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POWER OPTIMIZATION OF THE COMPLEX PUMPING SYSTEM

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ABSTRACT
This paper proposes a solution of the problem of reducing production costs for supplied domestic water, which directly affects the reduction of the electric power consumption. The paper presents the methodology and the program of calculus for the transport's optimization of the water under pressure in the system of supply with water of Iasi city.
The optimization process will take into account that the profitability of water distribution activity depends on the relationship between supply capability and operating costs, i.e. Therefore, the process depends on the volume of required investment, on the specific consumption electrical power for pumping, on the price of electricity, as well as on the volume of water billed on a monthly basis.
The optimization calculation will use two target functions: total maximum efficiency and total electric power consumption required for transport of each cubic meter of supplied water, and cubic meter of sewage water, respectively.
The mathematical methods may be improved by taking into account all active consumers in the network with simultaneous water requirements, at each moment of the day.

KEY WORDS
Adduction, hydrophore, pipe network, pumping station, optimization and tank

Nomenclature

Latin symbols

a_p	[-]	average overall quota in pumping station
a_p''	[-]	yearly average expenses quota in pumping station
a_r	[-]	average overall quota in pipe
a_r''	[-]	yearly average expenses quota in pipe
D	[m]	pipe's rated diameter
e_s	[Wh/m^4]	unitary specific energy consumption
E_p	[kWh]	basis energy
E'_p	[kWh/y]	energy yearly average consumption
F, f, g	[-]	constant
H_{gH}	[m]	hydrophore geometrical head
H_H	[m]	hydrophore head
H_i	[m]	pipe network load with different static head on hydrophore
$H_{(O),u}$	[m]	hydrophore head in section *O*, filling stage
$H_{(O),g}$	[m]	hydrophore head in section *O*, emptying stage
H_{pf}	[m]	pump head
H_{PS}	[m]	pumping station head
i_o	[€/m]	coefficient investment in pipe network
i_p	[€/kW]	investment coefficient in constructions and installations
I_p	[€]	investment in pumping station
I_R	[€]	investment in pipes
k	[-]	economic coefficient
k_{pf}	[s^2 m^{-5}]	pumps resistance hydraulic modulus
L	[m]	pipe length
m	[-]	load loss parameter
$M_{rH,u}$	[s^2 m^{-5}]	hydrophore resistance hydraulic modulus for filling
$M_{rH,g}$	[s^2 m^{-5}]	hydrophore resistance hydraulic modulus for emptying
M_{ro}	[s^2 m^{-5}]	pipes network resistance hydraulic modulus
n	[rpm]	pump rotational speed
n_N	[-]	upsetting pipes number
n_o	[rpm]	optimum number of discharge pipes
N	[kW]	installed power for water transport
p	[-]	pumps number
p_e	[€/kWh]	electric energy unit cost
p_o	[€/kWh]	unitary average cost
p_b	[€/kWh]	basis energy unitary cost
p_v	[€/kWh]	vertex energy unitary cost
$p(q_i)$	[-]	relative debit frequency
q_i	[-]	relative debit
$Q_{H,u}$	[m^3/s]	hydrophore debit for filling
$Q_{H,g}$	[m^3/s]	hydrophore debit for emptying
Q_M	[m^3/s]	maximum debit of pumping station in *O* section
Q_{PS}	[m^3/s]	pumping station debit
r	[-]	monthly average rate for updating
r_c	[-]	credit interest
r_e	[-]	credit interest
R_{po}	[%]	nominal pump outturn
t_p	[h/day]	pumping daily average time
t_{vp}	[h/day]	pumping daily average time in vertex period

T_r	[-]	existence standardised duration analysed system
u_a	[-]	annual average increase instalment
u_c	[-]	average parameter of cost annual increase
u_e	[-]	actualisation coefficient
Z	[€]	economic function
W_o	[m^3]	water volume absorbed from sources

Greek symbols

α	[-]	heading grade on network
β	[-]	constant of hydraulic slope
γ	[-]	constant of hydraulic slope
η_p	[%]	outturn for one pump
η_m	[%]	overall outturn for action engine
$\eta_{g,PA}$	[%]	overall outturn ensemble, in emptying stage
$\eta_{u,PA}$	[%]	overall outturn ensemble, in filling stage

1. Introduction

Clearly explain the nature of the problem, previous work, purpose, and contribution of the paper The paper shows a determination method about the pumping installation's average global output in the adjustment situation through hydro – pneumatic heads.

