1)$$

where t_i - arbitrary time interval.

The water supply fire protection system should start at any given time and work continuously for a given time interval τ. The main indicator of reliability will be the operational readiness coefficient K_{OR}

$$K_{OR} = K_R P(\tau), \quad (2)$$

where K_R – readiness coefficient.

For the second group water supply systems, the average time to failure ***T*** and the average time to restore the capacity of T_R, and the main indicator – the readiness coefficient K_R must be taken as the basic reliability indicators

$$K_R = \frac{T}{T + T_R}. \quad (3)$$

The opposite is a downtime rate $K_D = 1 - K_R$. (4)

Taking into account the above, Novokhatniy V.G. has developed [5] the reliability classification of water supply systems (Table 1).

Table 1: Classification of consumers and water supply systems for reliability

Groups of consumers	Groups and categories of water supply system	The values of main and basic reliability indicators		
1	**First group** Subgroup A – water supply systems of hazardous industries	Maximum probability of faultless operation during the service term $maxP(T_{el})$		
	Subgroup B – water supply fire protection systems	Maximum coefficient of operational readiness for **3** hours of fire localization $maxK_{OR} = K_R \cdot P(\tau)$		
2	**Second group** Centralized water pipelines of settlements with the number of inhabitants	Time to failure ***T***, hours	Average recovery time of workable state T_R, hours	Readiness coefficient K_R
	1 category cities N ≥ 50 thousand inhabitants	***T ≥ 2160 hours (3 months)***	$T_R \leq 3$ ***hours***	***0,9986***
	2 category cities 10 тис. ≤ N ≤ 50 thousand inhabitants	***T ≥ 360 hours (0,5 month)***	$T_R \leq 6$ ***год***	***0,9836***
	3 category urban-type villages and villages N< 10 thousand inhabitants	***T ≥ 360 hours (0,5 month)***	$T_R \leq 24$ ***год***	***0,9375***

4.1 The purpose of the "Failure" Criterion

According to [18, p. 12.5], centralized water supply systems in settlements may have a branched network of unlimited length, if these systems are not used for fire extinguishing, and pipe diameters do not exceed 100 mm.

The directions of water supply from the water source to the end users will be considered. These consumers are the most distant ones. Determine, how often and how long they will have no water. The failure criterion of the water supply system in the direction of water supply will be considered as the lack of water for the most distant consumer.

A consumer of drinking water is a legal or private customer (owner of a mansion house or apartment – a subscriber), who uses water.

The most distant consumer is a consumer who is located in the final network site (by the way of the water). **The operating state** of the system in the chosen direction is the operating state of all structures on the way from source to the most distant consumer. **Nonoperating** state of the system in the chosen direction − failure of at least one of the structures on the way from the source to the most distant consumer. **The failure** of the water supply system in the chosen direction is the moment of its transition from the operating to the nonoperating state.

4.2 The reliability of the supply-distribution complex

The supply-distribution complex of a centralized water supply system includes the 2nd lift pumping station (collecting the water from the surface source), a water supply system, and a water supply network. The mathematical model for calculating the reliability of the supply-distribution complex (SDC) is a consistent combination of renewable elements (structures).

Failure flow parameter of SDC in the selected direction

$$\omega = \sum_{i=1}^{n} \omega_i \text{ , 1/h,} \tag{5}$$

where ω_i – failure flow parameter of the ***i-th*** structure, 1/h.

The mean operating time to failure of SDC

$$T = 1/\sum_{i=1}^{n} \omega_i \text{ , h.} \tag{6}$$

Average time for SDC workable state recovery

$$T_R = \frac{\sum_{i=1}^{n} T_{R_i} \omega_i}{\sum_{i=1}^{n} \omega_i}, \text{ h,} \tag{7}$$

where T_{R_i} − average time for recover the workable state of ***i-th*** structure, hours.

