Потребує обгрунтування метод визначення кількості контрольних вузлів при проектуванні мереж з урахуванням умов її живлення, а також в процесі її експлуатації при зміні гідравлічних характеристик ділянок. Це необхідно для суттєвого зменшення енергоспоживання насосного обладнання, попередження значних витоків. Досліджено процеси утворення зон недостатнього напору у водопровідних мережах. Запропоновано методику управління потокорозподілом у водопровідній мережі, який дозволяє обгрунтовувати необхідну і достатню кількість контрольних вузлів та місця їх розташування.

Показано, що отримані при цьому рішення узгоджуються з існуючими методами забезпечення необхідних напорів в мережі. Але при цьому відкриваються додаткові можливості в управлінні потокорозподілом, а саме уточнення розташування контрольних вузлів на водопровідній мережі при її експлуатації.

В результаті досліджень запропоновано спосіб визначення кількості контрольних вузлів, який дозволяє в залежності від площі зон з недостатнім напором визначати необхідну їх кількість при проектуванні водопровідної мережі та уточнювати розташування в процесі експлуатації.

Згідно з представленою методикою управління потокорозподілом у водопровідних мережах, виконуються гідравлічні розрахунки для різних режимів водорозбору, визначаються витрати води в ділянках, які є дійсними на момент виміру п'єзометрів в контрольних вузлах. Визначаються фактичні вузлові напори, встановлюються вузли, що знаходяться на межі зон з недостатнім напором, з числа яких при необхідності призначаються додаткові вузли контролю тиску. На стадії проектування мереж моделюється зміна параметрів роботи мережі. П'єзометричні позначки у вузлах визначаються відносно вузлів живлення, значення напору в яких задаються. Критерієм вибору кількості контрольних вузлів та місць їх розташування є величина мінімального тиску в них та розмір зон з недостатнім напором.

Розроблені рекомендації та доповнення до діючих методів управління потокорозподілом, за якими визначається кількість та розташування контрольних вузлів. Це дозволяє підтримувати необхідні тиски у вузлах мережі, попереджати їх перевищення, що сприяє зменшенню витоків та витрати на енергоспоживання в насосних станціях

Ключові слова: водопровідна мережа, керування потокорозподілом, методика управління, зони недостатнього тиску, контрольні вузли

UDC 621.144.2
DOI: 10.15587/1729-4061.2018.147656

DEVELOPMENT OF PROCEDURE TO CONTROL FLOW DISTRIBUTION IN WATER SUPPLY NETWORKS IN REAL TIME

O. Dobrovolska
PhD, Associate Professor
Depatment of water supply and sanitation
Zaporizhzhia State Engineering Academy
Soborny ave., 226, Zaporizhzhia, Ukraine, 69006
E-mail: dogoks@gmail.com

1. Introduction

Water supply and distribution systems of municipal water supply networks are the most power consuming part of the city water supply system. That is why one of the main directions of reducing power and material consumption in water supply systems is to improve flow distribution control in the networks [1–3].

The actual head in the network nodes should be as approximated to the required one as possible. This is the essence of optimization of the flow distribution control to reduce the overall power consumption in the network. This requires establishing a distinct relationship between the system of collecting information and the system of feedback with executive elements. That is why the substantiation of the choice of the number and location of head control nodes with regard to the zones of insufficient head during designing the networks taking into consideration the changes of hydraulic characteristics is promising.

The subject matter of the research is becoming increasingly relevant due to the fact that a considerable part of the water supply networks in the European countries, including Ukraine, Poland, Slovenia, Croatia and others, is constructed from steel piping, the throughput of which varies over time as a result of the exposure to corrosive processes [4–7]. That is why the presented recommendations can be offered for using by public utilities of the specified countries.

2. Literature review and problem statement

One of the main problems of flow distribution control in water supply networks is ensuring the values of node heads at the level of the required minimum. The problem situations that occur during the operation of the networks are related to the formation of the zones of insufficient or excessive head. In the first case, it decreases the water supply quality. In the second case, it becomes the cause of the occurrence of irrational leakage and accidents in networks.

The standard-technical documentation of the studied problem is presented by the State construction standards SCS B.2.5-74:2013 [8] and directive [9]. According to this, the values of the required water head, which is recommended to maintain in water supply systems of construction sites, were established:

$$H_{\text{ні}} = 10 + 4(n-1), \quad (1)$$

where n is the number of floors in a building.

The development of information technologies at the modern stage contributes to deepening the exploration of the hydraulic aspects of water distribution. Thus, it is noted in paper [10] that the application of parameter measurement in the on-line monitoring mode is a common way of pressure control. Paper [11] gives the findings of the research into application of the specialized City Com platform to control the networks operation, which offers extended opportunities for hydromodeling and inventory of water supply networks. However, achievements in the development of information technology are related to the problems of storage, processing, and visualization of the elements of a water supply system. Given a considerable length of water supply networks, experts conclude the feasibility of division of water supply networks into smaller subsystems – sectors, as specified in paper [12]. The main idea of sectoring, according to experts [13], is the improvement of operative control. Paper [14] focuses on the creation of such measurement zones [14]. The method for reducing total excessive heads in water supply networks by zoning is explored in [15]. The popularity of the idea of creation of such control zones is explained by the objective difficulties associated with the regulation of heads in a large number of nodes. Efficiency of application of the equipment to support the minimum required head [16] in such local zones increases. However, creation of such sectors needs additional studies of the formation of zones with insufficient and excessive heads with respect to changes of hydraulic characteristics of water supply sections. The feasibility of modeling such zones is proved by the conclusions of experts on the application of active monitoring of the flow, pressure to detect hidden leaks, presented in article [17]. Determining the pressure control zones is needed when mounting regulating valves to reduce excessive pressure, which is proved by the findings of the research, presented in paper [18].