It is presented an analyze method about power and economical efficiency of the pumping installations equipped with only one type of pumps. The adaptation to variable regimes is done by the hydrophore's usage.

The best power and economical performances will correspond to the pumping solution which ensures the covering of the request area (Q, H) with the best output.

The theoretical considerations are accompanied by the examples concerning an under pressure station from a collective system about supplying with urban water.

Profitability of water distribution activity depends largely on the relationships between operational capability and service costs, related to supplier's performance, volume of distributed water and effective operating costs. The main variables that influence the total selling price are required investment value, specific consumption of electrical energy for pumping power, unit price of the electrical energy and total volume of monthly consumed water billed, [2].

The selection of rehabilitation and modernization measures must rely on market studies results that appropriately establish the quantities of water that may be distributed and billed. Present and future water requirements will be determined based on the analysis of actual operation data and on estimation of future trends in water consumption on national and international levels.

Authors used original mathematical algorithms to develop original computer programs that calculate, at each moment in time, depending on the number of active consumers connected simultaneously to the network, the functional parameters of the ensemble pumping station – hydrophore – pipe distribution network, as well as the available consumer parameters. This may be done in the hypothesis of a minimum price of cubic meter of pumped water.

The automatic calculation program defines the exploitations regimes for the overall output's installation to be maximum and the total typical energy consumed to be minimum on the work cycle ensemble.

2. Optimization problem's wording

The pumping efficiency is established by studying technical implications of modernization measures of the power station. Energy efficiency and economic efficiency for the pumping supply system are tightly connected to the proper choice of pumping device and appropriate operation of the hydraulic system, [4].

The best performances are obtained when, in order to meet the consumer requirement, the pumps are set to operate for regimes with efficiencies that are close to their maximum values. The equipment required for the pumping station must meet the operational characteristics of the network, as well as the relationships between the flow rate and specified hydraulic energy required by pumps, depending on various operational configurations.

The paper presents the authors efforts to find the optimum solutions to ensure proper servicing of consumers, 24 hours a day, and reduction of operation costs, proposing the following measures:

1. Rehabilitation of pumping stations, as the capacity of supply has to meet the requirements of the consumers and to take into account the present trend in domestic heating and hot water preparation by individual apartment heating units. The rehabilitation activity consists in replacing the present pumping devices with new ones that feature functional characteristics that correspond to the present and future requirements of the consumers. These new devices will exhibit technologies present today on the worldwide market.

2. Modernize the pumping station to ensure the increase of energy efficiency and economic efficiency of the domestic and industrial water supply activity, that is, introduce the process automation for a reduced specific consumption of electric energy and reduced operational workforce.

To solve the optimization problem, the authors developed a general mathematical model that will emphasize the importance of the relationship between energy side and technological side of the analyzed process.

The calculation of the ensemble's overall output formed by the pumping station, the distribution network, consumers, loads into consideration the charge specific features which correspond to each ensemble's element, for the two work phases of hydrophore: fill up and emptying. It will correspond in (Q, H) plane by one specific feature of the network – consumer ensemble, for each combination (number, type, position) of active consumers. The head in the analyze section is shown by the following mathematical relation:

$$H_{(O),u} = H_{gH} + H_H + M_{rH,u}\, Q_{H,u}^2 \;, \tag{1}$$

compared to the water level from the pumping station's aspiration basin, in the analyze section *O,* for filling up $H_{(O),u}$ and for emptying $H_{(O),g}$:

$$H_{(O),g} = H_{gH} + H_H - M_{rH,g}\, Q_{H,g}^2 \tag{2}$$

It was made a program of automatic calculation which can determinate the functional and energetic specific feature of hydraulic machines, for ordinary speed and nominal speed.
The gap between the flow delivered by a pump with discontinuous running and the one the network is really supplying (keeping head H in the range that ensures the prescribed quality of the supply), compensation capacity has to allow the creation - between the minimal level, corresponding to the necessary pressure which keeps the minimal head requested by the network H_m, and the maximal level H_M, which is accepted through technical and energetic criteria and ensures the maximal superior limit head on the recommended operating range of a serviceable water volume V_u. This value is calculated from the condition that imposes that, compared to the average pump flow Q_{pm} - on the recommended field (H_m, H_M), duration of the filling-emptying cycle T_c - between two successive pump start-ups - to be at least equal with a minimal admitted time T_e, which is specific to the chosen electric drive:

$$V_u \geq \frac{Q_{pm} . T_c}{4} \; ; \; T_c \geq T_e \, . \tag{3}$$

The outturn specific feature of the pump R_P written as parabola with equation without free term:

$$R_p = R_1 . Q - R_2 . \, Q^2 \, , \tag{4}$$

The program calculates the resistance hydraulic modulus for any pipe - line network, taking notice of all singularity types. The head specific feature for pumping station H_{PS} is:

$$H_{PS} = H_{pf} - \frac{K_{pf} + M_{ro}}{p^2}\, Q_{PS}^2 \, , \tag{5}$$

The mathematical expressions that define the flow $Q_{PS\text{-}R\text{-}H,u}$ and the head for pumping station – networks – hydrophore filling stage ensemble, in *O* section $H_{PS\text{-}R\text{-}H,u}$ are:

$$Q_{PS\text{-}R\text{-}H,u} = \sqrt{\frac{H_{pf} - H_{g,R\text{-}H,u}}{M_{R\text{-}H,u} + \dfrac{K_{pf} + M_{ro}}{p^2}}} \, , \tag{6}$$

$$H_{PS\text{-}R\text{-}H,u} = H_{pf} - \frac{H_{pf} - H_{g,R\text{-}N}}{\dfrac{M_{R\text{-}H,u} . p^2}{K_{pf} + M_{ro}} + 1} \, . \tag{7}$$

The power asked by network $N_{c,u}$ has the following mathematical relation, [7]:

$$N_{c,u} = \gamma . \, Q_{PS-R-H,u} \, . \, H_{(O),PS\text{-}R\text{-}H,u} \; . \tag{8}$$

The total outturn of pumping aggregate – networks – hydrophore fill – up stage ensemble $\eta_{u,PA}$ has the following mathematical relation:

$$\eta_{u,PA} = \eta_p \;\; \eta_m . \, \frac{1}{1 + \dfrac{K_{pf} + M_{ro}}{p^2} \; \dfrac{Q_{PS\text{-}R\text{-}H,u}^2}{H_{(O),PS\text{-}R\text{-}H,u}}} \, . \tag{9}$$

The hydrophore is acting in the network like a generator and has the following debit $Q_{H,g}$, in the emptying stage is:

$$Q_{H,g} = \sqrt{\frac{H_{g,H} + H_H - H_{(O)}}{M_{rH,g}}} \, . \tag{10}$$

It can be written these relations in accordance with the continuity equation, for the *O* section in the emptying stage of hydrophore:

$$Q_{(O),H\text{-}SP,g} = Q_{(O),H,g} + Q_{(O),PS} \, . \tag{11}$$

The debit $Q_{PS\text{-}R\text{-}H,g}$ and the head $H_{(O),PS\text{-}R\text{-}H,g}$ for pumping station – networks – hydrophore emptying stage ensemble, in *O* section are:

$$Q_{PS\text{-}R\text{-}H,g} = \sqrt{\frac{H_{PS\text{-}H,g}}{M_{PS\text{-}H,g} + M_R}} \tag{12}$$

$$H_{(O),PS\text{-}R\text{-}H,g} = H_{PS\text{-}H,g} \left(1 - \frac{1}{1 + \dfrac{M_R}{M_{PS\text{-}H,g}}} \right) \tag{13}$$

The power asked by network $N_{c,g}$ and pump $N_{a,g}$, in the emptying stage has the following mathematical forms:

$$N_{c,g} = \gamma \cdot Q_{PS\text{-}R\text{-}H,g} \cdot H_{(O),PS-R-H,g} ;$$

$$N_{a,g} = \frac{\gamma \cdot Q_{p,g} \cdot H_{p,g} \cdot p}{\eta_m \cdot \eta_p} ; Q_{p,g} = \frac{Q_{PS-R-H,g} - Q_{H,g}}{p} . \quad (14)$$

The overall outturn of the pumping station – networks – hydrophore emptying stage ensemble $\eta_{g,PA}$, in O section has the following mathematical relation:

$$\eta_{g,PA} = \frac{N_{c,g}}{N_{a,g}} = \frac{\eta_m \ \eta_p}{\left(1 - \frac{Q_{H,g}}{Q_{(O),PS\text{-}R\text{-}H,g}}\right)} \cdot \frac{1}{\left[1 + \frac{k}{p^2 \ H_{(O),PS\text{-}R\text{-}H,g}} \ \left(Q_{PS\text{-}R\text{-}H,g} - Q_{H,g}\right)^2\right]} \quad (15)$$

