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ABOUT ONE APPROACH TO SOLVE THE PROBLEM OF MANAGEMENT OF THE DEVELOPMENT AND OPERATION OF CENTRALIZED WATER-SUPPLY SYSTEMS

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A b s t r a c t . One of the approaches to solve the problem of resource and energy saving in centralized water-supply systems by reducing the total excess pressure in water-supply nodes is examined in the present work. The implementation of this approach is provided due to re-engineering of water-supplies by their zoning and optimal flux-distribution in the water-supplies. Mathematical formulations of the problems to be examined and efficient algorithms of their solving are presented.

K e y w o r d s : resource and energy saving, zoning, pressure regulators, pump station, adjustable drive.

INTRODUCTION

There are many problems in modern centralized water-supply systems (CWS) of Ukraine and main of them are out-of date technological equipment and a high degree deterioration of water-supply systems. This leads to significant loss of water due to undetected and unrepaired leaks, which are sometimes more than 50% of the volume of supplied water; to over-expenditure of the electricity, reagents spent on the preparation of drinking water. A radical solution of this problem is the replacement of the out-of-date technological equipment with more productive and less power-consuming one, the use of adjustable drives on the pump units, sanation and relining of water-supply systems. However, this requires huge material and financial costs.

It is known [1], that the volume of leakage is proportional to the value of excess pressure in the water-supply nodes. Therefore, any measures aimed to the reduction of excess pressure in water-supply nodes are effective means of resource and energy saving in CWS.

One of the approaches to solve the problem of resource and energy saving in centralized water-supply systems by reducing the total excess pressure in water-supply nodes is examined in the present work. The implementation of this approach is provided due to re-engineering of water-supplies by their zoning and optimal flux-distribution in water-supplies.

The principal feature of the proposed approach is the point that the problems of management of the development and operation of CWS are considered in their close functional interconnection and are solved at the different time intervals with different control parameters.

The problem of management of the development of CWS is solved at the time interval [0, T], where T = 1 year (365 days) and provides an optimal zoning of water-supply systems.

The problem of optimal management of the operation of CWS is solved at the time interval [0, T], where T = 1 day, in the form of a two-staged problem of nonlinear stochastic programming: the problem of effective planning of modes of transport and distribution of drinking water in CWS with prediction of 24 hours is solved on the first stage; on the second stage the problem of pressure stabilization in the dictating points of water-supply in the real time is solved. Let us examine sequentially each of these problems.

The actual operation modes of CWS are essentially non-stationary. In real conditions, the main disturbing factors are stochastic processes of water consumption, which depend on a huge number of non-controlled and non-controllable factors. The huge dimension of water-supplies (WS) and limitation of the operational data do not allow to evaluate adequately all the basic parameters of technological elements and the structure of WS. Moreover, the main parameters of the model of established flux-distribution, which are basic for solving the problems of engineering, management of the development and operation of CWS are estimated according to the experimental data of final length and therefore are themselves random varieties. This makes it necessary to use stochastic models of quasi-stationary modes of CWS at a given time lag [0, T], which take into account both the stochastic nature of the process of water consumption and the statistical properties of the model parameters [2, 3, 20]. This provides their much greater conformity and ability of their effective application to solve the problem of management of the development and operation of CWS.

THE PROBLEM OF ZONING OF CWS

The separation of WS on the zones is used while engineering of WS with a significant difference between the geodetic marks of the zones serviced by WS, different number of stores in buildings in city districts, therefore a significant difference of free heads required by different categories of consumers. The implementation of zoning of WS is provided either by the construction of additional pump stations (PS) which work on the selected zones, or by equipping with additional trunk pipelines or additional clean water reservoirs [1]. The appearance of new highly reliable and relatively inexpensive pressure regulators of high diameter allows to approach in a new way to solving of the problem of resource and energy saving in CWS. Zoning of WS using pressure regulators can significantly reduce the capital costs on the implementation of zoning of WS, significantly reduce the excess pressure in the nodes of WS and, therefore, the loss of water-leakage and reduce electricity consumption on PS.

At the substantive level, the problem of zoning of WS is the following: those nodes of water-supply in which excess pressure significantly exceeds the predetermined threshold value, it is necessary to group them into connected sections (zones) [4, 21], which should have at least two inputs (for providing of a given level of reliability and survivability of WS) and to provide the installation of pressure regulators at each of these inputs as well as to estimate the parameters of each regulator. If there are high-rise buildings (HRB) in the selected zone, it is necessary to provide each HRB with a pump station and to determine its parameters.

From the formal point of view, the solution of the problem of zoning of WS is taken to the decision of a number of interrelated problems:

- optimal load distribution between PS for the mode of maximum water consumption at the interval of management,
- selection of the zones of WS including HRB,
- determination of the parameters of pressure regulators installed at the inputs of the selected zones of WS,
- determination of the parameters of pumping stations for HRB in the selected zones.

While formulating the problem of zoning it is assumed that we know: the entire referenced data of the structure and parameters of WS (technological schemes, length and diameters of pipeline sections, type and characteristics of pump units (PU), adjustable and shut-off valves, etc.); operating data– minimum admissible values of heads (pressures) in all nodes of WS, predictable values of daily total water consumption in each node of WS, calculated at time zero with prediction of 365 days and their dispersion. We assume that the calculated values of predictions have normal distribution:

$$q_{i0}(\omega,l) \sim N\left(q_{i0}(l),\sigma^2_{q_{i0}}(l)\right), \qquad l=1,2,...,365.$$

The formulation and solution of the problem of zoning performed using a stochastic model of quasi-stationary operation modes of WS [17] and the maximum water consumption, i.e. for:

$$q_{i0}(k): \quad q_{i0}(k)=\max_l q_{i0}(l), \quad l=1,2,...,365.$$

At that the value of maximum water consumption $q_i^+(k)$ in i node determined according to the statement:

$$q_i^+(k): \ P(0 \le q_{i0}(k) \le q_i^+(k)) = 0,997. \quad (1)$$

To represent the structure of WS in the form of an orgraph G(V,*E*), where V – vertex set, E – arc set (*e*=Card(E), *v*=Card(V)), the real net is added by a zero top and fictitious chords which connect the zero top with all the inputs and outputs of WS [6, 7]. In order to construct the stochastic model of quasi-stationary operation modes of CWS let us produce the following net coding: choose a tree graph so that the fictitious sections of the net become chords. In this case, the actual sections will become partly chords, and partly – branches of the tree. Let us give number 1 to the branch of the tree with PS, the rest of the branches – from 2 to *v-1*, the chords of the actual sections – from *v* to $v+\eta_2-1$, the fictitious ones with given node costs from *v* to e, where η_2 - the quantity of chords of the actual sections. Under the above-mentioned coding, the stochastic model of quasi-stationary operation modes of WS takes the form [6, 7]:

