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RESEARCH ARTICLE

Energetical optimization of water distribution systems in large urban centers

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Abstract

In the present conditions of water distribution towards the users by pumping, in large urban centers, the reconsideration of the structure and functioning principles of the distribution systems, from the point of view of the energetical optimization, becomes a necessary and major problem, which can be solved by a new structural design. This paper presents and analyses in a detailed manner, giving numerical examples, certain optimization methods and solutions for the distribution systems, with a view to diminishing the pumping energetic consumption, using interior potential elements, ascertaining the energetical and economical efficiency.

Keywords

water distribution · pumping · energetic-functional optimization · interior potential elements · energetic-economical efficiency

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1 Introduction

Water distribution to users by pumping is a process that consumes a huge quantity of electric energy. Classic water distribution systems, equipped exclusively with exterior pumping stations, are characterized by an energy consumption of 60...70 % of the energy consumed by the operation of the whole supply system of the large urban centers. This fact generates a great increase of the national energetic system load, during average consumption hours and especially in peak consumption hours.

In case of classic water distribution at Romanian users, available pressure is great at periphery consumption points where lower pressure is necessary and in central zones the pressure is insufficient. The absence of water at consumers can also be often observed during certain hours in 24 hours due to system under dimensioning, raising above consumption by some users, inadequate functioning of pumping station or a combination of these factors.

These disadvantages are amplified by overlapping of peak hours for water, heat, and electric energy consumption, especially between 7 and 9 in the morning and between 17 and 21 in the evening, contributing to raising operation expenses.

A major problem, necessary and opportune in this context is reconsidering organizing and functioning principles of water distribution systems for energy optimization point of view. Some procedures and solutions for optimization of water distribution systems using interior potential elements to save pumping energy are presented in this paper. Energetic-economical efficiency of these elements is determined and the principle that stays at the base of this new conception of structural development of water distribution systems in large urban centers is also presented.

2 Energetic consideration about water distribution

Large water distribution systems, equipped only with exterior pumping stations, are characterized by great electric energy consumption necessary for moving important volumes of water and for assuring useful pressure at using site. During peak hours, energy cost is 2-3 times expensive than during hours of minimum consumption.

Therefore, beside reducing electric energy consumption, it is very interesting even reducing energy consumption during peak water distribution hours. As a technical solution for this reason can be considered diminishing pumping power (even stopping pumps if it is possible) during peak hours, in change an extensive delivery outside these hours. Consequently distribution systems must be equipped with compensatory reservoirs. These reservoirs are known as interior reservoirs (zone reservoirs) and re pumping stations are known as interior pumping stations.

A desire of great importance is absolute reducing of energy consumption for pumping, which is possible only by system division into zones. For this purpose it can be used a special form of parallel zoning procedure or a vertical division into zones with intermediary pumps mounted in main pipes, or a combined solution with more potential elements.

3 Procedures of energetic-functional optimization with interior potential elements

3.1 Use of underground zone reservoirs and interior pump stations

This procedure consists of optimal positioning a few underground reservoirs on some main pipes of distribution system. They would be supplied through some low pressure adductions, if it is possible even by means of gravity, with necessary discharge for downstream users. From these reservoirs, transported discharge would be pumped in pipe network by adductions at relatively low pressure of water main at the junction point. This will not permit a considerable energy loss which would take place if the reservoirs would be filled from distribution network.

Using this procedure it is realized a subdivision of discharges and hydraulic loads of exterior potential elements in this way:

- from total discharge delivered by *NP* to exterior pump stations, a part Q_{pr} is transported through main pipes network and another part Q_{pa} is transported through adductions at *NR* reservoirs, according to the following equation:

$$\sum_{j=1}^{NP} Q_{p,j} = \sum_{j=1}^{NP} Q_{pr,j} + \sum_{k=1}^{NR} Q_{pa,k} \tag{1}$$

- pumping heads $H_{pe,j}$ of exterior pump stations, for reference water distribution system with the network supplyed by one-sided pumping from the exterior is diminishing at the values $h_{pe,j}$, in such a mode that total pump stations power P is computed with Eq. (2) if adductions are realized by gravity or (3) if adductions works by pumping:

$$P = \frac{\gamma}{\eta}\left(\sum_{j=1}^{NP} Q_{pr,j} h_{pe,j} + \sum_{k=1}^{NR} Q_{pa,k} H_{pi,k}\right) \tag{2}$$

$$P = \frac{\gamma}{\eta}\left(\sum_{j=1}^{NP} Q_{pr,j} h_{pe,j} + \sum_{k=1}^{NR} Q_{pa,k} H_{pa,k} + \sum_{k=1}^{NR} Q_{pa,k} H_{pi,k}\right) \tag{3}$$

where:

γ is water specific weight; η – efficiency of pump stations; $Q_{pa,k}$ – pumped discharges of interior pump station k; $H_{pi,k}$ – pumping head corresponding to necessary pressure in zone served by interior station k; $H_{pa,k}$ – pumping head in adductions at reservoir k.