The greater the number of head control nodes in the network, the more reliable the result about the distribution of the values of head in the network can be obtained. However, considering the costs of the equipment of control nodes, it is necessary to determine their minimum sufficient number and the places of location in the network. The option to overcome this problem can be the application of numerical methods for determining control nodes, as specified in paper [19], but the authors point out that this problem was not completely resolved. For example, in paper [20], it was proposed to apply a diagnostic matrix using numerical calculations of the hydraulic model for determining the locations of head sensors. However, complexity of calculations and changeability of water consumption conditions explain the imperfection of these methods. That is why the problem of finding the location of head controlling nodes remains unresolved and causes the need for research in this direction.

3. The aim and objectives of the study

The aim of this research is to determine the impact of the size of zones with insufficient head on the number and location of control nodes during designing and operation of water supply systems with respect to the conditions of supply and a change in hydraulic characteristics of separate sections.

It is directed at ensuring the minimum required head values in nodes of water supply networks.

To accomplish the aim, the following tasks have been set:

– to determine through calculation the influence of the zones with insufficient head on the number and location of control nodes;

– to develop a procedure for flow distribution control in real time for designed and operating water supply networks.

4. Materials and methods to study the influence of conditions of network supply on the dynamics of node heads and selection of control nodes

4. 1. Source data for modeling zones of heads in a water distribution network

The studies were conducted based on the theoretical designed schemes. Table 1 shows the schemes of the studied networks and gives the operation parameters: total daily consumption Q_{day}, (m^3/day), maximum feed to the network $Q_{\text{p.s.}}$, (l/s), numbers of nodes of water conduit connections, numbers of the network elements, in which the changes in hydraulic characteristics were modeled:

– circle network (scheme No. 1) from 14 circuits, 32 nodes and 45 sections;

– circle network (scheme No. 2) from 13 circuits, 26 nodes and 38 sections;

– circle network (scheme No. 3) from 8 circuits, 18 nodes and 25 sections;

– circle networks (scheme No. 4) from 15 circuits, 28 nodes and 43 sections.

For the schemes of water supply networks, presented in Table 1, the source data to perform hydraulic calculation of networks were generated:

– the estimated water consumption by the number of residents and normed water consumption was determined;

– the estimated circuit by the plan of the residential site was made, the nodes and sections were numbered;

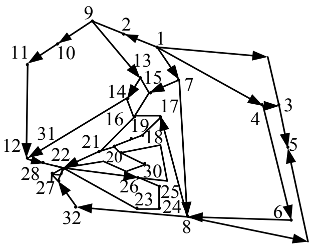
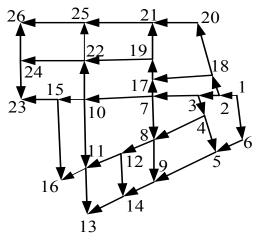
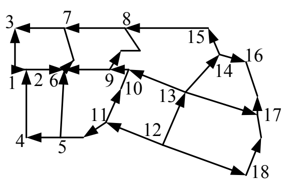
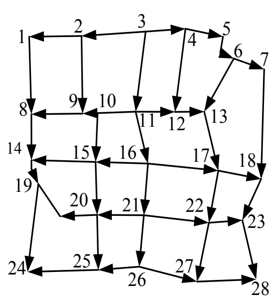
– the node consumptions were calculated; the initial flow distribution was performed;

– the source data to perform hydraulic calculation, shown in Table 1, were generated.

Thus, the studies were conducted on the example of water supply networks with capacity of Q=20,000–91,000 m^3/day. For each variant of network supply, the changes in hydraulic characteristics were modeled and hydraulic calculations were performed.

Table 1

Characteristics of circuits of water supply networks

No. of scheme	Network scheme	Variants of supply	Change of hydraulic characteristics
1		Q_{day}=20000 m^3/day $Q_{p.s}$=275 l/s 1) node No. 1; 2) node No. 8; 3) nodes No. 1 and No. 8; 4) node No. 6 and No. 11	Change of distribution in nodes No. 4; 5; 7; 9–11; 13–15; 19; 20; 26; 27; 29; 30
2		Q_{day}=31500 m^3/day $Q_{p.s}$=697 l/s 1) node No. 1; 2) node No. 14; 3) node No. 7 (underground source of supply).	Change in throughput of sections No. 20–21; 25–26; 2–3; 15–23; 5–9; 19–21; 7–8; 11–13
3		Q_{day}=63000 m^3/day $Q_{p.s}$=1192 l/s 1) node No. 1; 2) node No.14; 3) nodes No.11 and 12	Change in throughput of sections No.: 1) 1–2–6–9–10–13–17 2) 1–3–7–8–15–14–16–17–18–12–11–5–4.
4		Q_{day}=91000 m^3/day $Q_{p.s}$=1354 l/s 1) node No. 3; 2) node No26; 3) node No. 19: 4) nodes No. 11 and No.18; 5) nodes No. 7 and No. 24; 6) nodes No. 14 and No. 19	Change of distribution in nodes No. 8–11; 15–17; 20–22 and in nodes No. 2–6; 24–28.