$$\underset{\omega}{\mathrm{M}}\Big(sgn\, q_r(\omega) S_r\ (q_i(\omega)) q_r^2(\omega) + \sum_{i=1}^{v-1} b_{1ri}\, sgn\, q_i(\omega) S_i(q_i(\omega)) q_i^2(\omega)\Big) = 0,$$
$$(r = v,\dots,v+\eta_2-1), \quad (2)$$

$$\underset{\omega}{\mathrm{M}}\Big(h_r^{(c)}(\omega) - h_1^{(a)}(\omega) + \sum_{i=1}^{v-1} b_{1ri}(sgn\, q_i(\omega) S_i(q_i(\omega)) q_i^2(\omega) + h_i^{(g)})\Big) = 0,$$
$$r = (v+\eta_2,\dots,\ e), \quad (3)$$

$$M(q_i(\omega)) = \underset{\omega}{\mathrm{M}}\left(\sum_{r=v}^{v+\eta_2-1} b_{1ri} q_r(\omega) + \sum_{r=v+\eta_2}^{e} b_{1ri} q_r(\omega)\right),$$
$$\left(i=1,\dots,v-1\right). \quad (4)$$

$$P\left(h_i^{(c)}(\omega) \ge h_i^+\right) \ge \alpha, \quad (\alpha \cong 1), (i = v+\eta_2,\dots,\ e), \quad (5)$$

$q_i(\omega)$, $S_i(q_i(\omega))$, $h_r^{(c)}(\omega)$, $h_1^{(a)}(\omega)$ - random varieties, characterizing: $q_i(\omega)$ - water flow on i- section of the pipeline, $S_i(q_i(\omega))$ - hydraulic resistance of the i- section of the pipeline, $(i=1,\dots,v+\eta_2-1)$, $h_r^{(c)}(\omega)$ - free heads in the nodes of the net $r=(v+\eta_2,\dots,\ e)$, h_i^+ - minimum admissible heads in the nodes of the net, $h_1^{(a)}(\omega)$ -head of the pump station, $\underset{\omega}{\mathrm{M}}\{\cdot\}$ - mathematical expectation of a random variety $\{\cdot\}$.

To solve the system of equations (2) – (5) it is supplemented by the boundary conditions of the form:

$$q_r(\omega) \sim N(\overline{q}_r, \sigma^2_{q_r}), \quad r = (v+\eta_2,\dots,\ e). \ (6)$$

In this case, the problem of zoning of WS CWS represented in the form:

$$\underset{\omega}{M}\sum_{i=1}^{v-1}\left(h_i^{(c)}(\omega,k) - h_i^+\right)^2 \to \min_{S\in\Omega}, \qquad (7)$$

where: the domain of allowable solutions Ω is a system of equations (2) – (5) of the stochastic model of quasi stationary operation modes of WS. To solve the equations (2) – (5) we will give the boundary conditions (6) in the form (1) $q_i^+(k)$, (i=1,…,*v*).

The problem (7) under the contingencies (2) – (5) and the conditions (6) belongs to the class of one-stage non-linear stochastic programming problems.

The formulation of the deterministic equivalent of the problem (2) – (7) is carried out by replacing the random varieties with their expectation values.

The solving of the deterministic equivalent of the problem (2) – (7) is carried out in two stages.

1) The optimal load distribution between pump stations, operating on the common WS is carried out by solving the following problem:

$$\underset{\omega}{M} \sum_{rV} \left(h_r^{(c)}(\omega) - h_r^{+} \right)^2 \to \min_{h_j^{(a)} \in \Omega}, \quad (8)$$

where: $h_j^{(a)}$ - head values at the outputs of PS (j=1,…,n), n – the number of PS, operating together on WS; the area Ω is determined by the system of contingencies (2) – (5) and the condition (6).

If WS has significantly different number of stores, at this HRB is up to 5%, the values of the minimum admissible heads for the nodes with HRB are selected $h_{i*}^{+} = 10$ m ($i*$ - node number with HRB). At this, it is assumed that in case if there are these HRB in the selected zone, the pump stations will be installed.

2) ***The selection of zones.*** While zoning of WS we will allocate isolated zones of WS that have at least two inputs (for the providing of a given level of reliability and survivability of WS). Consider all the water-supply nodes in which the excess pressure exceeds a threshold value, which form the set P (card(P)=p). Nodes allocated to one zone must meet the following conditions:

1. $h_{izbi} = h_i^{(c)} - h_i^{+} \geq Porog$,

$$i \in P_k \quad (k = 1,.., p), \quad (9)$$

where: h_{izbi} - excess pressure in i- node, $h_i^{(c)}$ - free head in i- node, h_i^{+} - minimum admissible pressure in i- node, *Porog* - excess pressure threshold.

2. All nodes of the allocated zone constitute one connected component.

Let the set P consist of k connected components (zones):

$$P = P_1 \bigcup P_2 \bigcup ... \bigcup P_k, \quad P_i \bigcap P_j = \varnothing \quad (\forall i \neq j). \quad (10)$$

Let $M_{p \times p}$ – be an adjacency matrix composed for all the nodes from the set P.

For any node $i \in P_n$ (n=1,…,k) exists at least one node $j \in P_n$, for which $m_{ij} = 1$.

3) ***Determination of the pressure regulator's parameters for the zone $P_к$.***

To determine the parameters of pressure regulators for each selected zone P_n, a subgraph $G_k(V_k, E_k)$ of WS is selected (where $V_k: \; v_k \in P_n; \quad E_k = E_{1k} \bigcup E_{2k}$, E_{1k}, E_{2k} - the set of real arcs corresponding to inputs into the zone P_n and the set of fictitious arcs corresponding to outputs from the zone P_n), and we solve the problem of optimal load distribution between pressure regulators $E_{1к}$, installed at the inputs into the zone P_n, i.e. the problem (8) with contingencies (2) - (6) for the subgraph $G_k(V_k, E_k)$ with replacement of head values at the outputs of pump stations $h_1^{(a)}$ with heads at the outputs of the regulators $h_{Ri}, \; i \in E_{1k}$. As a result we obtain minimum necessary values of heads to be stabilized at the outputs of the regulators and maximum admissible values of consumption trough them. Based on this information, in accordance with [9] optimal type of regulators and minimum admissible head at its input $h_{\min Ri}$ are determined. The ends of the arcs $E_{1к}$ with defined pressure regulators are assigned with new numbers of nodes of WS, for which as a minimum admissible heads values h_l^{+} ($l \in E_{1k}$) the values of minimum admissible head at the input of the regulator are taken $h_i = h_{\min Ri}$. As the mathematical expectation flow in these nodes the maximum flow value at the output of the regulator is taken $q_i = q_{\max Ri}$, and as a measure of dispersion flow – the sum of dispersion flows in the nodes of the zone $P_к$,:

$$\sigma_{q_i}^2 = \sum_{r \in P_k} \sigma_{q_r}^2 .$$

All remaining nodes of the selected zone are removed from the graph of WS.

