



Research article

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Optimization of the pipeline diameter of the water supply system

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Abstract. This study addresses the main pipeline of a water supply system. The paper reviews existing methods for determining the optimal pipeline diameter with the aim of minimizing both capital investment and operating costs. The aim of the study is to improve the method for calculating the optimal diameter by incorporating the dependence of electric motor power consumption on pump performance. The input data comprise the performance, energy and cost characteristics of centrifugal pumps; the physical and cost characteristics of high-pressure polyethylene (HPPE) pipes; and electricity tariffs. As in the conventional approach, the dependence of the cost and hydraulic losses of HPPE pipes on internal diameter is established. The proposed method introduces three substantive improvements. First, the performance and energy characteristics of pumps are approximated by second-order polynomials. Second, the pipeline inner diameter is determined such that the required flow rate is achieved at the operating point for each pump installed. Third, the hypothesis of constant efficiency is no longer required: power consumption is calculated directly from the corresponding dependence provided in the technical documentation. It is shown that efficiency changes significantly as the design flow rate or pipeline length increases. Under the conditions considered, efficiency decreases from 0.793 to 0.648 as the water flow rate rises from 60 to 80 m³/h. The influence of various factors on the optimal diameter of the main pipeline is examined. The optimal diameter decreases from 0.175 to 0.166 m as the pipeline length increases from 1000 to 9000 m. It increases with a longer project lifecycle and decreases with a higher interest rate.

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1. Introduction

Water is essential for meeting both present and future human needs. However, its uneven distribution in time and space remains the principal barrier to reliable access [1, 2]. The importance of water supply systems increases as infrastructure becomes more complex. Therefore, a substantial body of research has addressed the challenges of improving these systems. Given the breadth of this literature, no single article can cover it in full, and specialized reviews have consequently emerged in particular subfields. A review of publications on the issues of public water supply and water scarcity is presented in [3]. It is indicated that fresh water availability in certain regions is minimal – in some cases insufficient even to meet basic population needs. The need for sustainable and reliable water supply is emphasized. To do this, a revision of water management system is proposed, particularly in water-scarce regions. General recommendations and possible solutions are discussed, such as advanced technological interventions that enhance water-use efficiency, the use of unconventional water resources, and others.

Water supply networks are essential for delivering high-quality water in sufficient quantities to consumers. A water supply system comprises interconnected hydraulic components that ensure the supply

and distribution of water in accordance with demand. Optimization of water distribution networks is carried out in order to minimize resource use and costs or to enhance system efficiency and realize greater performance gains. Genetic algorithms (GA) are widely used to solve problems of nonlinear optimization in water supply systems.

In [5], a review of research on the optimization of water supply systems using GA methods is provided. These studies address the design of new water supply systems and the expansion, strengthening, and rehabilitation of existing infrastructure. A comprehensive analysis of all GA-based optimization studies spanning the period from the 1990s to 2021 is presented.

Determining pipe diameters is the simplest application of GA. A set of pipes is selected from commercially available standard sizes so as to minimize construction costs for a given network. Within the GA framework, the network structure is defined as a "chromosome", a binary or integer sequence of numbers. The first GA simulation program analyzes each investment project in terms of nodal load. The second GA simulation program analyzes the cost of construction. A reasonable choice of the objective (penalty) function enables GA to converge on an optimal solution.

GA and related methods are based on the classical problem of determining the optimal economical diameter of a simple (unbranched) pipeline [6–9]. This problem was first solved in [10]. An increase in the internal pipeline diameter d , on the one hand, raises construction cost through greater material consumption. On the other hand, a larger d reduces the hydraulic pressure loss in the pipeline, thereby lowering the operating cost of the pump motor. The capital cost of water supply is determined by the unit cost per pipe length:

$$C_{pipe} = B \cdot d^{\alpha} \cdot (1 + \omega) \cdot L, \quad (1)$$

where B , α are the empirical constants, the correction ω takes into account valve cost, fittings and pipeline installation.

The operating costs of C_{exp} are defined as the product of the power consumed by the pumping unit during operation and the cost of 1 kWh of electricity. The power required for pumping is the product of the volumetric flow rate (pump supply) and the pressure drop, divided by the efficiency of the pumping unit. In [10], the coefficient of hydraulic losses along the pipe length was adopted as for new steel pipes under turbulent flow (the resistance region of hydraulically smooth pipes). Total costs reduced to one year are given by:

$$C_c(d) = F \cdot C_{pipe} + C_{exp}, \quad (2)$$

where F is a coefficient that takes depreciation into account. Equating the derivative of the $C_c(d)$ function to zero yields the diameter d_0 at which this function reaches a minimum. The approach proposed in [10] proved highly fruitful: a large number of subsequent publications used and developed it.

Modern research considers various special cases or accounts for factors that were previously overlooked. Many applications of the method [10] to the calculation of specific water supply systems have been published. In [11], for instance, two special cases of economic optimization of pipe diameter under turbulent flow are considered: hydraulically smooth and rough pipes. Different optimal pipe diameters were obtained for flow rate of 20 l/s: 155 mm for rough pipes and 147 mm for smooth pipes.