4.3 Reliability of the water supply network and system

Failure flow parameter of the ***i-th*** section of the water supply network or system

$$\omega_{s_i} = \sum_{i=1}^{n} \omega_{0_i} \cdot L_i, \text{ 1/h,} \tag{8}$$

where L_i – the length of the ***i-th*** diameter pipeline section, km;

ω_{0_i} − specific failure flow parameter of the ***i-th*** diameter pipeline and the material of the pipes, 1/h·km.

Failure flow parameter of a network or a water supply system

$$\omega_n = \sum_{i=1}^{n} \omega_{s_i}, \text{ 1/h,} \tag{9}$$

where n – number of the network sections in the selected direction.

Average recovering duration of the network workability

$$T_{R_n} = \frac{\sum_{i=1}^{n} T_{B_{si}} \omega_{s_i}}{\sum_{i=1}^{n} \omega_{s_i}}, \text{ h,} \tag{10}$$

where $T_{R_{si}}$ − average workability recovery duration of the ***i-th*** network section or water supply system in the chosen direction, h.

4.4 Reliability of Pumping Stations (PS)

Pumping station technological part elements are pump units, gate valves and return valves. The operational data analysis shows that pipelines that combine these elements have much higher reliability and are therefore considered not to be denied in the pumping station operation.

Methods of the reliability calculation of elements that have a consistent or parallel combination are widely developed in the reliability theory. But in the technological part of the pumping stations, the elements have a mixed combination, that is, one that can not be sequential, parallel or sequential-parallel. In the reliability theory methods for calculating structures with a mixed combination of elements are developed [19]. The exact formulas are cumbersome, and therefore do not find widespread use in engineering calculations. V.G. Novokhatniy has developed the methods of the faultlessness calculating [20] and the repairability of the technological part of pumping stations [21] on the basis of the method of "contribution" for assessing the reliability of renewable systems, which was developed in the reliability theory by I.O. Ushakov [22].

For pumping stations, "contributions" of elements to the failure flow of pumping station are calculated by the formula.

– failure of the element leads to the failure of the pumping station;

$$v_i = \begin{cases} \omega_i \\ \omega_i \sum_{s=1}^{k} K_{\Pi_j} \end{cases}$$

− the failure of the pumping station occurs in the event of a failure of the ***i-th*** element with the repair of the ***j-th*** element, where ω_i – failure flow parameter ***i-th*** element, 1/h;

K_{FT_j} – fault time coefficient of ***j-th*** element

$$K_{\Pi_j} = \omega_j T_{B_j}, \tag{11}$$

where T_{R_j} – average workability recovery duration of the ***j-th*** element, h.

Failure flow parameter of the pumping station is calculated as the sum of the contributions of all N elements

$$\omega_{ps} = \sum_{i=1}^{N} v_i \text{ , 1/h.} \tag{12}$$

The mean operating time to failure of pumping station

$$T_{ps} = 1/\omega_{ps} \text{ , h.} \tag{13}$$

Let us consider a technological scheme of PS, which consists of k elements and has a failure flow parameter of ω_{ps}.. It is possible to construct an equivalent structure consisting of a sequential combination of fictitious elements for which the condition is fulfilled

$$\omega_{ps} \cong \sum_{i=1}^{u} \omega_i^f \text{ , 1/год,} \quad (14)$$

where ω_i^f – failure flow parameter of the i-*th* fictitious element, 1/h;

r – the number of fictitious elements.

If the average recovery duration of fictitious elements $T_{R_i}^f$ is known, it can be determined the average recovery duration of the system, as for purely sequential combination

$$T_{R_{ps}} = \frac{\sum_{i=1}^{u} \omega_i^f T_{R_i}^f}{\sum_{i=1}^{u} \omega_i^f} \text{ ,h.} \quad (15)$$

Given that each enlarged element brings its "contribution" υ_i to the total failure flow of the PS, the failure flow parameter of the pumping station is defined as the sum of the contributions of all N aggregate elements. In this way, the mixed structure of the pumping station is conditionally converted into a sequentially combined structure consisting of fictitious elements in the number $r = N$, and the corresponding indices of faultlessness of these elements $\omega_i^f = \upsilon_i$ and repairability $T_{R_i}^f = T_{R_i}$.