4. 2. Procedure for determining zones of insufficient head

Determining the influence of the structure of location of the network water suppliers on the dimensions of the zones of insufficient head was explored on the example of water supply networks, the schemes of which are presented in Table 1. When modeling the network supply conditions, the options of conduits connection that were close to actual conditions were considered. When modeling a change in hydraulic characteristics of the sections, the structural data of pipelines were taken into consideration, specifically, their material and numerical values of water distribution from the nodes.

A change in throughput of the sections was modeled on the example of schemes No. 2 and No. 3 by reducing the diameter from 10 % to 30 % at step Δ=10 % by formulae (2) and (3):

$$d_{f.i} = K_r \cdot d_{out.i}, \tag{2}$$

where $d_{out.i}$, $d_{f.i}$ are the outlet and fictitious diameters of the studied i-th network section, respectively, m; K_c is the coefficient of change in resistance:

$$K_r = 1 - P/100, \tag{3}$$

where P is the percentage of a change in the throughput of a pipe, %.

For scheme No. 2, a change in resistance of 8 sections was modeled: No. No. 20–21; 25–26; 2–3; 15–23; 5–9; 19–21; 7–8; 11–13, for scheme No. 3, modeling of a change in resistance was performed for 18 sections: No. 1–2–6–9–10–13–17 and No. 1–3–7–8–15–14–16–17–18–12–11–5–4.

Modeling of the structure of water distribution was performed on the example of the schemes of networks No. 1 and No. 4 through a change in water distribution from 10 % to 20 % with step Δq=10 % in the following nodes:

– for scheme No. 1, a decrease in water intake in 9 nodes was modeled: No. 4–5; 7; 9–11; 14; 15; 30 and an increase in intake in 6 nodes was modeled: No. 13; 19; 20; 26; 2; 29;

– for scheme No. 4, re-distribution of water intake was modeled among 10 central nodes No. 8–11; 15–17; 20–22 and 10 end nodes No. 2–6; 24–28.

Network consumption remained constant due to decreasing water distribution from other nodes. For each of the studied network schemes, hydraulic calculations were performed and free heads in its sites under normal operation conditions for different options of network supply networks taking into consideration the changes were determined. Under normal conditions, free heads in the nodes were determined relative to the critical point, during modeling changes in water consumption conditions – relative to the supply node.

To determine the influence of the structure of location of the network water suppliers on its hydraulic characteristics, the optimum conditions of supply to ensure the magnitudes of node head close to the required values were determined for the studied circuits (1).

For schemes No. 1–4, the areas of the zones with insufficient head that can be formed at a change of hydraulic characteristics, quantity and location of the control nodes to prevent the formation of such zones were analyzed.

5. Results of research into hydraulic characteristics of the network

5. 1. Formation of zones of insufficient head in a water distribution network

As a result of the conducted research, for each of the explored options of a change of water distribution, there were established the zones of insufficient head, the boundaries of which are determined by the location of the nodes with the head that meets the condition:

$$H_{fi} < H_n, \tag{4}$$

where H_{fi} is the value of free head in the i-th node, m; H_n is the value of the required head [8], m. The structure of the city was modeled with respect to prevalence of five-story buildings:

$$H_{\text{n}}=10+4(n-1),$$

where n is the number of floors in the buildings; the research explores the residential areas with five-story buildings, n=26 m.

The zone boundaries are formed as a result of the projection on the water supply system of a virtual piezometric surface of the plane relative to the ground level Z_i at the height Z_i+H_n on condition of (4) and are determined by the lengths of the sections l_i that are marked on the sections of main networks by this plane and service the houses, under condition (4).

As an example, plane graphs of the formation of zones of insufficient head in a water distribution network by scheme No. 1 during a change in water distribution in the network are presented in Fig. 1. Fig. 1 presents four options of pipelines to the network (fragments a, b, c, d). Modeling of the formation of the zones of insufficient head was performed at the simultaneous change in water distribution in nodes for each option of network supply. The numerical values of the area of these zones were: 48.75 hectares (Fig. 1, *a*) and 22.6 hectares (Fig. 1, *b*) for the options of network supply in a single node; 24.4 hectares (Fig. 1, *c*) and 33.9 hectares (Fig. 1, *d*) for the options of network supply in two nodes.

As Fig. 1, *a* shows, during the change in the structure of water distribution, one should expect the largest area of the zone of insufficient head $F_{\text{z.in.h}}$ relative to the total area $F_{tot.}$ ($F_{z.in.h.}/F_{tot.}$=12.5 %) under the condition of network supply in node 1.