The calculation of hydraulic losses in particular cases made it possible to simplify the Genereaux equation. Hydraulic losses in local resistances have been taken into account, but static pressure drop was not. The approach considered in [11] is therefore unsuitable when water must be raised to a certain height.

Capital recovery factor is used to calculate the amount of each level payment to be made at the end of each k period, to recover the present amount at the end of the period, at a predetermined interest rate of r [12]. The factor is computed as follows:

$$F = r \cdot (1 + r)^k / \left[(1 + r)^k - 1 \right]. \quad (3)$$

A significant part of [12] focuses on the analysis of the dependence of pipe cost on diameter and on determining the empirical constants B and α in (1). Costs for pipes of various materials (two types of reinforced cement concrete, galvanized iron, and three types of polyvinyl chloride) with a diameter from 40 to 160 mm are curved. The index of α degree ranged from 0.61 to 1.53. In some of the graphs shown, the

number of points is small and their scatter is large (e.g., PVC Grey Plain). This scatter is likely due to the fact that the author used price lists from various retail stores. Therefore, the representativeness of the sample is questionable. The solution of the set mathematical problem is postponed. Subsequently, the application of the Generaux method in combination with (3) to determine the economic diameter of the pipeline became known as Life-Cycle Cost Analysis (LCCA).

In [13], twenty different sections of a water pipeline in four regions of Brazil were considered, with length ranging from 533 to 45000 m and flow rate from 0.558 to 800 l/s. The material of the pipes is high-pressure polyethylene (HPPE). The calculated optimal diameters of d_0 ranged from 50 to 1000 mm across various sections. The authors compare three methods for calculating d_0 . In fact, only one LCCA method was used (with accepted values of $r = 0.12$ and $k = 20$), but with two models for pipe cost:

- 1) the linear dependence of pipe cost on its weight;
- 2) the linear dependence of pipe cost on inner diameter.

The results obtained made it possible to determine the values of the empirical coefficient K_1 in the approximate Bresse formula:

$$d_0 = K_1 \cdot Q^{0.5}. \quad (4)$$

Values of K_1 ranging from 0.6 to 1.7 were selected for different sections of the water pipeline. Clearly, this approach is untenable, since the value of K_1 depends on a large number of factors.

In [14], an optimized selection of pipe diameter for a farm at Hamelmalo Agricultural College (HAC) in the Anseba Region of Eritrea was presented. The LCCA method was used to formulate the problem, and the head loss gradient method was employed to solve it. Another attempt to apply an approximate formula was made to determine the optimal pipeline diameter. In particular, Smith's empirical formula was used:

$$d_0 = K_2 \cdot Q^{0.37}, \quad (5)$$

where d_0 is the pipe diameter, mm; Q is the system discharge, m³/h. The value of K_2 is selected from a dedicated table. It can vary from 25 to 34 depending on the operating time of the pumping unit T (h/y) and friction losses. The value of T affects the annual cost of electricity. The annual pumping time was assumed to be 2920 hours, and K_2 was determined to be 27.92 based on the analysis of hydraulic losses. It is clear that (5) is suitable only for preliminary, approximate estimates.

In [15], the results of calculated values of d_0 under different flow regimes are compared: laminar, transient, and turbulent. The calculations were implemented using media of different viscosities. The volumetric flow rates Q were 0.111, 0.167 and 1.667 m³/s, respectively. The pipeline length in all cases was the same $L = 4000$ m. Depreciation charges were 18 rubles per meter of pipeline length and per meter of diameter per year; the electricity tariff was 3 rubles per kWh. The calculated pipe diameters were 0.311, 0.392, 0.419 m, respectively. Therefore, with high viscosity of the pumped liquid, energy costs increase substantially.

The LCCA method was used in [16] to calculate the optimal diameter of the pipeline network on another farm located in the Anseba Region of Eritrea. The results for d_0 were compared with those obtained using 11 approximate formulas from different authors, including (4) and (5). This comparison was based on calculated total pressure losses and an economic analysis of the pipe diameters of the network in question. The authors claim that the Bresse formula proved the most adequate compared with the LCCA model.

The number of publications using specialized software in the field is increasing [17–19]. The WaterGEMS program is used in [17] to optimize the water supply system of Wukro Town in Ethiopia. Neural networks are used in [18] to determine the inner diameter of a drinking water supply system. These programs rely on the same LCCA method. However, specialized programs are not always used correctly.

In [19], the optimal pipe diameter for transporting treated water in Karbala in Iraq using WaterCAD V8i software is determined. WaterCAD is used for designing and analyzing the operation of a water supply network. Options with four pipe materials (ductile iron, GRIP, concrete, and plastic) with diameters from 0.8 to 2.0 m are compared. Operating costs for pipes of different diameters and materials were given. GRP

pipes had the highest operating costs. They are more than twice higher than those of concrete pipes. This is clearly an error. Operating costs are calculated based on electricity costs. The cost of electricity depends on the hydraulic losses along the pipeline. But GRP pipes have noticeably lower hydraulic losses than concrete pipes. The opposite was found in [19].