The average recovery workability duration of the PS in this case is calculated as the weighted mean value of the "contributions".

$$T_{R_{ps}} = \frac{\sum_{i=1}^{N} \upsilon_i T_{R_i}}{\sum_{i=1}^{N} \upsilon_i} = \frac{\sum_{i=1}^{N} \upsilon_i T_{R_i}}{\omega_{ps}}, \text{ h,} \quad (16)$$

where υ_i – "contribution" of the i-*th* enlarged element to the total failure flow of the pumping station, 1/h;

T_{R_i} – average recovery workability duration of the i-*th* enlarged element, h;

N – the number of enlarged elements of the pumping station.

5. Reliability Calculation of the Village Water Supply System

The village is located in the Poltava region (Fig. 1), it has 960 inhabitants; maximum daily water consumption 253 m^3/day, maximum consumption per second is 7.7 l/s.

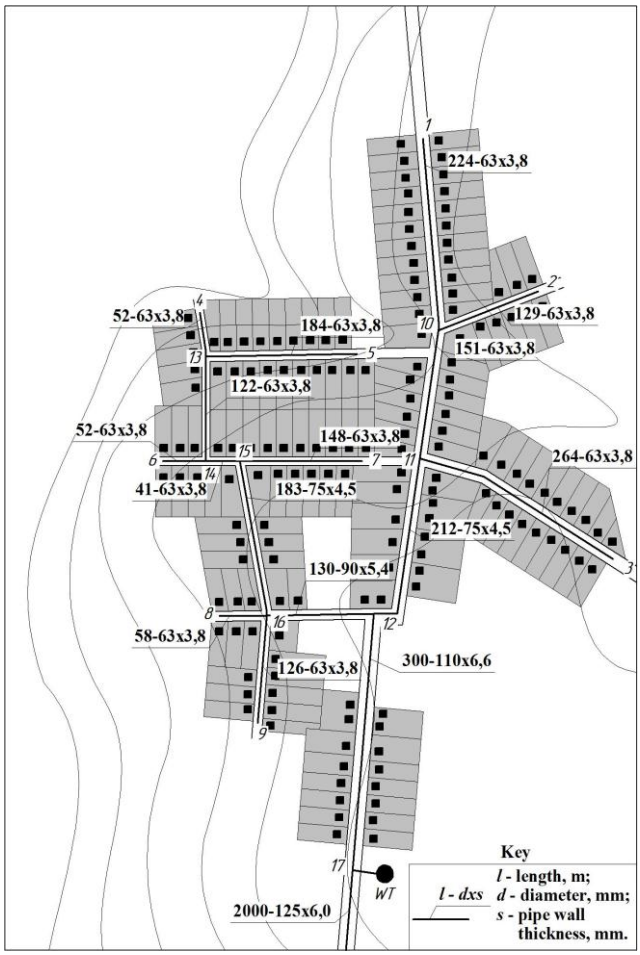


Fig.1: Plan of the village water supply network

The source of water supplies is a reservoir. Surface water is cleaned at water treatment facilities located at a distance of 2 km and enters the reservoirs of clean water (RCW). From the RCW drinking water is collected by the pumping station of the 2nd rising (PS-2) and fed by a water supply system to the branched network. Fire trucks from fire tanks and from the reservoir carry out fire extinction. At the highest point of the village water tower is located. The diameters of pipes are determined as a result of the hydraulic calculation. Polyethylene pipes are accepted: the minimum diameter is 63x3.8 mm, the maximum diameter in the village is 110x6.6 mm, water supply system diameter is 125x6.0 mm.

5.1. Sections Faultlessness of the Network or Water Supply System

Failure flow parameter of a network site or water supply system site

$$\omega_s = \omega_0 \cdot L, \quad (17)$$

where ω_0 – specific failure flow parameter of the polyethylene pipes, 1/(h·km);

L – length of the water supply system site or network site, km.