4) Definition of the pumping station's parameters. As a result of solving the problem of load distribution between the pressure regulators we obtain the values of the actual free heads in all nodes of the set P_n zone, including nodes with HRB h_{i*}^{c}. The calculation of the required head of the pumping station for the nodes with HRB is determined in accordance with the statement:

$$\text{Hst}=h_{i*}^{+}-h_{i*}^{c}, \qquad (11)$$

h_{i*}^{+}, h_{i*}^{c} - minimum admissible pressure in i- node of HRB and actual pressure in i- node with HRB of the zone $P_к$.

THE EFFECTIVE PLANNING PROBLEM OF THE CWS OPERATION MODES

The problem of effective planning of operation modes of CWS should be solved at time zero with the prediction of 24 hours. The initial data for the solution of the problem of planning are: all referenced data about the structure and parameters of WS (technological schemes, length and diameters of pipeline sections, type and characteristics of PU, adjustable and shut-off valves, etc.) with the replacement of the selected zones with their equivalent characteristics; operating information – minimum admissible values of heads in all nodes of WS, predicted values of hour volumes of water consumption in each node of WS, calculated at time zero with the prediction of 24 hours and their dispersion [11-13].

The problem of effective planning of the operation modes of CWS is considered as two interrelated problems: the problem of optimal load distribution between PS operating on the common WS CWS and the problem of optimization of the operation modes of each PS of CWS.

THE PROBLEM OF OPTIMAL LOAD DISTRIBUTION BETWEEN PS

The problem of optimal load distribution between PS is solved at the interval of planning [0, T], (T=24). Taking into account the specificity of water consumption the interval of planning is divided into 4 subintervals: $[t_1,t_2]$ – period of minimum water consumption, $[t_2,t_3]$ – transition from minimum to maximum water consumption, $[t_3,t_4]$ – period of maximum water consumption, $[t_4,t_5]$ – transition from maximum to minimum water consumption.

For each subinterval $[t_i,t_j]$ the estimations of expectation of the predicted volume of water consumption by all categories of consumers of WS and their dispersions:

$$q_{i0}(l), \sigma_{q_{i0}}^{2}(l), l=1,...,24, \ i=1,\dots,4$$

are calculated:

$$\bar{q}_{10}=\frac{1}{t_2-t_1}\sum_{l=t_1}^{t_2} q_i(l),$$

$$\sigma_{q10}^{2}=\frac{1}{t_2-t_1}\sum_{l=t_1}^{t_2}\sigma_{q_i}^{2}(l), \qquad (12)$$

$$\bar{q}_{20}=\frac{1}{t_3-t_2}\sum_{l=t_2}^{t_3} q_i(l),$$

$$\sigma_{q20}^{2}=\frac{1}{t_3-t_2}\sum_{l=t_2}^{t_3}\sigma_{q_i}^{2}(l), \qquad (13)$$

$$\bar{q}_{30}=\frac{1}{t_4-t_3}\sum_{l=t_3}^{t_4} q_i(l),$$

$$\sigma_{q30}^{2}=\frac{1}{t_4-t_3}\sum_{l=t_3}^{t_4}\sigma_{q_i}^{2}(l), \qquad (14)$$

$$\bar{q}_{40}=\frac{1}{t_5-t_4}\sum_{l=t_4}^{t_5} q_i(l),$$

$$\sigma_{q40}^{2}=\frac{1}{t_5-t_4}\sum_{l=t_4}^{t_5}\sigma_{q_i}^{2}(l). \qquad (15)$$

Without breaking the generality, we consider the mathematical formulation and algorithm of solving the problem of load distribution between PS for the interval $[t_i,t_j]$:

$$\underset{\omega}{M}\sum_{rnV^{*}}\left(h_r^{(c)}(\omega)-h_r^{+}\right)^2 \to \min_{h_j^{(a)}\in\Omega}, \qquad (16)$$

$$\underset{\omega}{M}\sum_{r\in E_{i2}} q_r(l,\omega)=\bar{q}_{i0}, \ (\text{i}=1,\dots,4), \qquad (17)$$

where: V^{*} - the set of nodes of the graph of WS G(V,E), with the exception of the nodes of all selected zones P_n (n=1,…,k) and adding the nodes corresponding to the inputs of each of the pressure regulators in all zones of P_n; $q_r(l,\omega)$ - predicted value of consumption by rconsumer at the interval [t_i, t_j]; $h_j^{(a)}$ - head values at the outputs of PS (j=1,…,n1), n1 – number of PS operating together on WS; the area Ω is defined by the system of contingencies (2) – (5) and condition (6) with an additional balance condition (17). The problem is solved using Nelder-Mead's modified algorithm [14]. As a result of solving of the problem of load distribution between PS we obtain the estimations of expectations of optimal values of consumption $\bar{q}_{iNS}$ and heads $\bar{h}_{iNS}$ at the outputs of each PS and their dispersions. These values are the starting points for solving the problem of optimization of operation modes of PS.

THE OPTIMIZATION PROBLEM OF PS OPERATION MODES

On the PS for pumping water several single-type or multi-type pump units (PU) working simultaneously are used. The number of simultaneously operating on a common pipeline PU can be different, depending on the desired operation mode of PS. The direction of the operation mode of PS is carried out by switching PU on/off; changing the degree of opening of the adjustable valve (AV) at the output of PU; changing of the speed of shaft rotation of PU, if PU is equipped with an adjustable drive.

In the work [21] we propose the strategy of effective planning of operation modes of PS at the given time slice [t_i,t_j] based on a stochastic model of quasi-stationary operation modes of PS.

In the present work this strategy is applied for planning of operation modes of PS consisting of m working simultaneously PU in which:

1) the operation of all m PU is controlled with the help of AV;

2) one PU is equipped with adjustable drive, the rest are controlled with AV;

3) all m PU are equipped with an adjustable drive.

To represent the structure of PS in the form of an orgraph $G_{NS}(V,E)$, where V – a vertex set, E – an arc set (e=Card(E), v=Card(V), a real PS is added by a zero top and fictitious chords connecting the zero top with the input and output of PS. For the mathematical formulation of the problem, the following coding of PS is made: each branch of the tree graph contains one PU, one AV (adjustable valve) and passive areas connecting PU and AV with the input and output of PS. The vertices of the graph of PS are the connection points of two or more elements [22, 23].