These works do not take into account that a decrease in diameter and an increase in hydraulic losses will require a more powerful pump. This means that the cost of the pump depends on the diameter. Moreover, this dependence is inverse. In [15], it was noted that the required pump power depends on the diameter. In particular, for fully developed turbulent flow in the pipeline, the required pump power depends inversely on d^5 . However, this fact is not taken into account in the costs.

It was proposed to take into account not only the dependence of pipeline cost on the diameter, but also the cost of pumping station on the required capacity in the investment costs [20]:

$$C_{pump} = F \cdot N \cdot p_0, \quad (6)$$

where p_0 is the cost of one installed kW pump at its actual capacity N . It was proposed to calculate N as hydraulic power divided by efficiency ($\eta = 0.77$). In [20], the speed of water movement through pipes (0.8 m/s) is recorded instead of flow rate. The examples given have not been brought to a decision. The analysis of (1) has been performed. The dependence of p_0 on d is not defined in (6). Optimal diameters have not been found.

A similar approach was used in [21]. It was noticed that the cost of a polyethylene pipeline is directly proportional to its weight. The mass was calculated using the formula:

$$M_1 = \pi \cdot d^2 \cdot L \cdot \rho_{PE} \cdot (SDR - 1) / SDR^2, \quad C_{pipe} = p_1 \cdot M_1, \quad (7)$$

where SDR is the ratio of the inner diameter of the pipe d to its wall thickness s ; ρ_{PE} is the density of polyethylene; p_1 is the cost of 1 kg of HPPE. It is important that plastic pipes are selected from a line with the same ability to withstand a given pressure PN , which is determined by the SDR value.

In [21], in order to evaluate investment projects of water supply systems, in addition to discounting (interest rate) according to (2), it was proposed to take inflation into account. But the method of accounting for inflation expectations is not yet generally accepted, unlike (2). The hypothesis about the connection between the pipeline diameter and the capacity of the pumping station has been put forward:

$$d^2 = \xi_1 \cdot \ln(N) + \xi_0, \quad (8)$$

where ξ_0 , ξ_1 are the empirical constants of the regression dependence. They should be selected when processing the results of multivariate hydraulic modeling for each water supply network. There are no specific examples and no solution to the problem in [21].

The approach proposed in [20] was brought to its logical conclusion in [22, 23]. It was found that the dependence of pump cost on pump power is close to a linear. In [22], the power in this function was additionally multiplied by the ratio D_{suc}/D_{dis} (the ratio of suction diameter to discharge diameter). The cost per pipe unit length, directly proportional to its volume V , was taken from price lists.

It is known that the volume of a cylindrical pipe can be found by the formula:

$$V = 0.25 \cdot L \cdot \pi \cdot (s^2 + 2 \cdot s \cdot t), \quad (9)$$

where t is the wall thickness of the pipe. But in [22], a formula like (9) does not contain a multiplier of 2 before the second term. Therefore, the calculation results cannot be considered reliable.

The approach proposed in [23] formally differs from the one in [20, 22], it is called "a new concept for the economic pipeline design". In fact, it was a transition from the independent variable d to the "economic design velocity" variable W according to the formula:

$$d = 2 \cdot Q / (\pi W)^{0.5}. \quad (10)$$

Using the example of a simple pipeline, a mathematical model was presented that allows relating various types of annual costs to W . The relationship between the design velocity and various pipeline parameters was presented. The influence of the pipeline length, static pressure, discount coefficient, and flow rate on the value of W was shown. Three different markets were considered in order to estimate the annual cost of the various pipeline components: those of Lebanon, the USA and India. Two different types of pipe materials were considered: ductile iron pipes and low-pressure polyethylene. The economic velocities for low-pressure polyethylene were 1.75 m/s, 1.00 m/s and 1.95 m/s for Lebanon, the USA and India, respectively. This approach is unlikely to hold much promise for design purposes. Apparently recognizing this, the authors of [23] calculated the values of d using W at the end of their article.

It is known that the power consumed by an electric pump unit N can be found by dividing the hydraulic power N_G by the efficiency η :

$$N = N_G / \eta, \quad N_G = \rho g Q H, \quad \eta = \eta_P \cdot \eta_E, \quad (11)$$

where ρ is the density of water, kg/m³; g is the acceleration of gravity, m/s²; H is the pump head, m; η_P is the efficiency of the pump; η_E is the efficiency of the electric motor.

All the articles listed above use (11). A common disadvantage of these articles is the assumption that efficiency can be considered constant ($\eta = \text{const}$). In fact, efficiency depends on the design and power of the pump. Efficiency is a function of flow rate for a particular pump.