Pumping heads $h_{pe,j}$ are much lower than pumping heads $H_{pe,j}$ because head losses are changing proportionally with square power of ratio $Q_{pr,j}/Q_{p,j} < 1$, in such a mode that exterior pump station power diminishes by reducing discharge as well as by reducing pressure, and total power is diminished by:

$$\Delta P = \frac{\gamma}{\eta}\left(\sum_{j=1}^{NP} Q_{p,j} H_{pe,j} - P\right) \tag{4}$$

In this mode energy consumption in the system will be reduced, and electric energy economy during the operation period T_o will be:

$$\Delta W_e = \Delta P T_o \tag{5}$$

According as the place of one zone reservoir linked with an interior pump station on main pipe is moved towards extreme upstream of water main (towards discharges bigger and bigger), interior station power P_i is rising higher and higher, and in the same time power P_e of the exterior station is diminishing in great measure because upstream water main sectors being unloaded, head losses are diminished according to the Darcy-Weisbach formula [11]. As a result, optimum location of reservoir is given by minimum amount of exterior and interior pump stations power (Fig. 1). For its evaluation a mathematical model was developed, which assumes as known the length L of main pipe (Fig. 1-a), discharge distribution along it (Fig. 1-b) and diameters D_M, D_m of supply section A and respectively of finishing section O.

In section A main pipe is unloaded with discharge $Q(x_o)$ by mean of an adduction located between section A and X_o. In section X_o is located underground reservoir and an interior pump station SP_i.

Head loss until a computing section (Fig. 1-c) is evaluated with equation:

$$H(x) = \int_0^x R_0(x) Q^\beta(x) dx \tag{6}$$

where: x is abscissa of computing section, reported at uperstream extremity of the main pipe; $Q(x)$ – discharge of pipe in section X; $R_o(x)$ – specific hydraulic resistance of the main pipe in computing section [11]; β – exponent with values between 1.85 and 2.

Discharge variations $Q(x)$ and specific hydraulic resistance variation $R_o(x)$ are evaluated by these equations:

$$Q(x) = q_0 + a x^\alpha \tag{7}$$

$$R_0(x) = r_0 - b x^2 \tag{8}$$

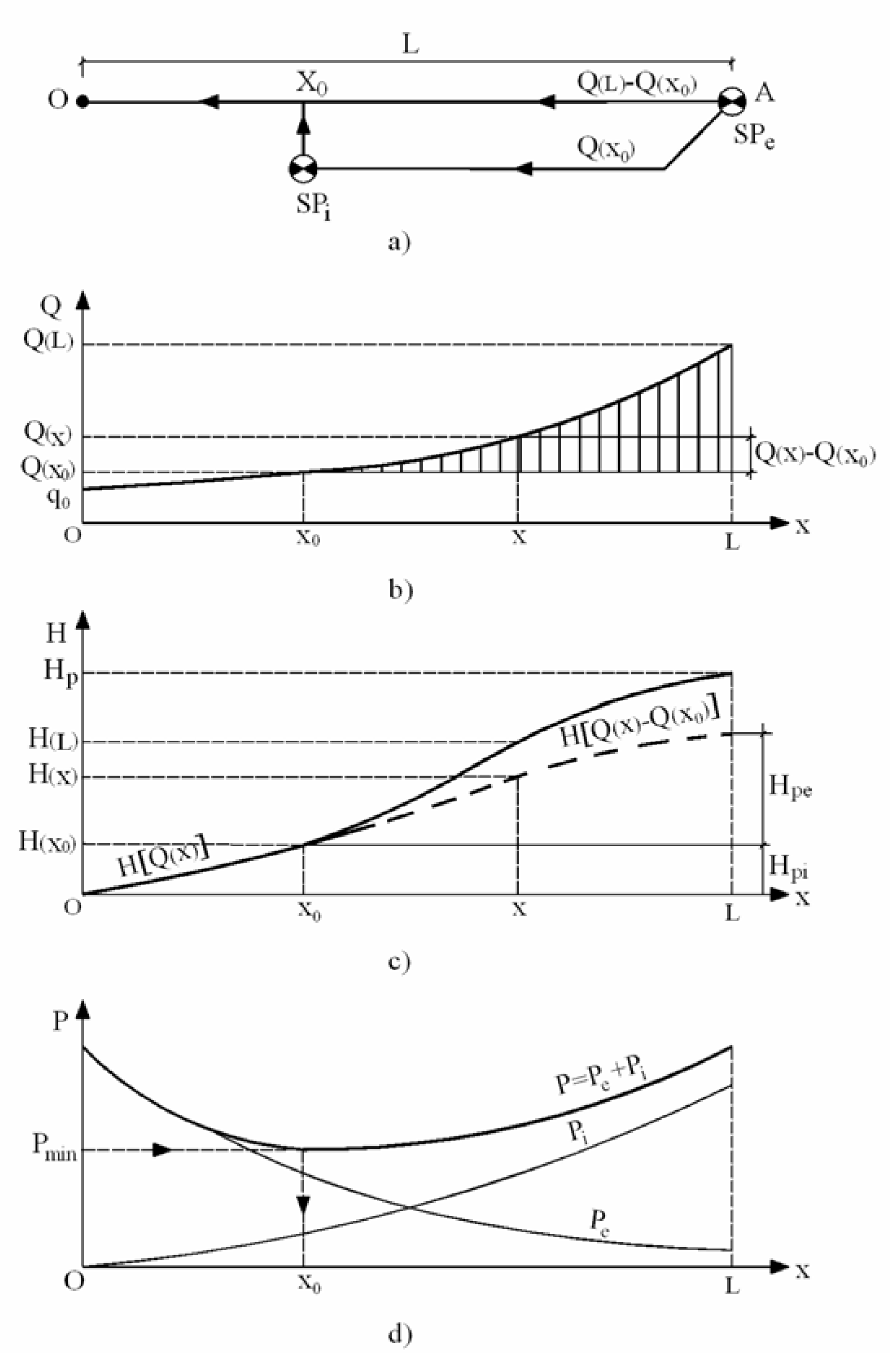

Fig. 1. Optimum location of one zone reservoir

in which real constants q_o, r_o, b are computed from boundary conditions, and parameters a, α, are determined statistically [6] knowing discharge distribution along main pipe.