The arc set E of the net graph PS can be presented as:

$$E = L \cup M \cup K \cup R,$$

where: L – arc set of the net graph corresponding to the areas with PU; M – arc set of the net graph corresponding to the passive areas, K – set of the fictitious areas of the net, R – arc set of the net graph corresponding to the adjustable valves (AV). For this labeling the stochastic model of quasi-stationary operation modes of PS is the following:

(The adjustment of PU is carried out by means of AV.)

$$\underset{\omega}{\mathrm{M}}\left(h_r(q_r(\omega)) + \sum_{i\in L} b_{1ri} h_{NAi}\ (q_i(\omega)) + \right.$$
$$\left. + \sum_{i\in R} b_{1ri} h_{RZi}\ (q_i(\omega)) + \sum_{i\in M} b_{1ri} h_i\ (q_i(\omega)) \right) = 0,$$
$$(r = v, \dots, v + \eta_2 - 1). \tag{18}$$

$$\underset{\omega}{\mathrm{M}}\left(\bar{h}_{NS} - h_{vh} + h_{NAr}(q_r(\omega)) + h_{NAr}^{(g)} + h_{RZr}(q_r(\omega)) + \right.$$
$$\left. + h_{RZr}^{(g)} + \sum_{i\in M} b_{1ri}\ (h_i(q_i(\omega)) + h_i^{(g)}) \right) = 0,$$
$$(r = 1, \dots,\ \mathrm{n}). \tag{19}$$

$$\underset{\omega}{\mathrm{M}}\left(\sum_{r=v}^{e} b_{1ri} q_r(\omega) \right) = \bar{q}_{NS}\ ,$$
$$\left(i = 1, \dots, v-1\right), \tag{20}$$

$$q_i\left(\omega\right) > 0, \quad i \in M. \tag{21}$$

$$\begin{gathered} h_{NAi}(q_i(\omega)) = a_{0i}(\omega) + a_{1i}(\omega) q_i(\omega) + \\ + a_{2i}(\omega) q_i^2(\omega), \quad i \in L, \end{gathered} \tag{22}$$

$$h_{RZi}(\mathrm{q}_i(\omega)) \ = \ \frac{\mathrm{q}_i(\omega)\mathrm{C}_i(\omega)}{\mathrm{E}_i^2}, \quad \mathrm{i} \in \mathrm{R}, \tag{23}$$

$$h_i(q_i(\omega)) = sgn\, q_i(\omega) S_i(\omega) q_i^2(\omega),$$
$$\bar{S}_i = 0,001736 \frac{l_i}{d_i^{5,3}}, \quad i \in M, \tag{24}$$

$$\eta(q_i(\omega)) = d_0(\omega) + d_1(\omega) q_i(\omega) +$$
$$+ d_2(\omega) q_i^2(\omega), \quad i \in L, \tag{25}$$

In this equations: the random varieties characterize $q_i(\omega)$ – water flow on i- section of the pipeline, $S_i(\omega)$ – hydraulic resistance of i- section of the pipeline ($i \in M$), $\bar{h}_{NS}$ –head at the output of PS, $h_{NAi}(q_i(\omega))$ – head of i- PU, $h_{RZi}(q_i(\omega))$ – drop of head on i-AV; $\eta(q_i(\omega))$ – efficiency of i- PU, $a_{0i}(\omega), a_{1i}(\omega), a_{2i}(\omega), d_{0i}(\omega), d_{1i}(\omega), d_{2i}(\omega)$ – parameters of PU ($i \in L$), $C_i(\omega)$ – parameters of AV ($i \in R$), h_{vh} – head at the input in PS, E_i – degree of opening of AV ($E \in (0,1]$), l_i, d_i, $h_i^{(g)}$ – length, diameter and geodetic mark of i- section of the pipeline ($i \in M$), b_{1ri} – cyclomatic matrix element, $\bar{q}_{NS}$ - evaluation of the expectation of the flow at the output of PS, $\underset{\omega}{M}\{\cdot\}$ - mathematical expectation of the random variety {.}.

If PU is equipped with an adjustable drive it is necessary to use in the system of contingencies (18) – (25) models (26) and (27) instead of the models (22) and (25).

The mathematical model of PU with an adjustable drive is:

$$h_{NAi}(q_i(\omega)) = a_{0i}(\omega) \left(\frac{n_1}{n_0} \right)^2 +$$
$$+ a_{1i}(\omega) q_i(\omega) \frac{n_1}{n_0} + a_{2i}(\omega) q_i^2(\omega), \quad i \in L, \tag{26}$$

$$\eta(q_i(\omega)) = 1 -$$
$$- \frac{1 - d_0(\omega) - d_1(\omega) q_i(\omega) - d_2(\omega) q_i^2(\omega)}{\left(n_0 / n_1 \right)^{0,36}}, \quad i \in L, \tag{27}$$

where: n_0, n_1 – nominal and operating speed (r/min) of the rotor drive motor.

The mathematical formulation of the problem of optimization of the operation modes of i- (i=1,…,n1) of SW CWS at the interval of adjustment $[0,T]$ can be represented as a non-linear stochastic programming problem:

$$\underset{\omega}{M} \sum_{t=1}^{4} \sum_{j=1}^{m} \frac{9,81 \cdot h_{NAtj}(q_j(\omega)) \cdot q_{tj}(\omega)}{\eta_{NAtj}(q_j(\omega))} \to \min_{S, E_{ij} \in \Omega}, \tag{28}$$

with statistical conditions (18) – (20) and additional conditions (21) – (27). Where the area Ω for i- of PS is determined by the system of PS (18) – (27), m – the number of PU on the selected PS, S – the structure of PS, i.e. the line-up of PU operating on PS, t – the interval of planning (1,2,3,4):

t=1 corresponds to the interval $[t_1,t_2]$,
t=2 corresponds to the interval $[t_2,t_3]$,
t=3 corresponds to the interval $[t_3,t_4]$,
t=4 corresponds to the interval $[t_4,t_5]$.

The building of a deterministic equivalent of the problem (18) – (28) is carried out by replacement of the random varieties with their expectations. As a result of solving of this problem we obtain S^*_{NSj}, n^*_{1jz} - optimal structure of i- PS, optimal values of the expectations of the drive speed z- PU, position of each AV.

THE PROBLEM OF THE PRESSURE STABILIZATION IN THE WS DICTATING POINTS

The statement of the problem of pressure stabilization in the dictating points of WS is the following:

$$\underset{\omega}{M}\, c \sum_{t=1}^{24 \cdot 60} \sum_{i=1}^{v^*} \left(h_i^{(c)}(t, \hat{\omega}) - h_i^+ \right)^2 \to \min_{\Delta n_{1jz} \in \Omega}, \tag{29}$$

where: v^* - quantity of the dictating points in WS, c – normalizing factor; Δn_{1jz} - modification of the value of rotation z- PU on j- PS; area of the contingencies Ω is determined by the equation (30).

Problem (29) – is one-stage problem of stochastic programming.