A method for calculating the optimal diameter of the pipeline using the pump performance characteristics was proposed in [24]. This made it possible to take into account the change in efficiency when switching to a different pipeline diameter. In addition, it was shown that the mass and cost of HPPE pipes should be calculated not according to (7), but according to the following formula:

$$M_1 = 0.25\pi \cdot d^2 \cdot L \cdot \rho_{PE} \cdot \left[SDR^2 / (SDR - 2)^2 - 1 \right]; \quad (12)$$

$$C_{pipe} = M_0 \cdot p_1 \cdot L \cdot d^2, \quad M_0 = 0.25\pi \cdot \left[SDR^2 / (SDR - 2)^2 - 1 \right] \cdot \rho_{PE}. \quad (13)$$

The use of the dependence of the consumed power N_P of the CNS-38 sectional pumps on the flow rate required additional recalculation to account for changes in the efficiency of the electric motor. Currently, many pump manufacturers include in the technical documentation not only the dependence of N_P (often denoted as $P2$) on Q , but also the dependence of the consumed power of the electric motor $N = N_P / \eta_E$ ($P1$). This makes it possible to improve the calculation method proposed in [24].

The aim of this article is to improve the method of calculating the optimal diameter d_0 of the pipeline of a water supply system using the energy characteristics of an electric pump unit (accounting for changes in efficiency).

The tasks to be solved are as follows:

- 1) development of an improved method for calculating the optimal diameter d_0 ;
- 2) verification of the significance of the change in efficiency at the operating point of the pumping unit when calculating d_0 ;
- 3) investigation of the influence of various factors on d_0 .

2. Materials and Methods

In addition to the water flow rate Q_0 , the pipeline length L , the static head H_C , and the pipeline material HPPE, the cost of a pipe unit length, the cost and performance characteristics of pumps must be determined.

The investment and operating costs of the pipeline of the water supply system are presented in [22–24]:

$$C = F \cdot C_K + C_E = F \cdot (C_{B0} + \psi(d)) + (C_{E0} + \varphi(d)), \quad (14)$$

where $F \cdot C_K$ is the investment cost with discount; C_{K0} is a part of investment cost that does not depend on the pipeline diameter; C_E is annual operating cost; C_{E0} is a part of operating cost that does not depend on the pipeline diameter.

To find the optimal pipeline diameter, we equate the derivative (14) to zero:

$$C = F \cdot \psi'(d) + \varphi'(d) = 0. \quad (15)$$

In order to find $\varphi'(d)$, the operating costs, depending on the pipeline diameter, are calculated using the following formula:

$$\varphi(d) = z \cdot A_E = N_E \cdot T_0 \cdot Y, \quad (16)$$

where z is the cost of electricity, \$/kWh; A_E is the work of the pump's electric motor per year, kWh; T_0 is the pump's operating time per day, h; N_E is the power consumed by the electric motor, kW; Y is the number of days per year.

The consumed power of the electric motor was calculated using (11) in previous publications. One of the important improvements of the calculation method is that the value of N_E in this article is calculated based on the energy characteristics of the pumps used. Here we will use the performance characteristics of a line of vertical multistage pumps CR-64¹. An example of the characteristics is shown in Fig. 1.

The dependence of the head H_{CR} and the electric motor consumed power N_E on the flow rate Q can be approximated by second-order polynomials:

$$H_{CR} = H_0 + a_1 \cdot Q + a_2 \cdot Q^2, \quad N_E = N_0 + b_1 \cdot Q + b_2 \cdot Q^2, \quad (17)$$

where H_0 , a_1 , a_2 , N_0 , b_1 , b_2 are the empirical coefficients that are determined by the least squares method based on experimental data for each pump. For example, their values for CR-64-4 are shown in Fig. 1: $H_0 = 118.3$ m, $a_1 = 0.1663$ m/(dm³/s), $a_2 = -0.0918$ m/(dm³/s)², $N_0 = 12.04$ kW, $b_1 = 0.6904$ kW/(dm³/s), $b_2 = -0.00827$ kW/(dm³/s)².

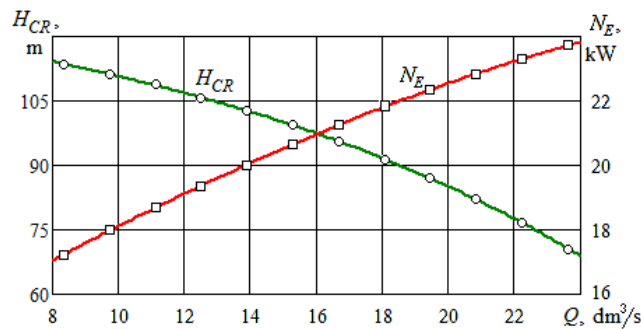


Figure. 1. Dependence of the CR-64-4 head and the electric motor consumed power on the flow rate. Points are experimental data²; lines are calculations using (17).

The characteristics of the pipeline will be calculated as in [22–24]:

$$H_{Pl} = H_C + (\lambda \cdot L/d + \zeta) \cdot W^2 / (2g) = H_C + (\lambda \cdot L/d + \zeta) \cdot 8Q^2 / (\pi^2 d^5 g), \quad (18)$$

¹ EuroWater. A Grundfos Company. Vertical multistage centrifugal pumps CR, CRN, CRT [Online]. URL: <https://product-selection.grundfos.com/products/cr-cre-cri-crie-crn-crne-crt-crte/cr?tab=models> (reference date: 15.07.2024).