Substituting relations (7) and (8) in expression (6) and integrating the resulting equation until section X$_o$, we obtain following formula:

$$H(x_0) = r_0 q_0^{\beta} x_0 - \frac{b q_0^{\beta}}{3} x_0^3 + \frac{r_0 a^{\beta}}{\beta\alpha + 1} x_0^{\beta\alpha+1} - \frac{b a^{\beta}}{\beta\alpha + 3} x_0^{\beta\alpha+3} \tag{9}$$

In order to describe hydraulic regime upstream section X$_o$, discharge equation can be written under a simple form:

$$Q'(x) = Q(x) - Q(x_0) = a(x^{\alpha} - x_0^{\alpha}), \tag{10}$$

resulting the piezometric head in supply node of main pipe:

$$\begin{aligned} H(L) =& H(x_0) + \frac{r_0 a^{\beta}}{\beta\alpha + 1} L^{\beta\alpha+1} - \frac{b a^{\beta}}{\beta\alpha + 3} L^{\beta\alpha+3} \\ & - \frac{r_0 a^{\beta}}{\beta\alpha + 1} x_0^{\beta\alpha+1} + \frac{b a^{\beta}}{\beta\alpha + 3} x_0^{\beta\alpha+3} \end{aligned} \tag{11}$$

and the expressions of pump stations' powers:

$$P_i = \frac{\gamma}{\eta} Q(x_0) H(x_0) \tag{12}$$

$$P_e = \frac{\gamma}{\eta} \left[Q(L) - Q(x_0)\right] \left[H(L) - H(x_0)\right] \tag{13}$$

Optimum solution for location of interior pump station is determined by the value of x_o for which total power $P = P_e + P_i$

becomes minimum (Fig. 1-d):

$$P = \frac{\gamma}{\eta}(c_0 + c_1 x_0 + c_2 x_0^{\alpha} + c_3 x_0^{\alpha+1} + c_4 x_0^3 + c_5 x_0^{\alpha+3} + c_6 x_0^{\beta\alpha+1} + c_7 x_o^{\alpha+\beta\alpha+1} + c_8 x_o^{\beta\alpha+3} + c_9 x_o^{\alpha+\beta\alpha+3}) \rightarrow min, \tag{14}$$

where $c_0, \ldots c_9$ are the coefficients of objective function [9].

Objective function minimum (14) is evaluated using interpolation numeric method, based on a searching algorithm with accelerated step coupled with square interpolation [6] that was implemented in a computer program.

3.2 Integration of intermediary pumping stations on main pipes

Procedure of assembly pumps direct on network main pipes is most rational possibility of distribution process energy preservation.

On main pipes where a pump station with parallel pumps are mounted, water is taken over at a lower pressure p_1 and repress at a higher pressure p_2,and pumping head is $H_{pi} = (p_2 - p_1)/\gamma$.

Using intermediary pump stations mounted in series on some main pipes (Fig. 2) amplifies discharge through these pipes. It also generates a small zone with low pressure uperstream in sucking node, but assures an important increase of pressure downstream in repress node. In this mode, favorable local increases of piezometric head in system are generated. Re pumping station is located almost in uperstream node of sucking, and connecting service pipes at uperstream pipes it is not made from the suction node but immediately down-stream from the pump.

Considering that in a distribution system served by *NP* exterior pump stations, on a number of *NA* main pipes are direct installed serial intermediary pump stations, total power in the system is:

$$P = \frac{\gamma}{\eta}\left(\sum_{j=1}^{NP} Q_{p,j} h_{pe,j} + \sum_{k=1}^{NA} Q_{pa,k} H_{pi,k}\right) \tag{15}$$

where: $Q_{p,j}$, $h_{pe,j}$ are discharge and pumping head for exterior pump station j; Q_{pak}, $H_{pi,k}$ – discharge and pumping head for intermediary pump station k.

Because pumping heads of exterior pump stations are diminishing ($h_{pe,j} \ll H_{pe,j}$), and discharges of intermediary pump stations became equal with local discharges of the main pipes on which they integrate, results a power reduction ΔP according with the relation (4). As a result, energy consumption in the system is reducing, and electric energy economy ΔW_e is given by the formula (5).

As Fig. 2 presents, in case of non conditioned optimization, pressure steps created by intermediary pump stations have to comply with necessary pressure limits H_n on water mains.

A conditioned optimization can be administer by connecting service pipes immediately downstream from the integrated pump stations, in knots like A$_1$, A$_2$, A$_3$, in such a mode that water main pressure will diminish even under assured values H_n, obtaining even a greater energy economy in the system.

Optimum solution for location of intermediary pump stations and choosing their number, and also aggregate from each of them, is that total installed power is minimum.