Contingencies for the problem of pressure stabilization in DP:

Suppose $y_{jit}(\omega) = h_{ji}^{(c)}(t,\hat{\omega}) - h_{ji}^{+}$ - the value of pressure increase in j - DP, caused by the change of pressure $h_{itNS}^{P}(\omega)$ on i - PS at the moment of time t. Then the values $y_{jit}(\omega)$ and $h_{itNS}^{P}(\omega)$ can be connected with each other by the dependence:

$$h_{ji}^{(c)}(t,\hat{\omega}) - h_{ji}^{+} = V_{ijt} h_{iNS}(\omega) + N_{it}(\omega), \quad (30)$$

where: V_{ijt} - operator of the linear discrete transfer function, connecting the change of pressure in j - DP with the change of pressure on i - PS at the moment of time t; $N_{it}(\omega)$ - the value of noise, determined by the stochastic nature of water consumption in the load zone i - PS and the actual operation mode of CWS at the moment of time t.

RESULTS AND DISCUSSION

Without breaking the generality let us examine as an example the segment of WS (fig. 1) with two PS- PS1 and PS2, each of which consists of m=3 connected in parallel PU such as AD4000-95-2. The schemes of PS1 and PS2 are shown in the fig. 2, the parameters of PU are given in the Table 1. The parameters of WS (l, d, h^g – length, diameter and geodesic mark of the section of WS, h^+, q_{i0} – minimum admissible pressure and predicted flow in the nodes of WS) are given in the Table 2.

The results of solving of the problem of optimal load distribution between PS1 and PS2 for each interval of planning are in the Table 3 ($\bar{h}_{NSi}$ – mathematical expectation of head of the pump station (i=1,2), $\bar{q}_{NSi}$, $\bar{Q} = \bar{q}_{NS1} + \bar{q}_{NS2}$ – mathematical expectation of water flow on the pump stations and in the water-supply).

The problem of zoning we will solve for the mode of maximum water consumption: $\bar{Q}$=7,06 m^3/s, $\bar{h}_{NS1}$=74,97 m, $\bar{q}_{NS1}$=3,56 m^3/s, $\bar{h}_{NS2}$=78,61 m, $\bar{q}_{NS2}$=3,5 m^3/s.

In the present WS (fig. 1) for a threshold value of the excess pressure value Porog=23 zone P* has been selected (selected in the Table 4 and in the fig. 1). $h^{(c)}$, $h^{(c)*}$ - free heads in the nodes of water-supply initially and after zoning (m); h_{izb}, h_{izb*} - excess pressure in the nodes of water-supply initially and after zoning (m).

In the node №11 the pumping station is provided.

As a result of solving of the problem of load distribution between the pressure regulators installed at the inputs in the zone, we determined the value of pressure regulators “behind”, at the inputs in the zone h_{R1}=41,47, h_{R2}=52,59 м, and based on these data we identified the type of the pressure regulator: Honeywell D15P.

The pressure of the pumping station in the node 11 Hst =26,944 m.

The analysis of the obtained results in the Table 5 and in the fig. 3.

After zoning, installation of pressure regulators at the inputs in the selected zone and the pumping station, the sum of squares of the excess pressures in the nodes of WS has decreased on 74,88%.

Table 6 – Table 9 are presented results of solving the problem of effective planning of the operation modes of PS1 and PS2. Where F - the function of power inputs:

$$F = \sum_{k=1}^{4} \sum_{i=1}^{3} \frac{9,81 \cdot \bar{h}_{NAi} \cdot \bar{q}_i}{\bar{\eta}_{NAi}}.$$

These results may be effectively used in many real situations in centralized water-supply systems.