The specific failure flow parameter is $0{,}5 \cdot 10^{-4}$ 1/h·km. Calculations are given in Table 4 column 7, and the results are shown in Fig. 2

5.2. Reliability Calculation of PS-2

Pumping station has 1 working and 1 reserve pump unit (Fig. 3). The reliability calculation is performed by the method of "contributions" [21], data for calculations are given in Table. 2

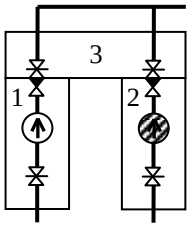


Fig. 3: Technological scheme of PS of the 2nd rising

Table 2: Data for the reliability calculation of PS-2

No.	Elements	Symbolic designation	Failure flow parameter ω, 1/h·10^{-4}	Average recovery duration T_R, h.
1	Pumping aggregates	p	1,25	60,0
2	Return valves	v	0,08	10,0
3	Gate valves: - upstream line	gu	0,1	20,0
	- downstream line	gd	0,6	10,0
	- suction header	gsh	0,1	20,0
	- discharge header	gdh	0,1	20,0

Failure flow parameter of enlarged elements

$\omega_1 = \omega_2 = \omega_{gd} + \omega_p + \omega_v = (0{,}1 + 1{,}25 + 0{,}08)\cdot 10^{-4} = 1{,}43\cdot 10^{-4}$ 1/год;

$\omega_3 = 2\omega_{gd} = 2\cdot 0{,}6\cdot 10^{-4} = 1{,}2\cdot 10^{-4}$ 1/h.

Average recovery time of enlarged elements

$$T_{R_1} = T_{R_2} = \frac{\omega_{gu} T_{B_{gu}} + \omega_p T_{R_p} + \omega_v T_{R_v}}{\omega_1} =$$

$$\frac{(0{,}1\cdot 20 + 1{,}25\cdot 60 + 0{,}08\cdot 10)\cdot 10^{-4}}{1{,}43\cdot 10^{-4}} = 54{,}4\text{h};$$