² EuroWater. A Grundfos Company. Vertical multistage centrifugal pumps CR, CRN, CRT [Online]. URL: <https://product-selection.grundfos.com/products/cr-cre-cri-crie-crn-crne-crt-crte/cr?tab=models> (reference date: 15.07.2024).

where H_C is the static head, m; L is the length of the pipeline, m; λ is the coefficient of hydraulic friction losses along the length of the pipeline; ζ is the total coefficient of head losses in local resistances; W is the velocity of water in the pipeline, m/s.

The coefficient of hydraulic friction losses will be calculated using Altschul formula:

$$\lambda = 0.11 \cdot (\Delta/d + 68/\text{Re})^{0.25} = 0.11 \cdot (\delta + 17\pi \cdot \nu \cdot d/Q)^{0.25}, \quad (19)$$

where $\text{Re} = W \cdot d/\nu$ is the Reynolds number; ν is the coefficient of kinematic viscosity of water, m²/s; $\delta = \Delta/d$ is the ratio of the absolute roughness of the pipe wall to the inner diameter. The analysis of experimental data in [24, 25] allowed for obtaining the dependence of this ratio on the diameter. For pipes of small and medium diameter (up to 340 mm) of Russian production, the $d - \Delta$ relationship is well approximated by a linear relationship: $\Delta = 8.09 \cdot 10^{-5} \cdot d$. This means that in the specified range, the relative roughness of small and medium HPPE can be considered constant $\delta_0 \approx 8.09 \cdot 10^{-5}$.

An accurate calculation is not possible in extended pipeline. Instead, we increase λ by 10 %, as in previous works. Then substituting (19) into (18), we get the function:

$$H_{PL} \equiv f(d, Q) = H_C + 0.968 \cdot (\delta + 17\pi \cdot \nu \cdot d/Q)^{0.25} \cdot L \cdot Q^2 / (\pi^2 d^5 g). \quad (20)$$

Next, for each pump of the CR-64 line, we will find the diameter of the pipeline d_1 , at which the flow rate will be equal to the set value Q_0 (at the operating point of the pumping unit). These values are determined from the equation:

$$f(d_1, Q_0) = H_0 + a_1 \cdot Q_0 + a_2 \cdot Q_0^2. \quad (21)$$

The pump head of the CR-64 H_{WP} line and the electric motor expended power N_{WP} at the operating point can be calculated by substituting Q_0 into (17).

Let us next find an approximation of the dependence of the consumed power on the values found:

$$N_{WP} \equiv U(d) = u_0 + u_1/d^\beta, \quad (22)$$

where u_0 , u_1 , β are the empirical constants determined by the least squares method for the pipeline and pump line.

Let us substitute (22) into (16) and differentiate:

$$\phi'(d) = U'(d) \cdot z \cdot T_0 \cdot Y = -\beta \cdot u_1/d^{\beta+1} \cdot z \cdot T_0 \cdot Y. \quad (23)$$

The cost of electricity z does not remain constant over time. It may vary markedly in different countries and regions. Here we will use the tariff values of Rusenergosbyt LLC for Russian regions in January 2024 for consumers of the first price category (power consumption up to 670 kW, voltage up to 0.4 kV)³. $z = 0.04776$ \$/(kW·h) in the Irkutsk region, $z = 0.07794$ \$/(kW·h) in the Kostroma region, $z = 0.1158$ \$/(kW·h) in the Leningrad region.

Let us find the first term in (15). The discount coefficient will be calculated using (3). We will find the cost of polyethylene pipes using (11). For certainty, we will take the cost of a unit of HPPE mass from the price list⁴ (from the 13th of July 2024) $p_1 = 2.1$ \$.kg.

CR-64 pumps with different number of sections at maximum efficiency have the same nominal capacity (64 m³/h), but different nominal head HN . It is necessary to install a pump with a high HN value while reducing the diameter of the pipeline. This, however, leads to an increase in investment costs. The

³ Tarify na elektroenergiyu dlya malyh predpriyatij [Electricity rates for small enterprises] [Online]. URL: <https://time2save.ru/tarify-na-elektroenergiu-dla-malih-predpriyatii-i-ip> (reference date: 23.02.2024).

⁴ Gruppa kompanij Prombaza. Prajs-listy. [Prombaza Group of Companies. Price lists] [Online]. URL: <http://www.prombase.ru/prices> (reference date: 20.07.2024).

cost of CP pumps of the CR-64 line was taken from the price list⁵. Some of the source data are presented in Table 1. The number of impellers is indicated in the pump model designation after the number 64. If another digit follows, this indicates the number of impellers of reduced size. Note that in some cases reducing the impellers does not affect the cost of the pump: for example, CR-64-4 and CR-64-4-1 cost the same.

Table 1. Price list⁴ of CR-64 pumps with calculated pipeline diameters, head and power consumption ($L = 3000$ m, $H_C = 40$ m).