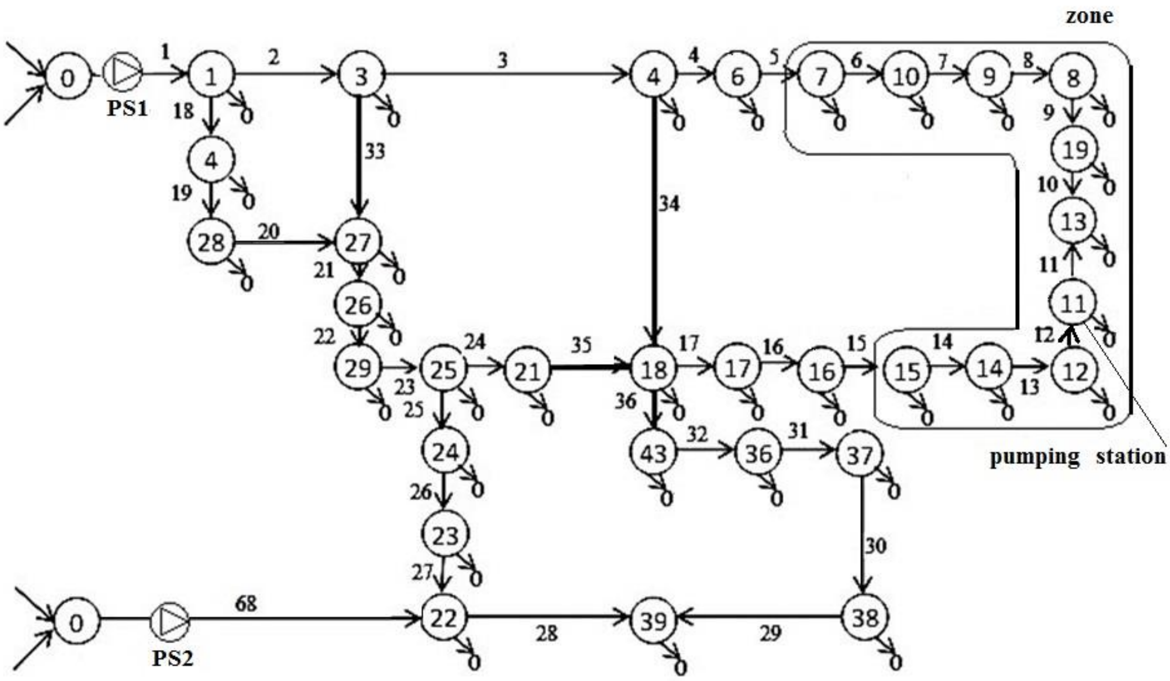

Fig. 1. The graph of water-supply with two pump stations PS1 and PS2

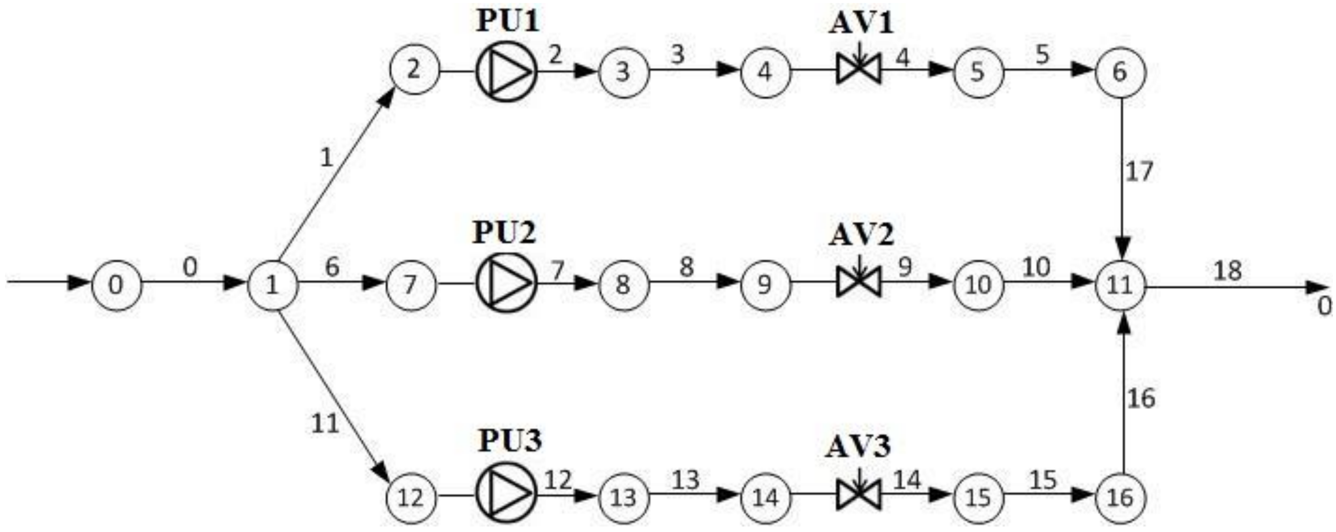

Fig. 2. The scheme of pump stations PS1 and PS2

Table 1. The estimated coefficient of approximation of the characteristics of PU

PU	a_0	a_1	a_2	d_0	d_1	d_2
PU1	108	-2,03524	-8,94861	0	147,0046	-61,030796
PU2	100	-2,03524	-8,94861	0	147,0046	-61,030796
PU3	95	-2,03524	-8,94861	0	147,0046	-61,030796

Table 2. The parameters of water-supply

Node couple	l, m	d, m	$h^{(g)}$, m	№ of the node	h^{+}, m	q_{i0}, m^3/s			
						$[t_1,t_2]$	$[t_2,t_3]$	$[t_3,t_4]$	$[t_4,t_5]$
0-1	0	0,8	0	-	-	-	-	-	-
1-3	478	0,8	0,79	1	52,6	0,1143	0,2857	0,4	0,3077
3-4	1036	0,8	1,19	3	51,309	0,0286	0,0714	0,1	0,0769
4-6	600	0,6	-8,99	4	49,464	0,0286	0,0714	0,1	0,0769
6-7	686	0,6	-12	6	48,048	0,1143	0,2857	0,4	0,3077
7-10	1693	0,8	-6	7	51,368	0,0114	0,0286	0,04	0,0308
10-9	566	0,25	-3	10	46,887	0,0069	0,0171	0,024	0,0185
9-8	302	0,3	-1	9	45,432	0,0023	0,0057	0,008	0,0062
8-19	500	0,3	-1	8	46,401	0,0057	0,0143	0,02	0,0154
13-19	442	0,3	-1	19	48,281	0,0033	0,0084	0,0117	0,0090
11-13	313	0,3	-2	13	49,835	0,0046	0,0114	0,016	0,0123
12-11	454	0,3	-2	11	85 (50)	0,0034	0,0086	0,012	0,0092
14-12	445	0,3	-1	12	50,919	0,0023	0,0057	0,008	0,0062
15-14	471	0,3	-1,99	14	52,915	0,0011	0,0029	0,004	0,0031
16-15	895	0,3	-4	15	54,946	0,0003	0,0007	0,001	0,0008
17-16	290	0,3	-10	16	56,379	0,0046	0,0114	0,016	0,0123
18-17	209	0,3	-10	17	52,8	0,0011	0,0029	0,004	0,0031
1-40	181	0,6	0,28	18	49,986	0,0011	0,0029	0,004	0,0031
40-28	212	0,6	-4,23	40	52,124	0,2286	0,5714	0,8	0,6154
28-27	432	0,6	-0,74	28	56,198	0,1429	0,3571	0,5	0,3846
27-26	375	0,6	1,15	27	56,783	0,0857	0,2143	0,3	0,2308
26-29	250	0,5	2,63	26	55,526	0,0914	0,2286	0,32	0,2462
29-25	266	0,4	2	29	52,74	0,1143	0,2857	0,4	0,3077
25-21	300	0,4	-0,1	24	49,5	0,1143	0,2857	0,4	0,3077
25-24	217	0,3	0,1	23	51,568	0,1429	0,3571	0,5	0,3846
24-23	215	0,3	0	22	54,288	0,2857	0,7143	1	0,7692
23-22	305	0,3	0,1	39	48,063	0,1429	0,3571	0,5	0,3846
22-39	671	0,25	-0,1	38	55,277	0,1371	0,3429	0,48	0,3692
38-39	497	0,3	0,1	37	53,842	0,0286	0,0714	0,1	0,0769
37-38	525	0,3	0	36	51,418	0,0286	0,0714	0,1	0,0769
36-37	274	0,3	0,1	43	50,848	0,0823	0,2057	0,288	0,2215
43-36	219	0,3	0	25	49,825	0,0286	0,0714	0,1	0,0769
3-27	400	0,6	-5,48	21	49,876	0,0286	0,0714	0,1	0,0769
4-18	700	0,6	-0,69	amount	-	2,02	5,04	7,06	5,43
21-18	350	0,4	0,3	-	-	-	-	-	-
18-43	214	0,4	-0,3	-	-	-	-	-	-

Table 3. The planning modes of PS1 and PS2

Interval of planning	$[t_1,t_2]$ min	$[t_2,t_3]$	$[t_3,t_4]$ max	$[t_4,t_5]$
PS1	$\bar{h}_{NS1}$=57,94 m $\bar{q}_{NS1}$=1,02 m^3/s	$\bar{h}_{NS1}$=65,65 m $\bar{q}_{NS1}$=2,54 m^3/s	$\bar{h}_{NS1}$=74,97 m $\bar{q}_{NS1}$=3,56 m^3/s	$\bar{h}_{NS1}$=67,205 m $\bar{q}_{NS1}$=2,74 m^3/s
PS2	$\bar{h}_{NS2}$=57,168 m $\bar{q}_{NS2}$=1 m^3/s	$\bar{h}_{NS2}$=67,1 m $\bar{q}_{NS2}$=2,5 m^3/s	$\bar{h}_{NS2}$=78,61 m $\bar{q}_{NS2}$=3,5 m^3/s	$\bar{h}_{NS2}$=68,92 m $\bar{q}_{NS2}$=2,69 m^3/s
The total supply of WS	$\bar{Q}$=2,02 m^3/s	$\bar{Q}$=5,04 m^3/s	$\bar{Q}$=7,06 m^3/s	$\bar{Q}$=5,43 m^3/s

Table 4. The results of solving of the problem of zoning for the modes of minimum and maximum water flow