$$T_{R_3} = T_{R_{gd}} = 10 \text{ h}.$$

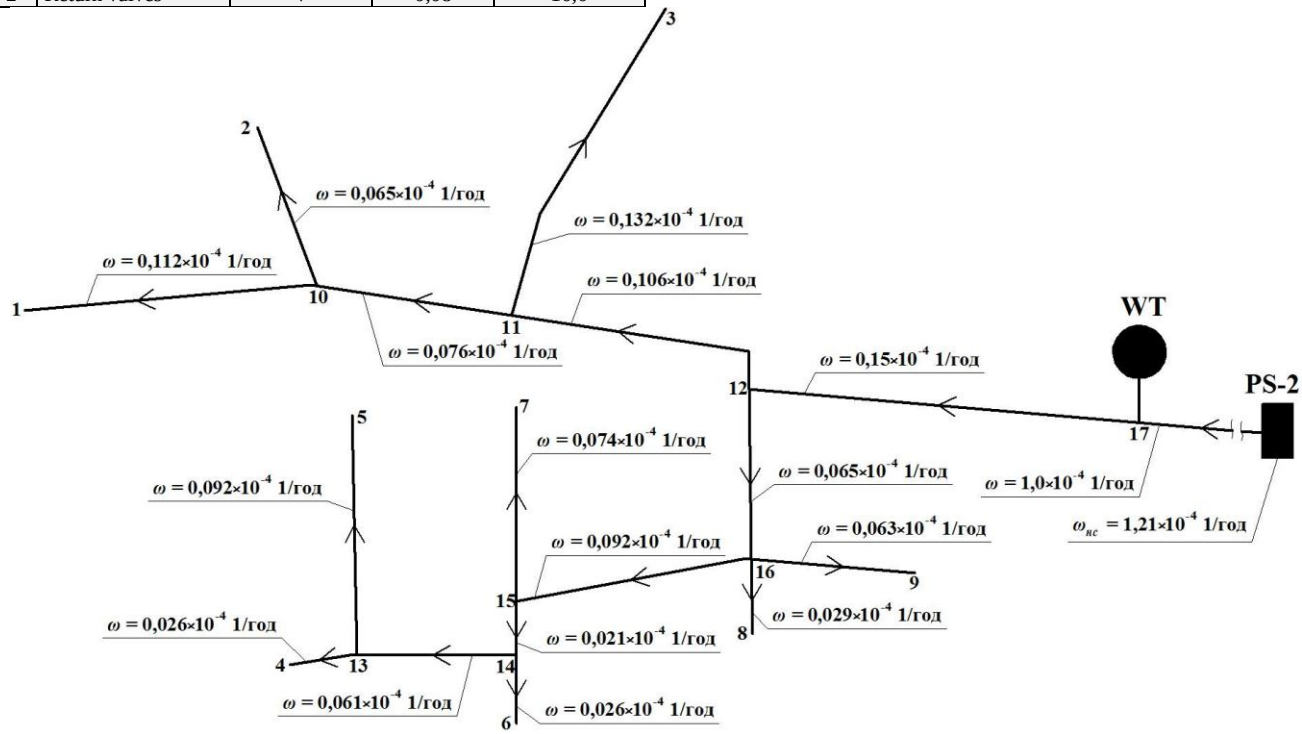


Fig.2: Failures flow parameter of a network site of village

Downtime rate of enlarged elements

$$K_{D_2} = \omega_2 T_{R_2} = 1{,}43\cdot 10^{-4}\cdot 54{,}4 = 77{,}8\cdot 10^{-4}.$$

Contributions of enlarged elements

$$\upsilon_1 = \omega_1 K_{D_2} = 1{,}43\cdot 10^{-4}\cdot 77{,}8\cdot 10^{-4} = 1{,}11\cdot 10^{-6}\,1/\text{h};$$

$$\upsilon_3 = \omega_3 = 1{,}2\cdot 10^{-4}\,1/\text{h}.$$

Pump station failure flow parameter

$$\omega = \upsilon_1 + \upsilon_3 = (0{,}0111 + 1{,}2)\cdot 10^{-4} = 1{,}21\cdot 10^{-4}\,1/\text{h}.$$

Pumping station operating time to failure

$$T = \frac{1}{\omega} = \frac{1}{1{,}21\cdot 10^{-4}} = 8257\,h.$$

Average workability recovery time

$$T_R = \frac{\upsilon_1 T_{R_1} + \upsilon_3 T_{R_3}}{\omega} =$$

$$\frac{(0{,}0111\cdot 54{,}4 + 1{,}2\cdot 10)\cdot 10^{-4}}{1{,}21\cdot 10^{-4}} = 10{,}4\text{h}.$$

5.3. Reliability of water supply in the directions

Failure flow parameter of SDC in the selected direction

$$\omega_c = \sum_{i=1}^{n} \omega_{s_i} + \omega_{ps}, \qquad (18)$$

where ω_{ps} – failure flow parameter of the 2nd lift pumping station, 1/h;

n – number of the network sections in the selected direction.
SDC operating time to failure in the selected direction

$$T = \frac{1}{\omega_c}, \quad (19)$$

Average workability recovery time of the system

$$T_R = \frac{\sum_{i=1}^{n} \omega_s T_{R_s} + \omega_{ps} T_{R_{ps}}}{\omega_s}, \quad (20)$$

$T_{R_{ps}}$ – average recovery time of the pumping station, h;

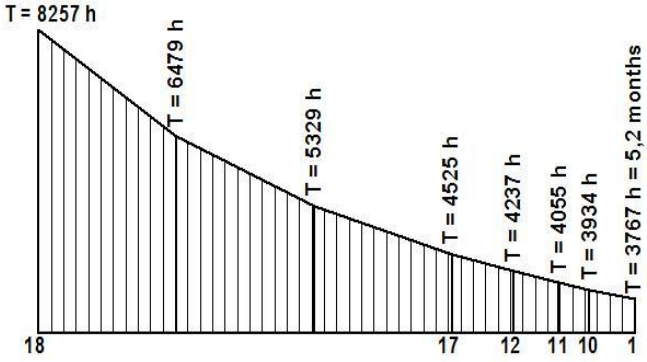
$T_{R_s} = 8h$ – average recovery time of the section.