The operational regimes for the pumping station supplies (ensemble of active pumps in the pumping station – open level tanks – slopes) will be analyzed taking into account required static loads / piezometric heads, which vary in a pre-established range. This will emphasize the options to increase the designed flow rate, and determine energetic and economic characteristics of the typical operational regimes. One of the goals is to increase the transport capability of gravitational supplies. To cover for the head losses in water transport of the annual volume W_o that is absorbed from the supply source, the energy required E'_p is, [1]:

$$E_p^{'} = F . E_p ; E_p = \frac{W_o . H_o}{367 . \eta_h . \eta_a} + \frac{1}{367} . \sum_{i=1}^{n} \frac{W_i . H_i}{\eta_h^i . \eta_a^i} . \quad (16)$$

Constant F is calculated with the form:

$$F = f^{-1} . g ; f = \sum_i q_i . p(q_i) ; g = \sum_i q_i^{\gamma+1} . p(q_i) \quad (17)$$

The investment in constructions and devices I_p for pressurized transport is:

$$I_p = I_{po} + i_p . N_i . \quad (18)$$

Processing the data acquired on the dependence between the investment in pipes I_R and the rated diameter D it follows that:

$$I_R = n_N . L . \left(i_o + b . D^{\alpha}\right). \quad (19)$$

The unitary cost of power energy is different in the vertex period of load curve against basis period:

$$p_o = p_b . \left[1 + \nu_p . (m_v - 1)\right] ; \nu_p = \frac{t_{vp}}{t_p} ; m_v = \frac{p_v}{p_b} . \quad (20)$$

The yearly average expenses quotas in pumping station $a_p^{''}$ and discharge pipe $a_R^{''}$ take into account different development rates for various economic domains that affect this analysis and all expenses are computed relative to the same moment in time:

$$a_{p,(R)}^{''} = a_{p,(R)}^{'} + \frac{1}{T_r} , \quad (21)$$

$$a_{p,(R)}^{'} = a_{p,(R)} \cdot \frac{\sum_{k=1}^{t} \left(\frac{1 + u_{a,(c)}}{1 + r}\right)^k}{\sum_{k=1}^{t} \left(\frac{1 + u_e}{1 + r}\right)^k} , \quad T_r = \sum_{k=1}^{t} \left(\frac{1 + u_e}{1 + r}\right)^k . \quad (22)$$

The energy unitary specific consumption e_s depend of debit, head hydraulic power and outturn corresponding to mathematical relation:

$$e_s = \frac{N_{H,u} . 10^3}{3600 . \eta_{H,u} . Q_{H,u} . H_{H,u}} . \quad (23)$$

The optimization problem consists in identification of the proper values for pumping station operational parameters that will determine the minimum specific consumption averaged on yearly basis, abiding by the operational and constructional restrictions as well as assuming normalized section dimensions; some of these variables (D, L, n, η) have direct or indirect influences on device's proper operation. The goal is to determine the values of the D, L, n parameters that minimize the economic target function $Z(D, n)$. This function is given by the equation, [3]:

$$Z = a_p^{''} . I_p + a_R^{''} . I_R + p_o . E_p = = a_p^{''} . \left(I_{po} + i_p . m . \frac{k . Q_M^{\gamma+1} . L}{\eta_{PA} . n_N^{\gamma} . D^{\beta}} \right) + a_R^{''} . n_N . L . \left(i_o + b . D^{\alpha}\right) + \frac{k . m . L . Q_M^{\gamma} . F . W_o . p_o}{D^{\beta} . n_N^{\gamma} . \eta . 3600} . \quad (24)$$

The solution for the pair of variables (D, n) is given by the values that minimize the economic target function $Z(D, n)$. The mathematical formulae for the optimum number of discharge pipes n_o and for the optimum pipe diameter D_o are:

$$\frac{\partial Z}{\partial n} = 0; \quad \frac{\partial Z}{\partial D} = 0 \quad (25)$$

$$n_o = \left[\left(\frac{\alpha . \gamma}{\beta} - 1 \right) . \frac{b^{\beta}}{i_o^{\alpha+\beta}} \right]^{\frac{1}{\alpha . (\gamma+1)}} . \left[\frac{k . m . \beta}{a_R^{''} . \alpha . \eta} . \left(i_p . Q_M^{\gamma+1} . a_p^{''} + \frac{Q_M . F . W_o . p_o}{3600} \right) \right]^{\frac{1}{\gamma+1}} ; \quad (26)$$

$$D_o = \left[\frac{k.m.\beta}{b.\alpha.\eta^{\gamma+1}.a_R''}.\left(a_p''.i_o.Q_M^{\gamma+1} + \frac{Q_M.F.W_o.p_o}{3600}\right)\right]^{\frac{1}{\alpha+\beta}}. \quad (27)$$

The optimum pump type and dimensions (number of stages and rotational speed) are determined such as it may ensure the required flow rate, with specified head, for the highest value of efficiency; this value will become the reference maximum efficiency for pump selection, [6].