At the same changes in water distribution in the nodes, the relationship between the areas of these zones for the schemes of networks with two supply nodes remains constant (Fig. 1, *c, d*). The dimensions of the zone of insufficient head do not exceed 8.5 % of the total area.

The smallest area of the zone with insufficient head ($F_{z.\,in.h.}/\,F_{tot.}$=5/8 %) is formed under the condition of supply in node 8 (Fig. 1, *b*). For this case, this is explained by the location of the highest geodetic marks in node 8. In addition, the dimensions of the expected areas of insufficient head decreases with increasing water distribution in the nodes located in area that is the nearest in relation to the supply point.

Hydraulic characteristics of a network change under the influence of structural and technological factors: resistance of steel and cast-iron sections of a network increases during the operation, which reduces the throughput of pipelines.

The process of emergence of possible zones of insufficient heads when changing the throughput of the sections on the example of the network by circuit No. 2 is presented in Fig. 2.

It should be noted that the largest areas of zones of insufficient head should be expected at a change in the throughput of the sections, in the sections that are far in relation to the supply node. Thus, at the water feed to node 1 (Fig. 2, *a*), the ratio $F_{z.in.h.}/F_{tot.}$=30.5 %, and at supply in node 14, $F_{z.in.h.}/F_{tot.}$=62.5 % (Fig. 2, *b*). This is due to a smaller throughput reserve of the remote sections.

It is possible to decrease the area of these zones significantly on the condition of supply to the central network nodes (Fig. 2, *c*) – for the specified option of supply – $F_{z.in.h.}/F_{tot}$=12.5 %.

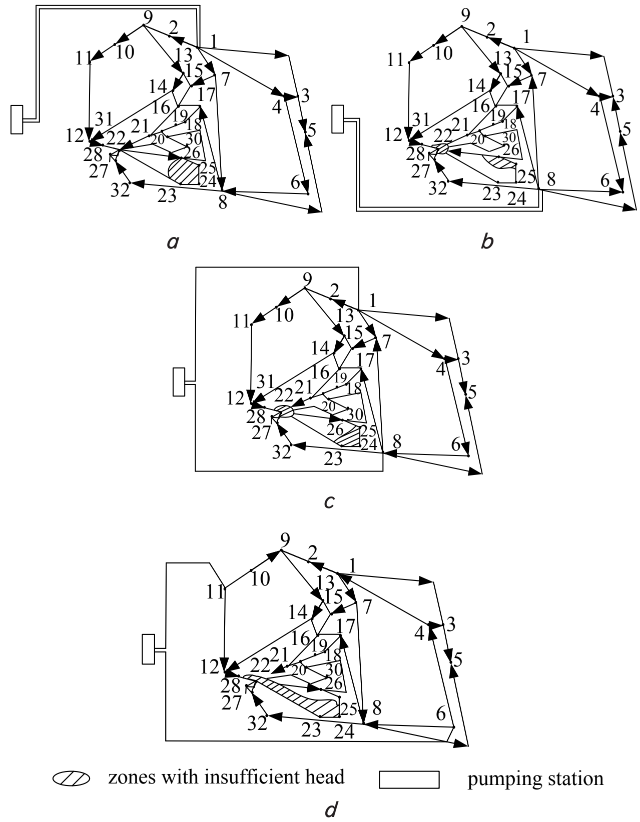


Fig. 1. Zones of insufficient head with respect to a change in the structure of water distribution for different options of network supply: *a* – water feed to node 1; *b* – water feed to point 8; *c* – water feed to points 1 and 8; *d* – feed to nodes 11 and 6

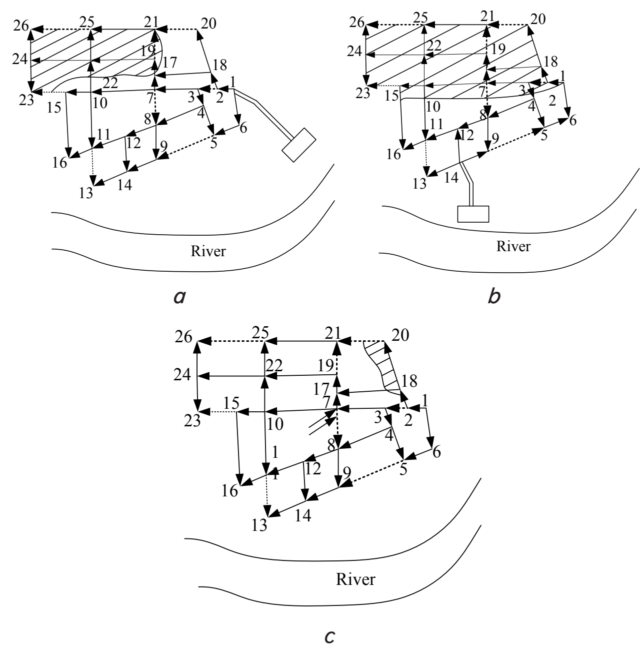
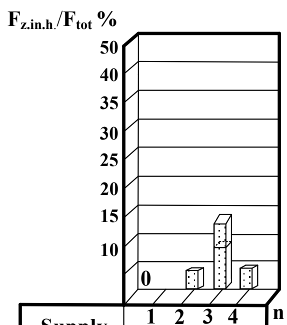