No.	Model	CP , \$	d_1 , m	H_{WP} , m	N_{WP} , kW
1	CR-64-2	7772.9	0.264	43.4	11.6
2	CR-64-3-2	8796.2	0.213	45.5	14.0
3	CR-64-3-1	8796.2	0.170	53.5	15.7
4	CR-64-3	10110.7	0.152	63.4	17.4
5	CR-64-4-2	10589.4	0.147	67.2	19.8
6	CR-64-4-1	11758.0	0.139	75.9	21.5
7	CR-64-4	11758.0	0.133	84.9	23.2
8	CR-64-5	12544.0	0.122	106.3	29.0
9	CR-64-6	15339.3	0.115	127.9	34.8

An approximation of the dependence of the pump cost CP on the electric motor consumed power N_{WP} (at the operating point) is necessary for calculating $CP = \Phi(N_{WP})$. This dependence turned out to be linear, as in [22, 23]: $\Phi'(N_{WP}) = \Phi_1 = \text{const}$. Then the first term in (15) can be expressed as follows:

$$F \cdot \psi'(d) = F \cdot \left(2 \cdot M_0 \cdot p_1 \cdot L \cdot d - \Phi_1 \cdot \beta \cdot u_1 / d^{\beta+1} \right). \quad (24)$$

Let us substitute (23), (24) into (15) and obtain the equations for determining the optimal diameter:

$$F \cdot \left(2 \cdot M_0 \cdot p_1 \cdot L \cdot d - \Phi_1 \cdot \beta \cdot u_1 / d^{\beta+1} \right) - \beta \cdot u_1 / d^{\beta+1} \cdot z \cdot T_0 \cdot Y = 0. \quad (25)$$

The algebraic equation (25) was solved numerically for different parameter values.

The efficiency at the working point of the pumping unit will be calculated using the following formula:

$$\eta = \rho \cdot g \cdot Q_0 \cdot H_{WP} / N_{WP}. \quad (26)$$

3. Results and Discussion

The power used and the pump pressure at the operating point depend on the pipeline parameters. Table 1 (column 4) shows the results of calculating such a diameter so the flow rate at the operating point is equal to the specified Q_0 . The calculation was performed using the following parameters: $Q_0 = 72$ m³/h (20 dm³/s), $H_C = 40$ m, $L = 3000$ m. Moreover, H_C includes necessary free head from the consumer. The pump head and the expended electric motor power at the operating point of the corresponding pumping unit are placed in the last two columns of Table 1.

A graphical interpretation of the examples of determining the operating point of three pumping units from Table 1 with the specified pipeline parameters is shown in Fig. 2. According to it, in order to ensure the flow rate of Q_0 at $d = 0.122$ m, it is necessary to install the CR-64-5 pump (the upper point in Fig. 2). At $d = 0.152$ m, it is enough to install CR-64-3 pump (the lower point). The latter is noticeably cheaper.

⁵ Kompaniya MNK-Plyus. Vertikal'nye mnogostupenchatye centrobezhnye nasosy [MNK PLUS Co. Vertical multistage centrifugal pumps] [Online]. URL: <https://mnk-plus.ru/katalog-tovarov/nasosy/nasosy-vertikalnye-mnogostupenchatye/> (reference date: 09.07.2024).

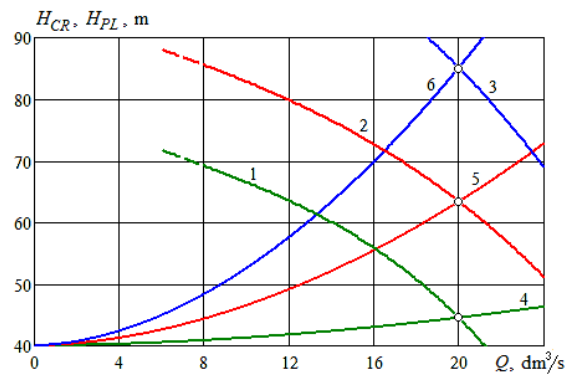


Figure 2. Examples of determining the operating point of pumping units at $Q_0 = 72 \text{ m}^3/\text{h}$, $L = 3000 \text{ m}$, $H_C = 40 \text{ m}$: 1) CR-64-3, 2) CR-64-4, 3) CR-64-5; 4) characteristic of the pipeline with $d_1 = 0.152 \text{ m}$, 5) $d_1 = 0.133 \text{ m}$, 6) $d_1 = 0.122 \text{ m}$.

The data of their price list⁶ and the approximation of the dependence of the cost CR-64 pumps on the electric motor consumed power at the operating point are shown in Fig. 3. The linear function is in good agreement with the points. The determination index, adjusted due to the small number of points, is 0.95. In this case, $\Phi'(N_{WP}) = \Phi_1 = 309.21 \text{ \$/kW}$.

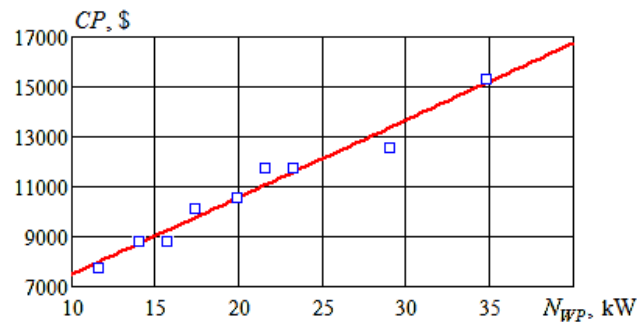


Figure 3. Relationship between the cost of CR-64 pumps and the electric motor consumed power at the operating point.