3.3 Water towers arrangement

High reservoirs from water distribution networks, performing their compensatory function, present important level fluctuations, is necessary that service pressure should be assured even at the lowest levels of water in vat.

From constructive point of view, water towers have cylindrical, truncated cone or a special shape. These shapes were optimized [4] to obtain technical and economical indicators as favorable as possible. At the optimum profile, due to static and strength considerations, water height in reservoir reaches high values, 6...10 m, which raises elevation head of pressure lines in the system and raises pumping energy consumption.

From energetic point of view, relatively high cost of water towers is justified by reducing energy consumption during peak hours. At the height of pumping schedule, between 7-9 and 17-21 hours, when electric energy is most expensive, it is recommended to deliver smaller water flow through exterior pump stations and compensatory difference to be completed from water towers, which should be filled outside these hours.

If pumping aggregates are stopped during peak hours (an average of 4 hours daily) and urban centre will be supplied from the volume accumulated in water towers during minimum consumption hours (during which electric energy cost is small) important cost reduction at electric energy is made.

The following equation evaluates the electric consumed energy:

$$W_e = \frac{9.81}{\eta} Q_p H_{pe} T_p \tag{16}$$

where: Q_p is pumped discharge in the network; H_{pe} – maximum pumping head (for network supplied by one-side pumping from the exterior); T_p – pumping time; η – efficiency of pump station.

Pumping head is established as a function of water tower location related to pump station, service pressure and head losses in transport pipes.

Savings obtained by transferring energy consumption from peak hours to base hours can be evaluated with equation:

$$C = \frac{9.81}{\eta} Q_p H_{pe} T_p (e_1 - e_2) \tag{17}$$

in which e_1, e_2 are estimated electric energy costs during peak hours and base hours respectively.

Because high level oscillations, advantages of peak energy saving could be lost by raising global energy consumption. This is the reason why it is necessary to study water towers behavior in different constructive solutions and the way in which their

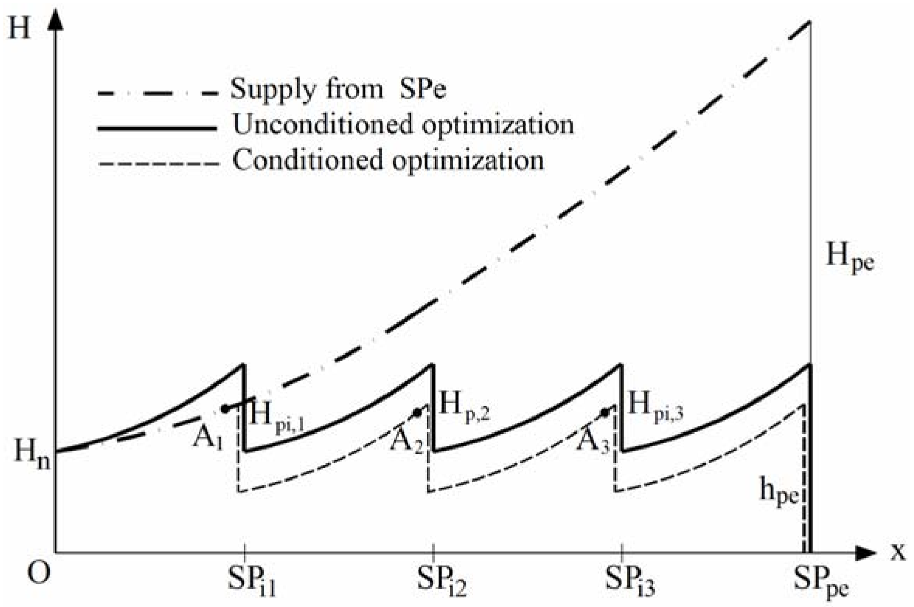

Fig. 2. Optimization scheme for integration intermediary pump station on main pipes

potential characteristics influence energetic balance of distribution.

4 Economical efficiency of optimizing procedures with interior potential elements

Introducing potential elements in water distribution networks asks for a supplementary investment, and its efficiency can be evaluated by differential recovering time T_r, calculated with formula:

$$T_r = \frac{\Delta I}{C_e - C_i} \leq T_n \tag{18}$$

where: ΔI is supplementary investment necessary in case of optimized system; C_e – annual operating expenses for reference system with the network supplyed by one-sided pumping from the exterior; C_i – annual operating expenses for system with interior potential elements; T_n – normal pay off time, assumed to be 10 years.

Relation (18) can be formulated in the following form:

$$T_r = \frac{\Delta I}{\Delta C_w - p\Delta I} \leq T_n \tag{19}$$

where ΔC_w is the difference between energy cost C_{we} in the reference system and energy cost C_{wi} in optimized system.

5 Numerical applications

5.1 Analysis of water towers potential characteristics influence over distribution energetic balance

Table 1 presents distribution of water consumption every hour by relative measures. Starting from these table, compensatory function will be analyzed for two types of water towers: truncated cone reservoir optimized, with generatrix angle of inclination 45^o from the horizontal line, diameters of 36 m and 16 m respectively, maximum height of 10 m and flat reservoir with height of 2 m. These water towers are located in distribution system of a large urban center, having an average hour loaded equal with daily maximum discharge of 3.59 m^3/s.