№ of the node	$h^{(c)}$	h_{izb}	$h^{(c)*}$ (in the zone)	h_{izb*}	$h^{(c)}$	h_{izb}	$h^{(c)*}$ (in the zone)	h_{izb*}
	$[t_3,t_4]$ max				$[t_1,t_2]$ min			
1	74,962	22,362	-	22,362	57,941	5,341	-	5,341
3	66,283	14,974	-	14,974	56,491	5,182	-	0,66
4	59,904	10,44	-	10,44	54,822	5,358	-	1,237
6	64,915	16,867	h_{R1}=41,47	16,867	63,437	15,389	-	11,278
7	76,674	25,306	53,226	1,858	75,41	24,042	41,595	2,2
10	82,611	35,724	59,162	12,275	81,402	34,515	53,568	12,673
9	82,921	37,489	59,472	14,04	84,11	38,678	59,56	16,836
8	83,53	37,129	60,081	13,68	85,065	38,664	62,268	16,822
19	84,407	36,126	60,959	12,678	86,05	37,769	63,223	15,926
13	83,406	33,571	59,957	10,122	85,049	35,214	64,207	13,371
11	81,505	31,505	58,056	0	83,059	33,059	63,206	3,032
12	79,915	28,996	56,466	5,547	81,102	30,183	61,216	8,34
14	79,557	26,642	56,108	3,193	80,169	27,254	59,259	5,411
15	78,395	23,449	54,946	0	78,265	23,319	58,326	1,476
16	76,042	19,663	h_{R2}=52,59	19,663	74,435	18,056	-	14,224
17	67,031	14,231	-	14,231	64,536	11,736	-	7,93
18	57,841	7,855	-	7,855	54,619	4,633	-	0,846
40	64,783	12,659	-	12,659	56,842	4,718	-	0,099
28	66,684	10,486	-	10,486	60,858	4,66	-	0,193
27	67,136	10,353	-	10,353	61,563	4,78	-	0,388
26	63,384	7,858	-	7,858	60,166	4,64	-	0,488
29	60,075	7,335	-	7,335	57,464	4,724	-	0,754
24	63,222	13,722	-	13,722	55,861	6,361	-	5,561
23	72,858	21,29	-	21,29	56,731	5,163	--=	6,323
22	78,607	24,319	-	24,319	57,168	2,88	-	4,716
39	68,557	20,494	-	20,494	56,392	8,329	-	9,664
38	55,634	0,357	-	0,357	55,277	0	-	0
37	53,842	0	-	0	55,089	1,247	-	0,167
36	53,628	2,21	-	2,21	55,153	3,735	-	1,912
43	53,913	3,065	-	3,065	55,18	4,332	-	0,974
25	60,463	10,638	-	10,638	55,691	5,866	-	3,696
21	59,061	9,185	-	9,185	55,635	5,759	-	2,697

Table 4. (continuation) The results of solving of the problem of zoning for transient conditions

№ of the node	$h^{(c)}$	h_{izb}	$h^{(c)*}$	h_{izb*}	$h^{(c)}$	h_{izb}	$h^{(c)*}$	h_{izb*}
	$[t_2,t_3]$↑				$[t_4,t_5]$↓			
1	65,643	13,043	-	13,043	67,205	14,605	-	14,605
3	60,827	9,518	-	9,518	61,734	10,425	-	10,425
4	56,993	7,529	-	7,529	57,467	8,003	-	8,003
6	63,949	15,901	-	15,901	64,099	16,051	-	16,051
7	75,816	24,448	53,468	2,1	75,947	24,579	53,44	2,072
10	81,78	34,893	59,432	12,545	81,906	35,019	59,399	12,512
9	83,296	37,864	60,948	15,516	83,212	37,78	60,706	15,274
8	84,076	37,675	61,728	15,327	83,963	37,562	61,456	15,055
19	85,004	36,723	62,655	14,374	84,881	36,6	62,374	14,093
13	84,002	34,167	61,653	11,818	83,879	34,044	61,372	11,537
11	82,054	32,054	59,705	1,515	81,938	31,938	59,431	1,25
12	80,272	29,353	57,923	7,004	80,188	29,269	57,681	6,762
14	79,614	26,699	57,265	4,35	79,58	26,665	57,073	4,158
15	78,064	23,118	55,716	0,77	78,095	23,149	55,588	0,642
16	74,941	18,562	-	18,562	75,1	18,721	-	18,721
17	65,467	12,667	-	12,667	65,703	12,903	-	12,903
18	55,898	5,912	-	5,912	56,197	6,211	-	6,211
40	60,314	8,19	-	8,19	61,061	8,937	-	8,937
28	63,356	7,158	-	7,158	63,909	7,711	-	7,711
27	63,94	7,157	-	7,157	64,468	7,685	-	7,685
26	61,458	5,932	-	5,932	61,767	6,241	-	6,241
29	58,461	5,721	-	5,721	58,711	5,971	-	5,971
24	59,121	9,621	-	9,621	59,755	10,255	-	10,255
23	64,128	12,56	-	12,56	65,508	13,94	-	13,94
22	67,079	12,791	-	12,791	68,917	14,629	-	14,629
39	61,996	13,933	-	13,933	63,016	14,953	-	14,953
38	55,277	0	-	0	55,277	0	-	0
37	54,31	0,468	-	0,468	54,18	0,338	-	0,338
36	54,236	2,818	-	2,818	54,087	2,669	-	2,669
43	54,387	3,539	-	3,539	54,269	3,421	-	3,421
25	57,72	7,895	-	7,895	58,142	8,317	-	8,317
21	57,015	7,139	-	7,139	57,328	7,452	-	7,452

Table 5. The results of zoning (f – sum of squares of the excess pressures in all nodes of WS)

f, м^2	$[t_1,t_2]$	$[t_2,t_3]$	$[t_3,t_4]$	$[t_4,t_5]$	Amount	f, %
f initially	11881	12410	14352	12644	51286	100%
f after zoning	1911	3144	4969	3370	13394	26,12%