Fig. 2. Zones of insufficient head with respect to a change in throughput of the sections for different options of network supply: *a* – water feed to 2; *b* – water feed to node 14; *c* – water feed to node 7

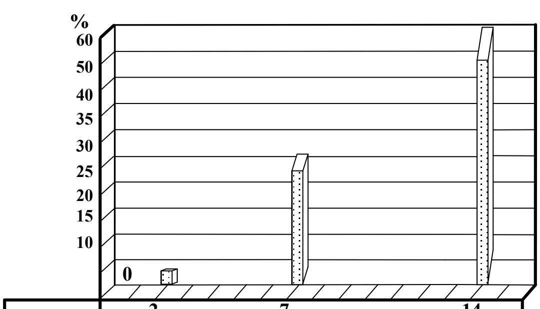
5. 2. Value of the number of head control nodes

To determine the influence of the dimensions of the zones of insufficient head on the location and the number of control nodes for water supply networks for schemes No. 1 and No. 2, the diagrams of a change in the number of these nodes for different options of network supply, which are shown in Fig. 3, were plotted. For the network by scheme No. 1, the smallest area of the zone with insufficient head is observed in the variant of network supply to node No. 8, the largest – at the supply in node No. 1 (Fig. 3, *a*). At the same changes in water distribution, the largest area of the zones of insufficient head occurs in networks with the highest geodesic marks at their beginning, which corresponds to the variant of supply in point No. 1. This is explained by the existence of the greatest excessive node heads for the networks with the highest geodesic marks at the end. For the water supply network by scheme No. 2, the largest number of nodes with insufficient head corresponds to the variant of the network supply in node No. 7 (Fig. 3, *b*). In this case it is explained by a more uniform flow distribution when receiving water in the central node of the network. This variant of supply is possible in the presence of an underground source.



Supply variant	$F_{z.in.h}/F_{tot}$ Scheme №1
a	12,5
b	5,8
c	6,3
d	8,7

a



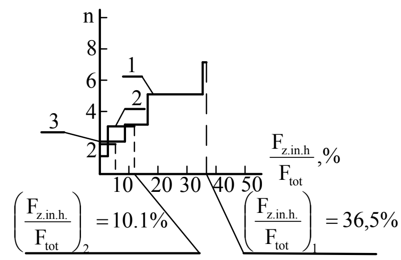
Supply variant	$F_{z.in.h}/F_{tot}$ Scheme№2
a	23,1
b	39,2
c	3,1

b

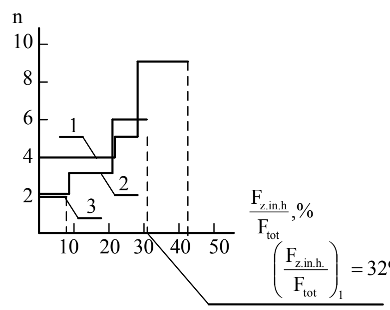
Fig. 3. Change in the number of nodes n with head that is lower than the required for different options of networks supply by scheme No. 1 and No. 2

If the information on free heads in the nodes of a network at the time of head measurement in its separate points is available, a dispatcher has an opportunity to assess the situation visually. If there is one node, the free head in which is less than required, which corresponds to minor changes in the network operation, it is a control node. If this node coincides with the existing point of head control, it is advisable to leave it unchanged at this stage. At the same change in water distribution, the number of nodes with insufficient head is by 2.5 times greater under the condition of water supply to the highest marks of a network (Fig. 4, *a*). This is explained by the smaller values of excessive heads in the network.

The number of nodes with the head, which is smaller than the necessary one, is not the main criterion for assessing a change in water distribution. There are situations where in the zone of insufficient head with a smaller area there is a greater number of nodes with the head that is lower than required.



a



b

Fig. 4. Dependence of the number of nodes *n* with the head that is lower than the necessary one on the changes in the areas of insufficient head $F_{z.in.h}$ with regard to hydraulic factors: *a* – at an increase in water distribution in nodes No. 8–11; 15–17; 20–22; *b* – at an increase in water distribution in nodes 2–6; 24–28; 1, 2, 3 – graphic dependences according to the variants of network in nodes No. 9; No. 26 and No. 3

Thus, for the first option of network supply in node No. 19 at $F_{z.in.h.}/F_{tot}$=30 %, the number of nodes with insufficient head is 9, and for the same scheme, but for the condition of water feed to node No. 26 at $F_{z.in.h.}/F_{tot}$=32 %, the number of the nodes in the zone of insufficient head is 5 (Fig. 4, *b*). Based on these results, we can state that the criterion for selection of the number of head control nodes is the dimensions of the expected zone of insufficient head. That is, at $F_{z.in.h.}/F_{tot}$≤40 %, it is enough to introduce one control node with the lowest free head among those that are located on the boundary of the expected zone, at $F_{z.in.h.}/F_{tot}$=40–60 %, it is necessary to equip 2–3 additional control nodes that is selected by the chosen criteria.