The calculation is done in Table 4, Columns 9 ... 12.

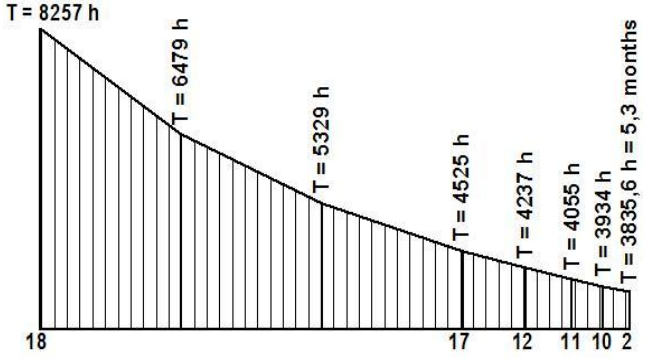
5.4. Graphic Presentation of Results

Novokhatniy VG [23] proposed graphical representation of consumers' water supply the continuity with diagrams of time in the form of a distribution diagram. On the horizontal line on a scale, the lengths of water supply network from the 2nd lift PS to the most distant consumers are delayed. On the ordinate axis, the operating time to failure T is delayed in hours. The distribution diagrams visualize the change and the operating time to failure of the SDC from the 2nd PS to the most distant consumer and determine the average time between the water supply breaks for each consumer of water (Fig. 4).