Water height was computed in every moment for both types of reservoirs and was represented graphic this variation in Fig. 3. On this basis, the comparative values of electric energy consumption are reported in Table 2.

Because of level oscillation and high water height, in case of truncated cone reservoir results an energy consumption of 67375 kWh/day, compared with only 59980 kWh/day in case of flat reservoir with small water height. In the second solution savings of 2662 kWh/year electric energy was realized, that mean an energy reduction of 11 %.

In general, for urban industrial centers with other technological characteristics, absolute values vary in a very large range, but proportions at the level of comparable parameters maintain, and in principle comparative computations maintain their validity.

5.2 Comparative energetic-economical analysis of optimization solutions with interior potential elements

In the following section is developed a comparative analysis of some structural solutions with interior potential elements, considering a large urban industrial centre, having the distribution network represented in Fig. 4. For our evaluation there are proposed four solutions for water distribution:

a) *first solution* represents classic reference variant with exterior pump station SP_e, at water plant, which delivers discharge Q_{omax}= 4.30 m^3/s and an average pumping head H_{pe}=60 m. Taking into consideration graphic of pumped discharge in every hour (Fig. 5) it can be determined electric energy consumed in every day W_{ee}, with the following equation:

$$W_{ee} = \frac{\gamma}{\eta} H_{pe} \sum_i Q_{0i} t_i \tag{20}$$

Tab. 1. Evaluation of water towers compensatory volume

Hour	Consumption coefficient, [%]		Pumping coefficient, [%]		Compensating coefficient, [%]		Compensat volume, [%]
	α_c	$\Sigma\alpha_c$	α_p	$\Sigma\alpha_p$	α_r	$\Sigma\alpha_r$	α_v
0	1	2	3	4	5	6	7
0–1	3.30	3.30	4.50	4.50	1.20	1.20	2.80
1–2	3.25	6.55	4.50	9.00	1.25	2.45	4.05
2–3	3.25	9.80	4.50	13.50	1.25	3.70	5.30
3–4	3.25	13.05	4.50	18.00	1.25	4.95	6.55
4–5	3.40	16.45	4.50	22.50	1.10	6.05	7.65
5–6	3.95	20.40	4.50	27.00	0.55	6.60	**8.20**
6–7	4.80	25.20	4.50	31.50	−0.30	6.30	7.70
7–8	5.25	30.40	2.50	34.00	−2.70	3.60	5.10
8–9	4.55	34.95	3.00	37.00	−1.55	2.05	3.55
9–10	4.55	39.50	4.50	40.50	−0.05	2.00	3.60
10–11	4.60	44.10	5.50	47.00	0.90	2.90	4.50
11–12	4.50	48.60	5.20	52.50	1.00	3.90	5.50
12–13	4.75	53.35	5.25	57.75	0.50	4.40	6.00
13–14	4.50	57.85	5.25	63.00	0.75	5.15	6.75
14–15	4.30	62.15	5.00	68.00	0.70	5.85	7.45
15–16	4.25	66.40	4.50	72.50	0.25	6.10	7.70
16–17	4.20	70.60	4.25	76.75	0.05	6.15	7.75
17–18	4.10	74.70	2.50	79.25	−1.60	4.55	6.15
18–19	4.20	78.90	2.50	81.75	−1.70	2.85	4.45
19–20	4.30	83.10	2.85	84.60	−1.45	1.40	3.15
20–21	5.00	88.20	3.00	87.75	−2.00	−0.45	1.15
21–22	4.80	93.00	3.65	91.40	−1.15	−1.60	0
22–23	3.60	96.60	4.25	95.50	0.65	−1.10	0.50
23–24	3.40	100.00	4.50	100.00	1.10	0	2.70

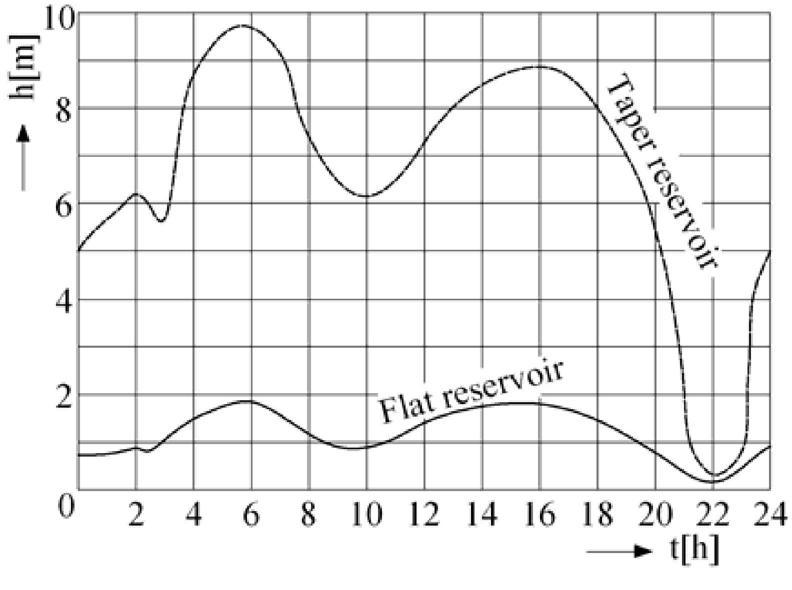

Fig. 3. Water level oscilation in water towers

where Q_{oi} is hour discharge corresponding to t_i time of the day.

b) *second solution* assume division the town into 7 distinct consume zones and in each zone centre there are located underground reservoir. Exterior pump station SP_e supplies reservoirs R_k (k= 1, ...,7) through a looped network of pipes of low pressure, in this way assuring discharge Q_{zimax} = 3.94 m^3/s and average pumping head h_{pe} = 15 m uniform and constant outside peak energetic consumption hours. Interior pump stations SP_i generate hour discharge Q_o from zone reservoirs, after graphics from Fig. 6, and necessary pressure for consumption zones.