For a given water supply system, with specified operational capacity, the same mathematical model is used, but this time the nominal diameter of the discharge pipe is known; it is possible to calculate an optimal flow Q_{opt} and then (with imposed conditions) the minimal annual average total cost. Then, comparing with the required supply capacity and analyzing previous data, the measures for modernizing and improving the studied water supply system may be chosen.

Efficiency of this control method is conditioned by satisfying the network requirements, maintaining the pump efficiencies in the neighbourhood of their maximal efficiency, [5]. Efficiency may be maintained at high levels if pump is properly sized and the compensation capacity is adequate. Also, it is mandatory to adequately operate the system composed of pumps, tank and network.

3. Experimental results

The optimization method is applied in the pumping station Codrescu, Iasi, for drinkable water, Figure 1. The pumping station is equipped with EP NK 64x4 pumps and rotational speed of $n = 2900$ rpm.

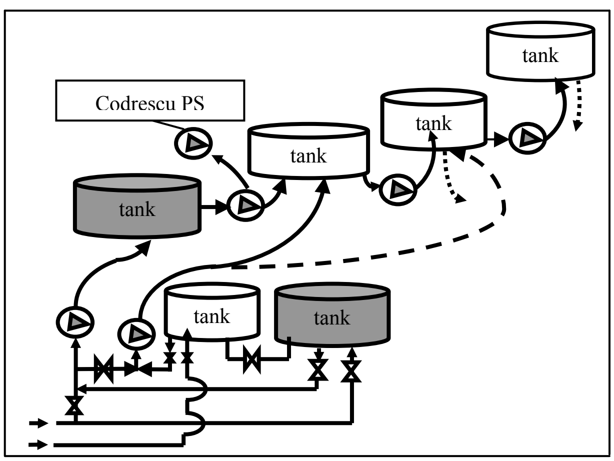

Figure 1. The drinkable water supply system scheme of Iasi city with Codrescu pumping station

Using several original mathematical algorithms, authors developed a computer program that calculates the functional parameters of the ensemble pumping station – hydrophore – pipe distribution network, as well as the available consumer parameters. This may be accomplished at each moment in time, depending on the number of active consumers simultaneously connected to the supply network, in the hypothesis of a minimum price of cubic meter of pumped water.

The Figure 2 shows the working regimes of Codrescu pumping station at hydrophore heads $H_H = 15$ m. It is drawn outturn curves for $R_{H,u} = 50 \div 68$ %; also are drawn the variations of debit $Q_{H,u}$, load $H_{H,u}$, hydraulic power $N_{H,u}$ and unitary specific energy consumption variation e_s for different static load on hydrophore H_H at filling stage, after system's optimization.

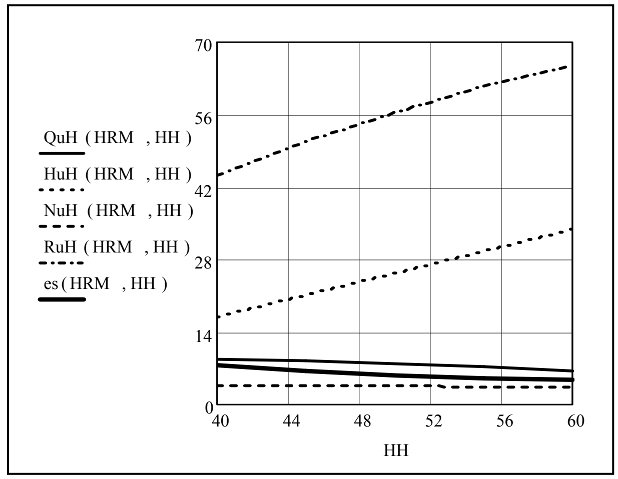

Figure 2. The working regimes of Codrescu pumping station with hydrophore head H_H = 15 m, filling stage, after system's optimization

Codrescu pumping station working on hydrophore and outturn depending on debit *Q,* after system's optimization is presented in the Figure 3.