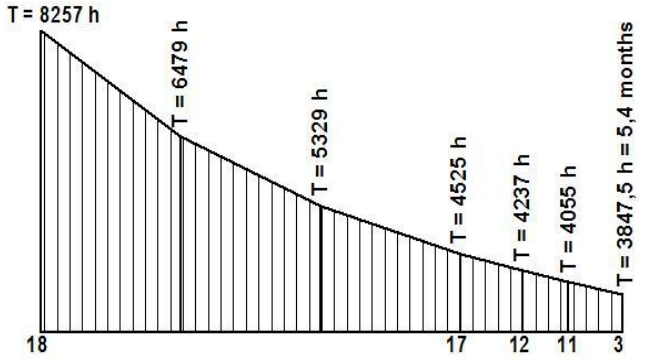
Direction 1-18



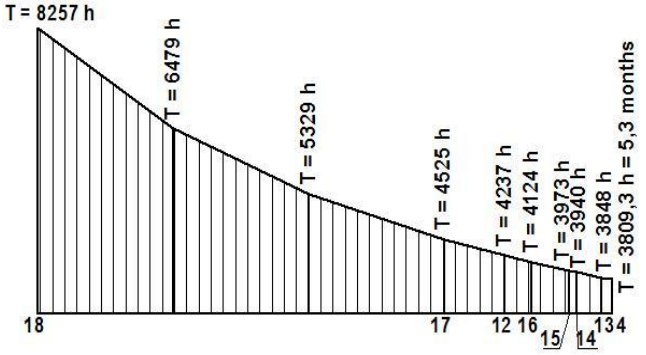
Direction 2-18



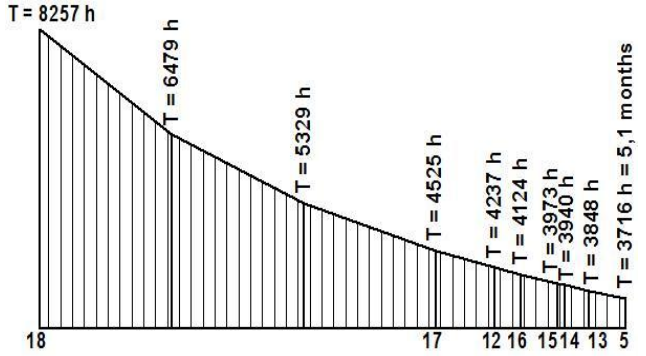
Direction 3-18



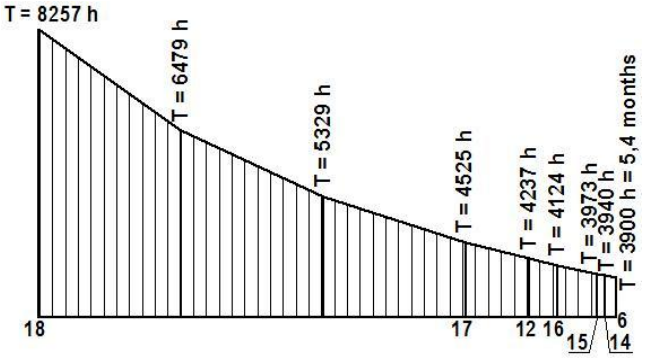
Direction 4-18



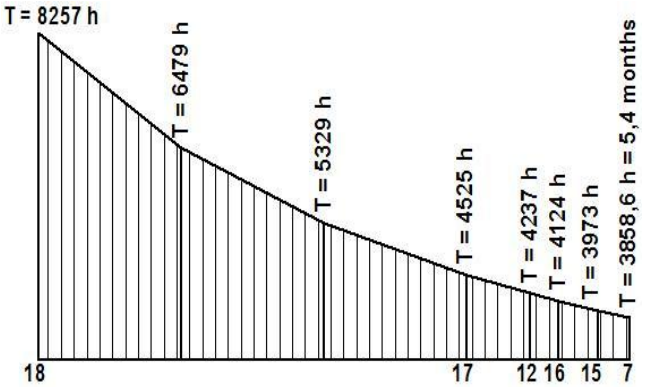
Direction 5-18



Direction 6-18



Direction 7-18



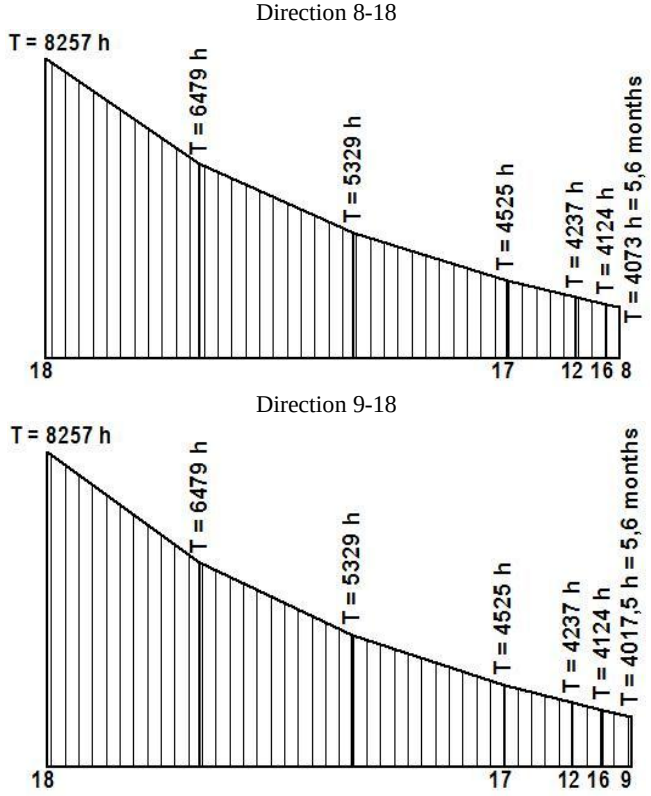


Fig. 4: Distribution diagrams for operating time to failure in water supply directions

5.4. Discussion of results and conclusions

Developed methods of the reliability calculation of the supply-distribution complex allowed:

1. To divide all water consumers into 2 groups, which fundamentally differ in the consequences of water supply breaks, namely – the first group includes the water supply systems of those consumers, the break of which water supply can lead to catastrophic consequences; communal water supply systems are classified in the 2nd group.
2. According to the defined groups, the basic reliability indicators are adopted: for group 1 – the probability of faultless operation ***P(t),*** for the second group – the mean operational time to failure ***T*** and the average workability recovery duration T_R,, and the main indicator is the readiness coefficient K_R.
3. Continuity of water supply from water source to the most distant consumers in directions of water supply by constructing distribution diagrams of average time to failure is presented graphically
4. The results of the reliability calculations of water supply by directions showed that the lowest value between the water supply breaks was for the consumer at the node number 5 ***T = 3716h = 5.1 months*** for the standard requirement ***T = 0.5 months***. Consequently, the continuity of water supply is much higher than the normative one. The average workability recovery time was T_R***=9,2 h***, which is significantly less than the normative value of T_R***=24h***. Thus, the designed water supply system in the village has sufficient reliability.

Table 4: Reliability of water supply to the most distant consumers

Selected directions characteristics						Reliability in the direction					
No.	Directions	Sections	*D* of sections	*L*, m	ω_0, 1/(h km)	ω_s	ω_{ps}, 1/h	ω_c, 1/h	*T*, h	T_R, h	K_D
1	2	3	4	5	6	7	8	9	10	11	12
1	1-18	1-10	63	224	0,00005	0,0000112	0,000121	0,000265	3767	9,1	0,002414
		10-11	63	151		0,0000076					
		11-12	75	212		0,0000106					
		12-17	110	300		0,0000150					
		17-18	125	2000		0,0001000					
						Σ=0,0001444					
2	2-18	2-10	63	129	0,00005	0,0000065	0,000121	0,000261	3835	9,1	0,002376
		10-11	63	151		0,0000076					
		11-12	75	212		0,0000106					
		12-17	110	300		0,0000150					
		17-18	125	2000		0,0001000					
						Σ=0,0001396					
3	3-18	3-11	63	264	0,00005	0,0000132	0,000121	0,000260	3847	9,1	0,00237
		11-12	75	212		0,0000106					
		12-17	110	300		0,0000150					
		17-18	125	2000		0,0001000					
						Σ=0,0001388					
4	4-18	4-13	63	52	0,00005	0,0000026	0,000121	0,000263	3809	9,1	0,002391
		13-14	63	122		0,0000061					
		14-15	63	41		0,0000021					
		15-16	75	183		0,0000092					
		16-12	90	130		0,0000065					
		12-17	110	300		0,0000150					
		17-18	125	2000		0,0001000					
						Σ=0,0001414					
5	5-18	5-13	63	184	0,00005	0,0000092	0,000121	0,000269	3715	9,1	0,002444
		13-14	63	122		0,0000061					
		14-15	63	41		0,0000021					
		15-16	75	183		0,0000092					
		16-12	90	130		0,0000065					
		12-17	110	300		0,0000150					
		17-18	125	2000		0,0001000					
						Σ=0,0001480					
6	6-18	6-14	63	52	0,00005	0,0000026	0,000121	0,000256	3900	9,1	0,002342
		14-15	63	41		0,0000021					
		15-16	75	183		0,0000092					

		16-12	90	130		0,0000065				
		12-17	110	300		0,0000150				
		17-18	125	2000		0,0001000				
						Σ=0,0001353				
7	7-18	7-15	63	148	0,00005	0,0000074	0,000121	0,000259	3858	9,1	0,002364
		15-16	75	183		0,0000092					
		16-12	90	130		0,0000065					
		12-17	110	300		0,0000150					
		17-18	125	2000		0,0001000					
						Σ=0,0001381				
8	8-18	8-16	63	58	0,00005	0,0000029	0,000121	0,000246	4073	9,2	0,002255
		16-12	90	130		0,0000065					
		12-17	110	300		0,0000150					
		17-18	125	2000		0,0001000					
						Σ=0,0001244				
9	9-18	9-16	63	126	0,00005	0,0000063	0,000121	0,000249	4017	9,2	0,002282
		16-12	90	130		0,0000065					
		12-17	110	300		0,0000150					
		17-18	125	2000		0,0001000					
						Σ=0,0001278				

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