Tab. 2. Computing energy consumption at water distribution using water towers

	Pumping		Truncated cone reservoir			Flat reservoir		
Hour	α_p [%]	Q_p [m^3/s]	H_p [m]	P [kW]	W_e [kWh/day]	H_p [m]	P [kW]	W_e [kWh/day]
0	1	2	3	4	5	6	7	8
0-1	4.50	4.25	53.6	2980	67375	43.7	2710	59980
1-2	4.50	4.25	54.4	3025		48.8	2715	
2-3	4.50	4.25	53.6	2980		48.7	2710	
3-4	4.50	4.25	56.8	3160		49.0	2725	
4-5	4.50	4.25	57.2	3180		49.5	2750	
5-6	4.50	4.25	57.7	3205		49.8	2770	
6-7	4.50	4.25	56.8	3155		49.8	2770	
7-8	2.50	2.36	56.4	1740		49.3	1520	
8-9	3.00	2.83	56.3	2085		48.9	1810	
9-10	4.50	4.25	54.0	3000		48.8	2710	
10-11	5.50	5.20	54.5	3705		49.0	3330	
11-12	5.20	4.91	55.7	3580		49.2	3160	
12-13	5.25	4.96	56.2	3645		49.3	3200	
13-14	5.25	4.96	56.7	3680		49.4	3205	
14-15	5.00	4.73	56.8	3515		49.5	3060	
15-16	4.50	4.25	56.9	3160		49.9	2775	
16-17	4.25	4.02	56.8	2985		49.7	2615	
17-18	2.50	2.36	56.5	1745		49.6	1530	
18-19	2.50	2.36	55.3	1705		49.3	1520	
19-20	2.85	2.03	54.2	1440		48.9	1300	
20-21	3.00	2.83	53.8	1990		48.4	1790	
21-22	3.50	3.30	49.4	2130		48.1	2075	
22-23	4.25	4.02	50.4	2650		48.1	2530	
23-24	4.50	4.25	52.8	2935		46.8	2700	
Energy economy, ΔW_e		[MWh/year]				2662		
		[%]				11		

Total energy consumed in every day in this solution W_e, can be determined with equation:

$$W_e = W_{ee} + W_{ei} \tag{21}$$

where:

$$W_{ee} = \frac{\gamma}{\eta} h_{pe} Q_{zimax} t \tag{22}$$

$$W_{ei} = \frac{\gamma}{\eta} \sum_{k=1}^{NR} H_{pi,k} \sum_{i} Q_{0i,k} t_{i,k} \tag{23}$$

in which: W_{ee} is pumping energy in water supply network of interior reservoirs; W_{ei} – energy consumed to pump water from reservoirs into zone pipe networks; t – number of pumping hours daily; $H_{pi,k}$ – average pumping heads corresponding to consuming zones k, having the following values, in m: 30.2; 40.8; 33.7; 43.6; 31.1; 37.5; 29.6.

c) *third solution* replaces underground reservoirs with water towers C_k (k= 1, ...,7) with smaller level oscillations, which assures in respective zones a gravitational distribution. From SP$_e$ discharge Q_{zimax} = 3.94 m^3/s is pumped at an average pumping head h_{pe} = 49 m, after program presented in Table 1, which sets reduced pumping during peak hours of energetic consumption.

d) *fourth solution* consists of direct pumping of water through intermediary pump stations SP_{i1} and SP_{i2} (Fig. 4) assuming that service pipes are connected immediately downstream of these. Exterior pump station delivers discharge Q_{omax} = 4.30 m^3/s, at a average pumping head h_{pe} = 40.5 m, and intermediary pump stations equipped with two, respectively three aggregates work with discharges of 0.94 m^3/s and respectively 1.78 m^3/s at average pumping head $H_{pi,1}$ = 13.0 m and $H_{pi,2}$ = 11.4 m, so as electric energy consumed daily can be determined with Eq. (21).