5. 3. Procedure for flow distribution for designed and operating water supply networks

The effectiveness of flow distribution control in water supply networks depends on the correct choice of the number and locations of head control nodes. Analysis of flow distribution for designed and operating water supply networks with the view to determining and specifying the location of the control units and the necessary number, presented in Fig. 5, includes the following stages:

1. Introduction of the source data involves drawing the circuit of a network and creating a database of its actual parameters (blocks No. 2 and 3). At this stage, the actual link to the area is needed for visual assessment of pressure distribution in the network nodes and the boundaries of the zones of insufficient head by a designer or a dispatcher. In this case, the places of equipment of control nodes and additional construction of the network sections are specified.
2. Determining the node consumption for different water supply modes (blocks No. 4 and 6).
3. Determining the consumptions in the network sections that are valid at the time of measurement of piezometers in control nodes.
4. Introduction of the values of difference of piezometers, measured in the control nodes, using the program module to adjust the source data at a change in the system operation (block No. 7).
5. Determining actual free heads in network nodes that match the specified flow distribution. Piezometric marks in the network nodes are determined relative to supply nodes according to the specified values of head in them. The nodes, for which condition (4) is not met, are located on the boundaries of the zones of insufficient head in the network.

Thus, a dispatcher has an opportunity to analyze the operative or predictive situation. This makes it possible to take into consideration a change in the parameters of network operation as a result of the influence of any factors: development of the area, the structure of water distribution, a change in throughput of sections, taking the terrain into consideration during designing.

6. Analysis of costs in the sections and free node heads, determined in terms of real time, to specify the location of control nodes and substantiation of flow distribution with the aim of adjusting the heads in nodes.
7. Calculation of water suppliers' head with respect to head measurement in the separate points of the circle water supply network.

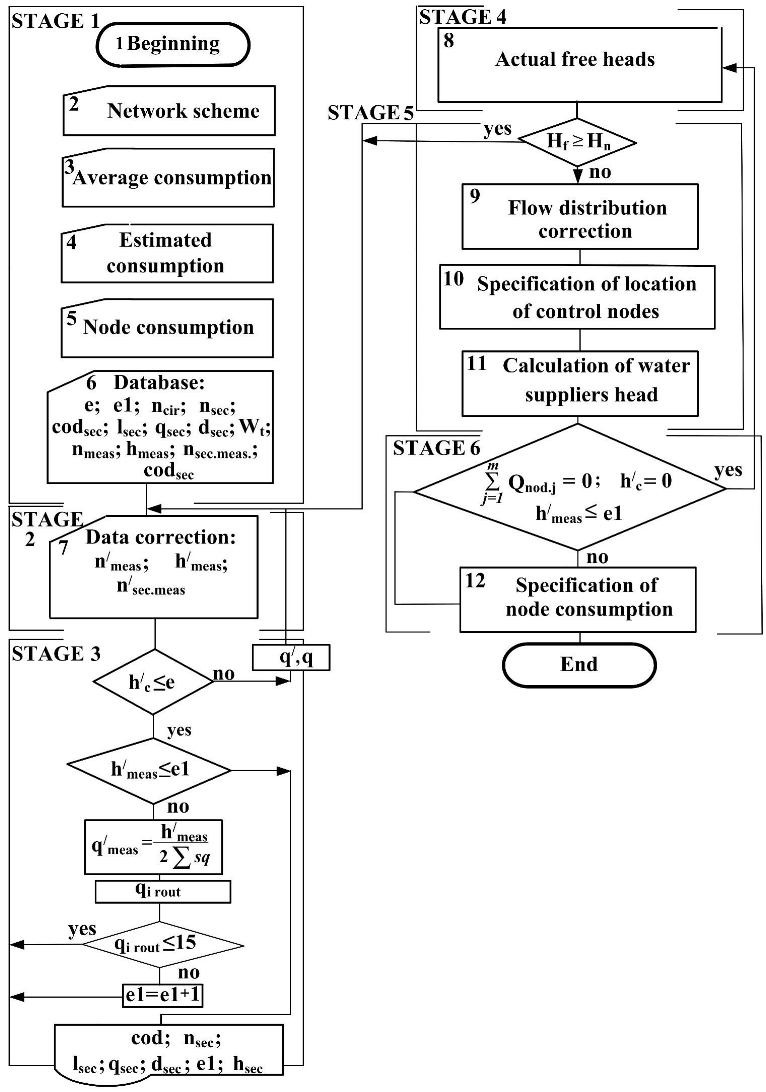


Fig. 5. Stages of the procedure for flow distribution control: e – permissible discrepancy in the circle; $e1$ – permissible discrepancy on the way of measurement of pressures; n_{cir} – number of circles in network; n_{sec} – number of section in network; cod_{sec} – code of section; l_{sec} – length of the i-th section; q_{sec} – consumption in the i-th section; d_{sec} – diameter of pipe in the i-th section; W_t – material of pipes; n_{meas}, n'_{meas} – number of measurement routes; h_{meas}, h'_{meas} – difference in piezometers in measurement nodes; $n_{sec.meas.}$ – number of sections on the i-th measurement route discrepancy in the circle; h'_c – discrepancy in the circle; q'_{meas} – correction consumption; H_f – actual head in the i-th node; H_n – necessary head in the i-th node.