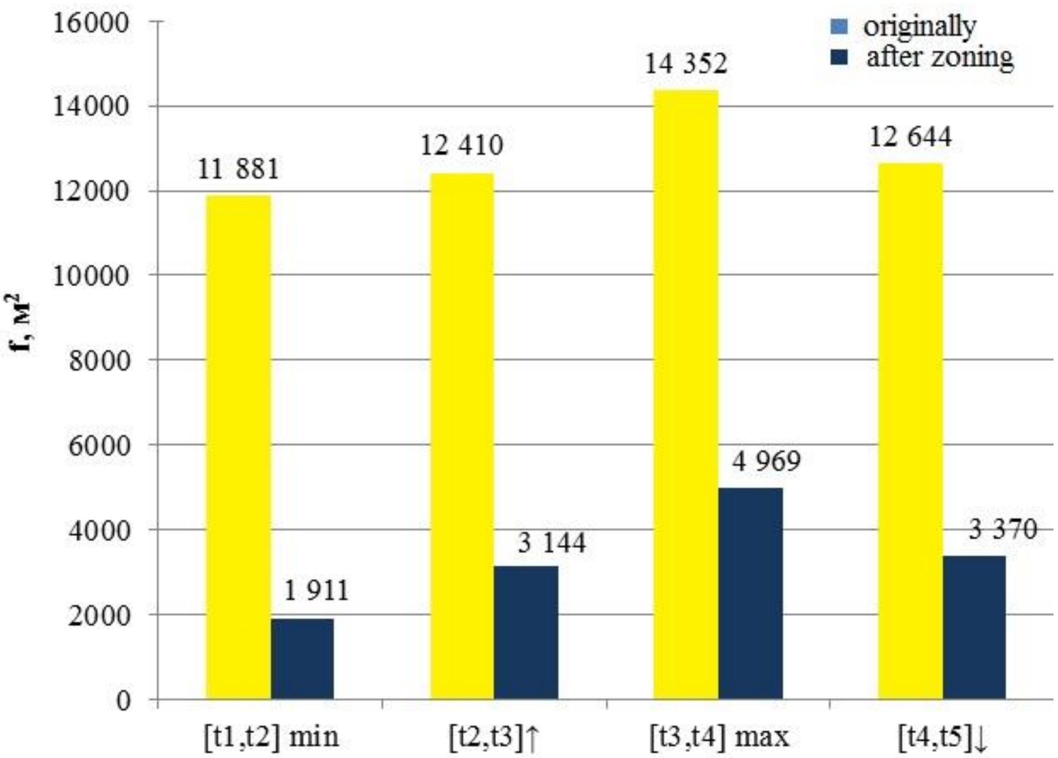

Fig. 3. The results of the zoning of WS CWS

Table 6. The results of solving of the problem of effective planning of the operation of PS 1 (the adjustment is carried out with the valves). (q_i – water flow on i- PU, E_i – the degree of opening of the adjustable valve (i=1, 2, 3))

PS1				
Time slice	$[t_1,t_2]$min	$[t_2,t_3]$ ↑	$[t_3,t_4]$max	$[t_4,t_5]$ ↓
PU1	----------------	--------------	q_1=1,155 m^3/s E_1=0,45	q_1=0,731 m^3/s E_1=0,25
PU2	---------------	q_2=1,213 m^3/s E_2=0,5	q_2=1,238 m^3/s E_2=0,75	q_2=0,93 m^3/s E_2=0,35
PU3	q_3=1,02 m^3/s E_3=0,351	q_3=1,327 m^3/s E_3=0,841	q_3=1,167 m^3/s E_3=0,969	q_3=1,079 m^3/s E_3=0,481
F, kw	967,8	2215,97	3392,8	2952,9
PS 2				
Time slice	$[t_1,t_2]$min	$[t_2,t_3]$ ↑	$[t_3,t_4]$max	$[t_4,t_5]$ ↓
PU1	-------------	-------------	q_1=1,254 m^3/s E_1=0,6	q_1=1,368 m^3/s E_1=0,5
PU 2	-------------	q_2=1,229 m^3/s E_2=0,5	q_2=1,19 m^3/s E_2=0,9	-------------
PU 3	q_3=1 m^3/s n_1=590	q_3=1,271 m^3/s E_3=0,672	q_3=1,055 m^3/s E_3=0,99	q_3=1,322 m^3/s E_3=0,892
F, kw	958,7	2245,7	3376,76	2500,57

Table 7. The results of solving of the problem of effective planning of operation of the pump station (one PU3 is with an adjustable drive). (n_1 – rotation of PU3 (r/min))

PS1				
Time slice	$[t_1,t_2]$min	$[t_2,t_3]$ ↑	$[t_3,t_4]$max	$[t_4,t_5]$ ↓
PU1	----------------	--------------	q_1=1,232 m^3/s E_1=0,5	q_1=1,324 m^3/s E_1=0,45
PU 2	---------------	q_2=1,213 m^3/s E_2=0,5	q_2=1,26 m^3/s E_2=0,8	--------------
PU 3	q_3=1,02 m^3/s n_1=596	q_3=1,327 m^3/s n_1=660	q_3=1,068 m^3/s n_1=666	q_3=1,416 m^3/s n_1=675
F, kw	750,2	2177,9	3370,98	2508,4
PS2				
Time slice	$[t_1,t_2]$min	$[t_2,t_3]$ ↑	$[t_3,t_4]$max	$[t_4,t_5]$ ↓
PU 1	-------------	-------------	q_1=1,206 m^3/s E_1=0,55	q_1=1,368 m^3/s E_1=0,5
PU 2	-------------	q_2=1,229 m^3/s E_2=0,5	q_2=1,216 m^3/s E_2=1	-------------
PU 3	q_3=1 m^3/s n_1=590	q_3=1,271 m^3/s n_1=660	q_3=1,079 m^3/s n_1=680	q_3=1,322 m^3/s n_1=671
F, kw	958,7	2178,6	3365,6	2468,5

Table 8. The results of solving of the problem of effective planning of operation of the pump station (all PU are equipped with an adjustable drive)

PS1				
Time slice	$[t_1,t_2]$min	$[t_2,t_3]$ ↑	$[t_3,t_4]$max	$[t_4,t_5]$ ↓
PU1	----------------	--------------	n_1=682	-------------
PU 2	---------------	n_1=621	n_1=633	n_1=639
PU 3	n_1=596	n_1=649	n_1=661	n_1=668
F, kw	750,24	2072,95	3253,49	2330,74
PS 2				
Time slice	$[t_1,t_2]$min	$[t_2,t_3]$ ↑	$[t_3,t_4]$max	$[t_4,t_5]$ ↓
PU 1	-------------	-------------	n_1=692	--------------
PU 2	-------------	n_1=624	n_1=643	n_1=641
PU 3	n_1=590	n_1=652	n_1=671	n_1=671
F, kw	730,7	2069,4	3332,9	2316,7

Table 9. The function of power inputs per 24 hours under the different ways of adjustment of operation of the pump station

PS	Adjustment with AV F, kw	One PU3 with an adjustable drive F, kw	All PU with an adjustable drive F, kw
PS1	9529,5	8807,48 (decreased on 7,6%)	8407,42 (decreased on 11,8%)
PS2	9081,73	8971,4 (decreased on 1,2%)	8449,7 (decreased on 7%)

CONCLUSIONS

The examined approach to solve the problem of resource and energy saving in CWS owing to optimal reengineering of WS by means of their zoning and optimal adjustment of the water flow in WS is an effective means of resource and energy saving in CWS.

The obtained results confirm that the efficiency of operation of CWS can be increased:

1) due to zoning of WS CWS and installation of the pressure regulators at the inputs in isolated zones,

2) due to installation of the pumping stations for HRB in the selected zone,

3) due to using of two-staged system of effective operation including the problem of effective planning of the operation modes of CWS and the problem of pressure stabilization in the dictating points of WS.

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