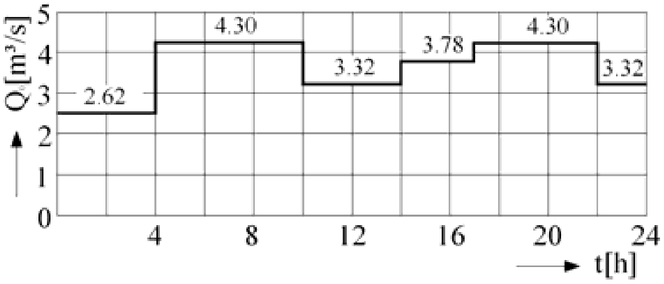

Fig. 5. Pumping graphic of SP$_e$ in reference solution

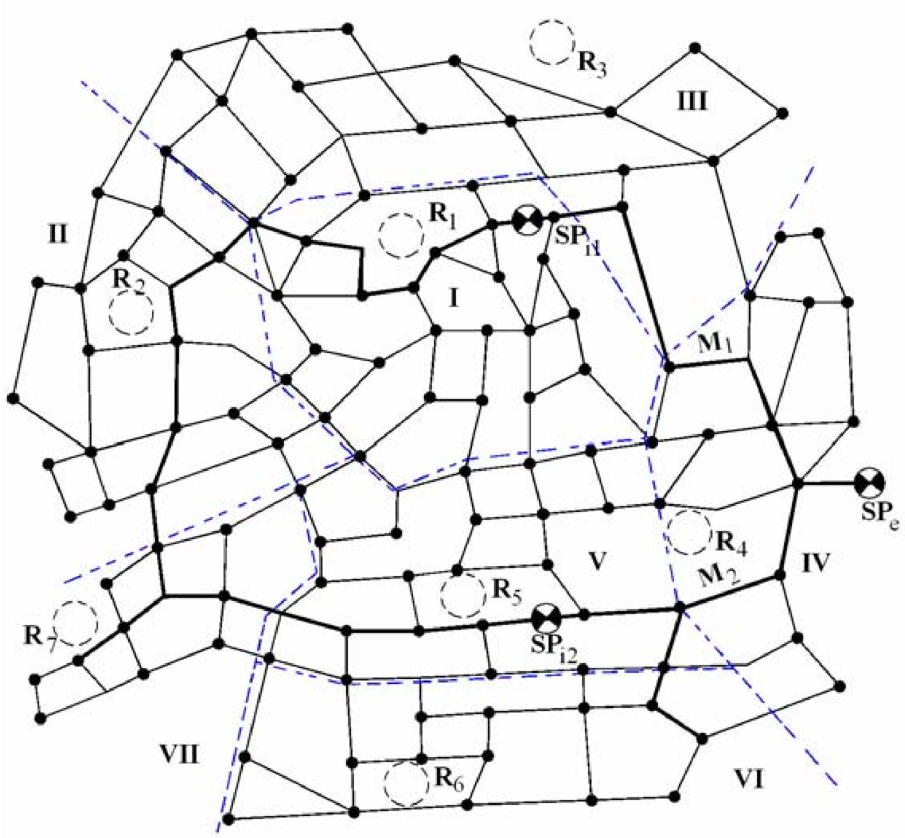

Fig. 4. Scheme of the analyzed distribution network

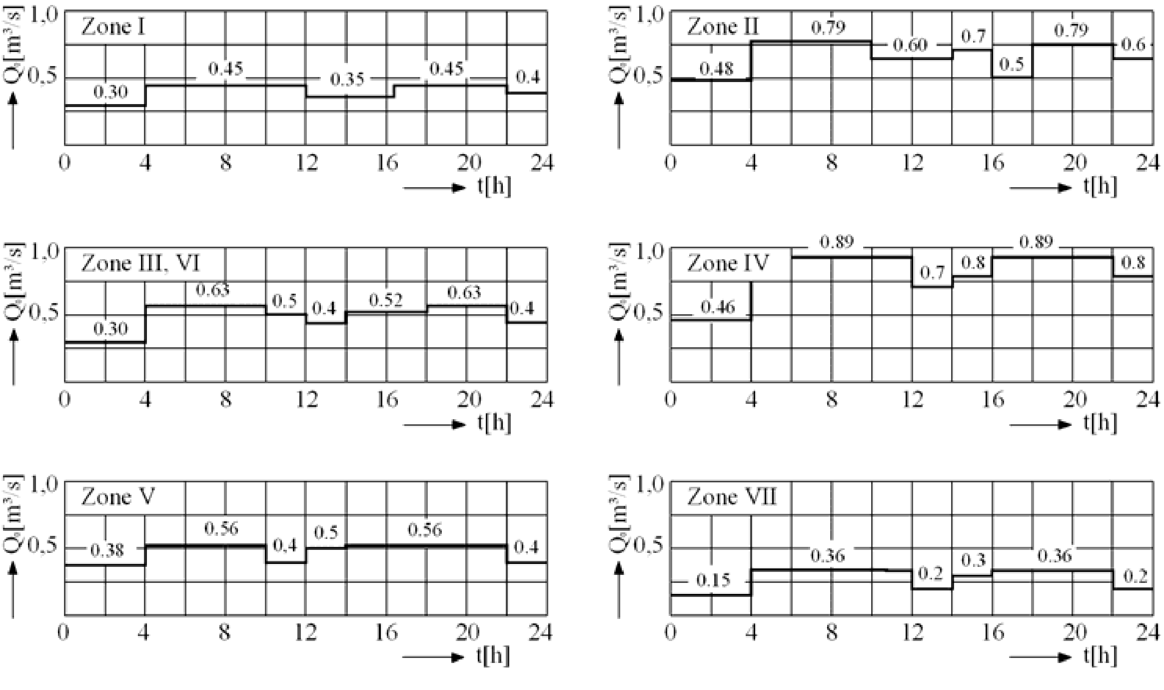

Fig. 6. Pumping graphic from zone reservoirs

Dimensioning of water supply network of zone reservoirs, computation of discharges and determination of pressures in network for analyzed solutions were made using computer programs DIOPREDA and ANOREC [10].