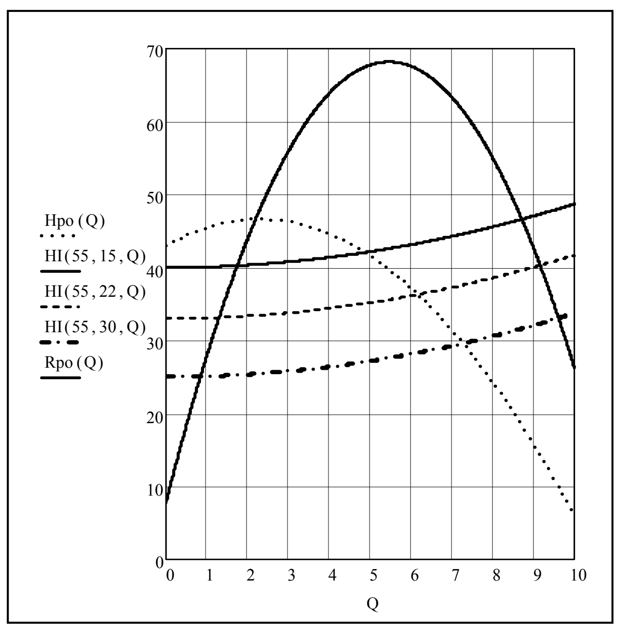

Figure 3. Codrescu pumping station working on hydrophore and outturn depending on debit *Q*, after system's optimization

The debit, power and unitary specific energy consumption variation depending on the hydrophore head are shown in the Figure 4, in filling stage, after system's optimization.

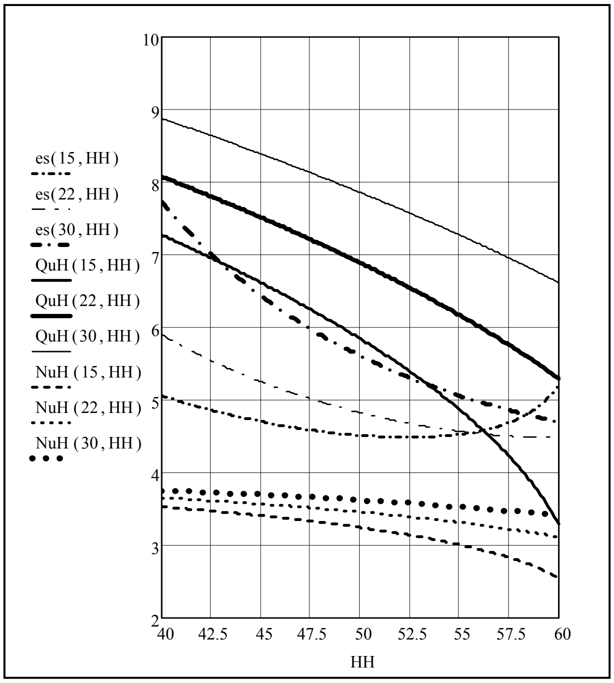

Figure 4. Debit, power and unitary specific energy consumption depending on hydrophore head, in filling stage, after system's optimization

The recovery time of investment for the rehabilitation of Codrescu pumping station depend on the pumped water volume W_o and the monthly instalments number of credit engaged for the rehabilitation's achievement.

4. Conclusion

The replacement of the existent equipment, that is obsolete from physical and technological point of view, must be done with new equipments with performances that will meet the requirements of an optimum operation from both energetic and economic perspectives. The water transport and distribution network must have the capability to meet the requirements of the consumers.
The insurance of efficient operation relies on automatic supervision and control of pumping installation, as well as automatic adjustments to variable consumer requirements.
The proposed analysis method is based on the system's mathematical modelling, simplified by analytic specific features of its components and the automated data processing system.
The research results are used for design optimization of the water supply installation for areas with various relief forms. The proposed method for energetic optimization allows a reduction with 10 ÷ 15 % of the energy consumption required to operate the pumping station – network – hydrophore – consumers ensemble.

Any deviation from the optimum parameter values leads to a corresponding increase of the operational energy consumption required for pumping. These increases depend on the relative deviation from the optimum parameters considered and the influence on total consumptions. Such deviations are justified if the increase of the total specific energy consumptions generated by the water supply is compensated by a reduction of the total specific energy consumptions in the associated substructure.

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