Fig. 4 shows that the calculation results according to (22) are in good agreement with the experimental points. The empirical constants in this case are $u_0 = 11.1$, $u_1 = 0.00274$, $\beta = 4.239$. The adjusted index of determination is 0.986.

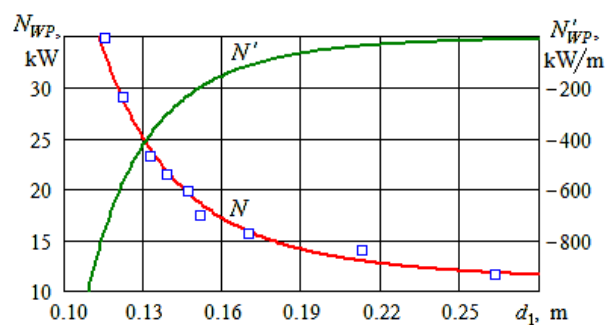


Figure 4. Dependence of the electric motor consumed power (N_{WP}) at the operating point and the derivative (N_{WP}') of CR-64 units on the pipeline diameter. Points are experimental data; lines are calculations using (22).

The results of (25) solved by numerical method for various parameter values are presented in Tables 2–4 and in Figs. 5 and 6: $k = 30$, $r = 0.12$, discount coefficient $F = 0.124$, $z = 0.07794 \text{ \$/kWh}$.

⁶ Kompaniya MNK-Plyus. Vertikal'nye mnogostupenchatye centrobezhnye nasosy [MNK PLUS Co. Vertical multistage centrifugal pumps] [Online]. URL: <https://mnk-plus.ru/katalog-tovarov/nasosy/nasosy-vertikalnye-mnogostupenchatye/> (reference date: 09.07.2024).

The efficiency decreases from 0.793 to 0.648 with an increase in water consumption Q_0 from 60 to 80 m³/h according to Table 2. Efficiency $\eta = 0.692$ at $L = 1000$ m, $\eta = 0.753$ when increasing the length of the pipeline to 9000 m according to Table 3. Efficiency $\eta = 0.637$ at $H_C = 10$ m, $\eta = 0.753$ with an increase in static head to 40 m according to Table 4. The efficiency changes very significantly. The change in efficiency is less significant (Figs. 5 and 6). Therefore, $\eta = 0.754$ at $T_0 = 4$ h, $\eta = 0.720$ at $T_0 = 24$ h (Fig. 5, line 1, $SDR = 21$), $\eta = 0.742$ at $T_0 = 4$ h, $\eta = 0.737$ at $T_0 = 24$ h (Fig. 5, line 3, $SDR = 13.6$). In Fig. 6, the efficiency increases from 0.731 to 0.755 with an increase in r from 0.05 to 0.3 (line 2, the project lifecycle is 15 years). At a constant value of $r = 0.1$, if $k = 15$ years, then $\eta = 0.740$; if $k = 30$ years, then $\eta = 0.734$.

Table 2. Effect of Q_0 on the optimal diameter and efficiency, $L = 3000$ m, $H_C = 30$ m, $T_0 = 12$ h.

Q_0 , m ³ /h	d_0	H_{wp} , m	N_{wp} , kW	η
60	0.147	47.1	11.6	0.793
64	0.151	48.2	12.5	0.758
68	0.154	49.6	13.4	0.725
72	0.157	51.3	14.4	0.695
76	0.160	53.5	15.7	0.669
80	0.162	56.1	16.9	0.648

Table 3. Effect of L on the optimal diameter and efficiency, $Q_0 = 68$ m³/h, $H_C = 30$ m, $T_0 = 24$ h.

L , m	d_0	H_{wp} , m	N_{wp} , kW	η
1000	0.175	31.9	9.0	0.692
2000	0.172	32.2	10.2	0.694
3000	0.170	41.2	11.4	0.707
6000	0.167	57.2	15.2	0.739
9000	0.166	71.9	18.7	0.753

Table 4. Effect of H_C on the optimal diameter and efficiency, $Q_0 = 68$ m³/h, $L = 3000$ m, $T_0 = 24$ h.

H_C , m	d_0	H_{wp} , m	N_{wp} , kW	η
10	0.155	26.5	8.1	0.637
20	0.154	37.8	10.8	0.688
30	0.154	49.6	13.4	0.725
40	0.153	62.8	16.2	0.757

Tables 2–4 and Figs. 5 and 6 allow for analyzing the influence of various factors on the value of the optimal pipeline diameter. An increase in water consumption Q_0 from 60 to 80 m³/h led to an increase in d_0 from 0.147 to 0.162 m (Table 2). A similar qualitative result was obtained in [13, 14] and other studies. But the quantitative results in this article differ markedly due to accounting for changes in efficiency. The optimal diameter decreased from 0.175 to 0.166 m with an increase in the pipeline length from 1000 to 9000 m (Table 3). A similar qualitative result was obtained, for example, in [13].