In Table 3 are reported numerical results of comparative economic-energetical study for analyzed optimization solutions.

Proposed optimized solutions provide corresponding technical solutions that have favorable indirect influence on line pressure stability.

Although economical efficiency is at the limit ($T_r = 10$ years), distribution with zone underground reservoirs has the important advantage of reducing energy consumption with 5300 MWh/year, from which 4600 MWh/year during peak hours.

Tab. 3. Economic-energetical indicators of optimized solutions

No.	Indicator	Solution			
		(a)	(b)	(c)	(d)
0	1	2	3	4	5
1	Supplementary investment, ΔI [thd. Ron]				
	– adduction pipes	–	5000	5000	–
	– reservoirs	–	630	2500	–
	– pump stations	–	210	–	250
	Total	–	5840	7500	250
2	Average pumping head, H_p [m]				
	– exterior pump station	60	15	49	40.5
	– interior pump stations	–	35	–	12
3	Consumed energy, W_e [MWh/year]				
	– exterior pump station	25300	6600	21600	19600
	– interior pump stations	–	13400	–	3600
	Total	25300	20000	21600	23200
	Peak	7300	2700	3400	5400
4	Operation expenses, C_w [thd. Ron/year]				
	– energy cost difference, ΔC_w	–	680	540	270
	– pay off coefficient, $p\Delta I$	–	110	150	5
	Different expenses, $\Delta C_w - p\Delta I$	–	570	390	265
5	Pay off time, T_r [years]	-	10	19	1
6	Energy economy, ΔW_e:	[MWh/y]	5300	3700	2100
		[%]	21	15	8

Solution of re pumping with intermediary stations asks for most cheap supplementary investments, but assures a small energy consumption only in hypothesis that service pipes are supplied from high pressure zone downstream integrated pump stations. If this condition is not realized from constructive reasons, pressure line must be raised with 9 m, to assure service pressure, so that energy consumption increases and solution looses its energetic efficiency, anyway smaller than that of solution with underground reservoirs.

In this conception it is considered that optimum solution is variant (b), with greatest electric energy economy, of 21 % compared with energy consumption in reference unzoned network and with convenient differential paying off time of 10 years.

6 Conclusions

Using interior potential elements in water distribution network generates better functioning conditions for the whole system, replaces expensive solution of doubling main pipes or increasing diameters of main pipes and leads always to reducing energy consumption of the system. Studies performed have confirmed favorable energetic-economical characteristics of the procedure of optimum location underground zone reservoirs in the network, equipped with interior pump stations, which leads to electric energy consumption diminishing with 20...30 % and provides possibility of chlorine step dosing for water disinfecting, accepting a smaller dose at plant tanks.

In case of distribution networks with water towers, usually it is not obtained an absolute reduction of electric energy consumption, it can be obtained even an increase of it, in spite of this, general energy cost is diminished because programming more intense pumping outside peak hours of energy consumption. Energy consumption in an absolute mode in case of high flat reservoirs of small water height demands these structures as rational solutions in water distribution technique. Water towers, as potential elements, besides assuring uniform distribution of discharges and pressures in network, it also contributes at shock diminishing from interior installation.

Procedure of intermediary pump station integration has the advantages of uniformization of pressure in case of large networks, avoiding zones with exaggerated high pressure. In change some low pressure zones appear at the beginning node of the main pipe on which re pumping station is located. This deficiency can be completely eliminated by connecting service pipes always uperstreams of pump.

Taking into consideration procedures and solution proposed for energetic optimization of water distribution systems in case of designing new systems as well as in case of those existing in operation, can lead to saving a significant quantity of pumping energy, which is of great importance, considering the general energy issues.

Notations

NP – number of exterior pump stations

NR – number of reservoirs (interior pump stations)

NA – number of main pipes with intermediary pump stations

$Q_{p,j}$, – pumped discharge of exterior pump station i

$Q_{pr,j}$ – pumped discharge through main pipe j

$Q_{pa,k}$ – pumped discharges of interior pump station k

Q_o – hour discharge

γ – water specific weight

η – efficiency of pump stations

$H_{pe,j}$ – maximum pumping head of the exterior pump station j(network supplyed by one-sided pumping from the exterior)

$H_{pi,k}$ – pumping head of the interior pump station k

$h_{pe,j}$ – pumping head of the exterior pump station j

P – total power of pump stations

ΔP – power reduction

T_o – operation period

ΔW_e – electric energy economy

P_e – exterior pump station power

P_i – interior pump station power

x – abscissa of computing section

$Q(x)$ – discharge of main pipe in computing section

$H(x)$ – head loss in computing section

$R_o(x)$ – specific hydraulic resistance of pipe in computing section

β – exponent of discharge, which has values between 1.85 and 2

H_n – necessary pressure limits

T_p – pumping time

W_e – electric consumed energy

W_{ee} – pumping energy in water supply network of zone reservoirs

W_{ei} – energy consumed to pump water from reservoirs into zone pipe networks

e_1, e_2 – estimated electric energy costs during peak hours and base hours respectively

ΔI – supplementary investment necessary in case of optimized system

C_e – annual operating expenses for reference system with the network supplied by one-sided pumping from the exterior

C_i – annual operating expenses for optimized system with interior potential elements

T_n – normal pay off time

ΔC_w – energy cost difference

T_r – pay off time

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