6. Discussion of results of research into the procedure of flow distribution control in real time

It is necessary to state the dependence between the number of nodes and the dimensions of these zones when determining the number and the places of control nodes equipment in the water distribution network, the need for which is the result of the analysis of the formation of zones of insufficient head (Fig. 1, 2).

Control over the flow distribution in water supply networks requires the visual assessment of the zone of insufficient head. In comparison with similar methods of establishing the number of control nodes [19, 20], the positive impact of research results involves the establishment of the relationship between the number of head control nodes and the area of the possible zone of insufficient head in the network. This allows employees of dispatching services of public utilities not only to assess a situation visually, but also to make a decision based on calculation results. In the presence of a single node with the head that is lower than required, and its coincidence with the existing head control point, it is advisable to leave it unchanged. Criteria for increasing the number of control nodes and determining their location is the magnitude of minimum free head in the node that is on the boundary of the expected zone of insufficient head and its dimensions. At $F_{z.in.h.}/F_{tot}$<40 %, it is enough to introduce one control node with the smallest free head from those that are located on the boundary of the expected zone, at $F_{z.in.h.}/F_{tot}$ =40–60 %, it is necessary to arrange 2–3 additional control nodes that are selected by the specified criteria.

Comparison of the application of different methods of determining of head control nodes for a particular scheme of the water supply network indicates mutual compatibility [19].

Obviously, the basis of the process of flow distribution control in the designed and operating water supply networks is determining and specification of location of control nodes, due to which it is possible to decrease leakage and costs of power consumption at pumping stations. Maintaining the head in control nodes prevents emergence of a significant head excess in others. For example, prevention of water losses at 64 emergency leaks throughout a year that last 1 day for the sections with the diameter of 400 mm (0.4 m) makes it possible to obtain water savings Q: $Q=2.5\times(3.14\times0.4^2)/4=0.314$ m^3/s or 27,130 m^3/s or 27,130 m^3/day. Taking into consideration the coefficient of flow distribution control of 0.04 on a decrease of consumption at leaking [8], the average water tariff of UAH 0.82/m^3, the savings E is: E=27,130×64×0.04×8.2=567,000 UAH/year.

However, unlike the research results published in [17, 18, 20], the data regarding the relationship between the area of zones of insufficient head and the recommended number of control nodes were obtained. For example, reliability of the method for determining leaks, which is based on the application of a diagnostic matrix for numerical calculations of hydraulic model [20] depends on the number of sensors. That is why the procedure of flow distribution control with respect to the minimum required number of control nodes helps to reduce investment costs for the equipment of such nodes.

These recommendations on the implementation of the procedure of flow distribution control in designed and operating water supply networks require implementation of the integrated systems of technical infrastructure control. As noted by experts [4, 7, 14], this process requires establishing the relationship between the water supply sites. It is necessary that public utilities should make initial capital investments in the system of the technical infrastructure control. The costs are also required for mounting additional nodes and re-equipment of the existing head control nodes if there is a transfer necessity. However, most public utilities already have automated control systems, and additional equipment will be repaid in the period of 5 years due to reducing leakage and power consumption of pumping equipment.

The article presents the results of studies of the formation of zones of insufficient head and analysis of the influence of their dimensions on the location and the number of control nodes for the schemes of water supply networks, located on the territory with the area of 390 ha. Terrain affects the dimensions and location of the zones with insufficient head, but the accuracy of determining these zones and the principle of choosing head control nodes are unchanged for any input parameters (water network productivity, its topology, the relief of the territory).

The presented procedure of flow distribution control requires the identification of the source data for a reliable display of the topology of a water supply system and the visual analysis of the dynamics of node heads in the on-line mode. This requires modern computer equipment for ensuring the operative work of the system of flow distribution control, which for many public utilities is a complicated task, but a necessary condition for ensuring the interrelationship of the information collection system and the system of feedback from executive elements.

7. Conclusions

1. As a result of the conducted calculations, the impact of the dimensions of the zones of insufficient head on the number and the places of control nodes equipment was determined. It was established that the criterion for the selection of control nodes and specification of the location is the dimensions of the expected zones of insufficient of head. In regards to the area of these zones $F_{z.in.}$ relative to the total area F_{tot} $F_{z.in.h.}/F_{tot}\leq$40 %, it is enough to introduce one control node. At $F_{z.in.h.}/F_{tot}$=40–60 %, in addition to the existing control point, we should foresee 2–3 control nodes on the boundary of the possible zones of insufficient head, the formation of which is modeled at the stage of network designing. When refining the location of control nodes in the process of operation, it is recommended to arrange them on the boundary of the expected zone of insufficient head, based on its dimensions and the tendency to increase.