The change in static pressure merely affect the value of the optimal diameter in the studied range of parameters (Table 4). At the same time, the pressure and power consumption at the operating point increased noticeably. This leads to an increase in the cost of the water supply system. The same result was obtained in [22].

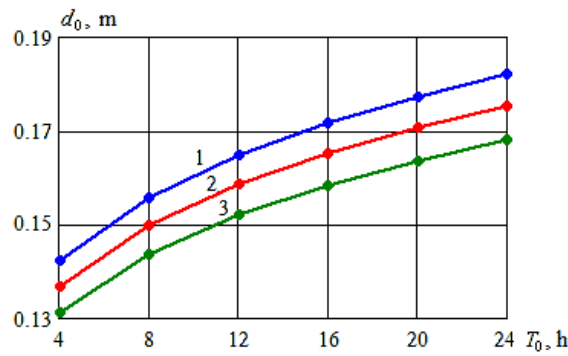


Figure 5. Dependence of the optimal diameter on T_0 at $Q_0 = 68 \text{ m}^3/\text{h}$, $L = 6000 \text{ m}$, $H_C = 30 \text{ m}$, $k = 30$, $r = 0.08$ and various SDR values: 1) 21 (8 bar), 2) 17 (10 bar), 3) 13.6 (12.5 bar).

The optimal diameter of the pipeline increases markedly with increasing T_0 according to Fig. 5. An increase in SDR entails an increase in the cost of HPPE pipes. Therefore, lines 1–3 are reduced. The optimal diameter decreases with an increase in the discount rate r , but increases with an increase in k (Fig. 6). However, the last increase will be noticeable only at small values of r .

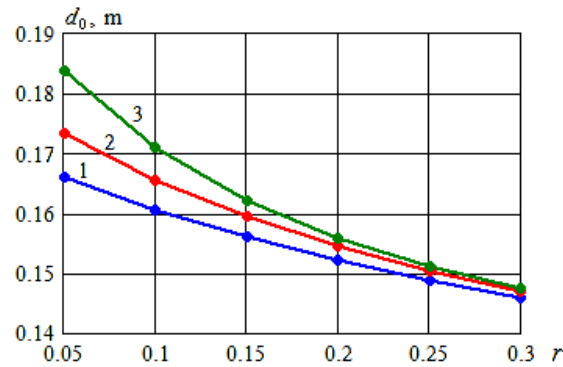


Figure 6. Dependence of the optimal diameter on the discount rate at $Q_0 = 68 \text{ m}^3/\text{h}$, $L = 6000 \text{ m}$, $H_C = 30 \text{ m}$ and various project lifecycles: 1) $k = 10$, 2) $k = 15$, 3) $k = 30$.

4. Conclusions

Thus, the study improved the method for calculating the optimal diameter d_0 of the pipeline of the water supply system using the energy characteristics of the electric pump unit. The main stages of the improved calculation method are as follows:

1. Approximation of head and energy characteristics for specific series of pumps using (17). It is mandatory to use the dependence of the electric motor consumed power P_1 on Q .
2. Formulation of the characteristics of the pipeline as a function of the diameter and the specified flow rate (20).
3. Determination of the values of the inner diameter d_1 at a given flow rate Q_0 at the operating point when installing each of the pumps.
4. Determination of the dependence of the pipe unit length cost on the internal diameter C_{pipe} using (13) and calculation of its derivative.
5. Determination of the pump cost function $CP(d)$, accounting for the power required for each calculated diameter, and calculation of its derivative $CP'(d)$.
6. Determination of the operating cost function and its derivative $\phi'(d)$ using (23).
7. Specification of the discount rate r and project lifecycle k using (25), and determination of d_0 .

The developed method can be used for design calculations of water supply systems. However, this requires additional steps:

8. Selection of commercially available pumps and standard pipe sizes that most closely match the values obtained in the previous stage.
9. Determination of the lower cost of the water supply system from the selected set of parameters.

Verification revealed a significant change in the pump unit's efficiency within its operating range during the calculation of d_0 . Thus, the efficiency decreases from 0.793 to 0.648 with an increase in water consumption Q_0 from 60 to 80 m³/h under the conditions considered. The efficiency increases from $\eta = 0.692$ at $L = 1000$ m to $\eta = 0.753$ at $L = 9000$ m. Increasing the static head H_C from 10 to 40 m resulted in an efficiency increase from $\eta = 0.637$ to $\eta = 0.753$. Allowing for constant efficiency may lead to variations in the error margin when selecting the pipeline diameter.

The study on the influence of various factors on the value of d_0 was performed. Increasing water consumption Q_0 from 60 to 80 m³/h resulted in an increase in d_0 from 0.147 to 0.162 m. The optimal diameter decreased from 0.175 to 0.166 m with an increase in the length of the pipeline from 1000 to 9000 m. The optimal diameter increases with a longer project lifecycle and shifts in response to rising interest rates.

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