2. The proposed procedure of flow distribution control in real time is based on modeling and analysis of the zones of heads in the network, which enables modifying the number and location of head control nodes, depending on the need. The distinctive feature of this approach to flow distribution control is timely prevention of emergency situations, assigning the optimal arrangement of the network and operation modes. The proposed flow distribution procedure can be implemented in the work of dispatching services of public utilities.

References

1. Jones G. Gravity-driven water flow in networks. John Wiley & Sons, 2011. doi: https://doi.org/10.1002/9780470939659
2. Di Nardo A., Di Natale M., Di Mauro A. Water supply network district metering: theory and case study. Springer, 2013. doi: https://doi.org/10.1007/978-3-7091-1493-3
3. Hulsmann A. Climate change, water supply and sanitation: risk assessment, management, mitigation and reduction. IWA Publishing. London, 2015. 408 p.
4. Condition of Ukrainian water supply networks and ways to prevent deterioration of drinking water quality // Journal of polymeric pipes – Ukraine. 2013. URL: http://polypipe.info/news/238-stanvodoprovidnuhmerezhukraini
5. Rajakovic-Ognjanovic V., Grgur B. Corroded scale analysis from water distribution pipes // Hemijska industrija. 2011. Vol. 65, Issue 5. P. 507–515. doi: https://doi.org/10.2298/hemind110523049r

6. Potential impacts of changing supply-water quality on drinking water distribution: A review / Liu G., Zhang Y., Knibbe W.-J., Feng C., Liu W., Medema G., van der Meer W. // Water Research. 2017. Vol. 116. P. 135–148. doi: https://doi.org/10.1016/j.watres.2017.03.031
7. Trębicka A. Modeling of water distribution system parameters and their particular importance in environment engineering processes // Inżynieria Ekologiczna. 2016. Issue 47. P. 47–53. doi: https://doi.org/10.12912/23920629/62846
8. DBN V.2.5-74:2013. Vodopostachannia. Zovnishni merezhi ta sporudy. Osnovni polozhennia proektuvannia. Kyiv, 2013. 172 p.
9. Directive 97/23/EC of the European Parliament and of the Council of 29 May 1997 on the approximation of the laws of the Member States concerning pressure equipment // Official journal. 1997. Issue L 181, 09/07/1997. P. 0001–0055.
10. Xhafa S., Avdullahu I., Ahmeti M. Automation Control on Water Supply Networks // IFAC-PapersOnLine. 2016. Vol. 49, Issue 29. P. 175–179. doi: https://doi.org/10.1016/j.ifacol.2016.11.098
11. Yeksayev A. Pipeline Networks E-modelling Based on CityComTM Technology: Experience of Industrial Implementation for Large Water-supply Systems // Procedia Engineering. 2016. Vol. 154. P. 107–114. doi: https://doi.org/10.1016/j.proeng.2016.07.427
12. A Graph Theoretical Sectorization Approach for Energy Reduction in Water Distribution Networks / Castro-Gama M. E., Pan Q., Jonoski A., Solomatine D. // Procedia Engineering. 2016. Vol. 154. P. 19–26. doi: https://doi.org/10.1016/j.proeng.2016.07.414
13. A Novel Water Supply Network Sectorization Methodology Based on a Complete Economic Analysis, Including Uncertainties / Campbell E., Izquierdo J., Montalvo I., Pérez-García R. // Water. 2016. Vol. 8, Issue 5. P. 179. doi: https://doi.org/10.3390/w8050179
14. Social Network Community Detection for DMA Creation: Criteria Analysis through Multilevel Optimization / Brentan B. M., Campbell E., Meirelles G. L., Luvizotto E., Izquierdo J. // Mathematical Problems in Engineering. 2017. Vol. 2017. P. 1–12. doi: https://doi.org/10.1155/2017/9053238
15. Tevyashev A., Matvienko O. I. Stochastic model and method of zoning water networks // Eastern-European Journal of Enterprise Technologies. 2014. Vol. 1, Issue 4 (67). P. 17–24. doi: https://doi.org/10.15587/1729-4061.2014.21080
16. Yu F., Li X.-Y., Han X.-S. Risk response for urban water supply network using case-based reasoning during a natural disaster // Safety Science. 2018. Vol. 106. P. 121–139. doi: https://doi.org/10.1016/j.ssci.2018.03.003
17. Karathanasi I., Papageorgakopoulos C. Development of a Leakage Control System at the Water Supply Network of the City of Patras // Procedia Engineering. 2016. Vol. 162. P. 553–558. doi: https://doi.org/10.1016/j.proeng.2016.11.100
18. Gençoğlu G., Merzi N. Minimizing Excess Pressures by Optimal Valve Location and Opening Determination in Water Distribution Networks // Procedia Engineering. 2017. Vol. 186. P. 319–326. doi: https://doi.org/10.1016/j.proeng.2017.03.254
19. Kwietniewski M., Kowalski D. The problem of the location of measurement points in monitoring systems of water supply systems // Gaz, Woda and Sanitary Technique. 2009. Issue 6. P. 24–29.
20. Stachura M., Fajdek B. Planning of a water distribution network sensors location for a leakage isolation // Proceedings of the 28th Envirolnfo Conference. Oldenburg, 2014.