Hydraulically most advantageous pipe diameters for supplying water to reclaimed land

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Abstract. Recently, some countries have been using treated wastewater to irrigate crops. In the administrative district of Kerbela, they also decided to borrow the experience of these countries, but on the condition that the treated wastewater would be environmentally safe in terms of sanitary and hygienic terms. It is necessary to comply with the requirements for the quality of water for irrigation of crops, and also not cause damage to the environment, soil and plants. From the treatment facilities of Kerbela 1000000 m^3/day (1.16 m^3/s) of water are formed, but the project provides for an increase to 400000 m^3/day (4.63 m^3/s) therefore, the selection of the diameter of the pipes for supplying water to the irrigation fields is provided for two flow rates. For preliminary calculation, the WaterCAD V8i simulation model was used, with the help of which the optimal pipe diameter and hydraulic characteristics of the flow were selected. Based on the results of the model, the optimal dimensions of the pipe diameter, modes of fluid movement and head loss are determined. The choice of pipe material was made from four types (ductile iron, GRP, concrete and plastic). The novelty of the work lies in the fact that for the first time a main scheme is being laid for transporting treated wastewater in this region and the hydraulic characteristics of water movement are being studied.

1 Introduction

One of the main tasks of the agricultural water supply system is to provide the necessary amount of water for irrigating crops [14]. In recent years, various software packages, simulation and mathematical models have been used to design water supply systems [2, 5, 9, 10]. With their help, it is possible to make hydraulic calculations of the flow in pipes, select the optimal pipe diameter, determine the velocity of water movement at certain flow rates, etc., [1, 3, 6, 11, 13].

The purpose of this article is to determine the optimal pipe diameter for the main network transporting treated wastewater in the city of Kerbala (Iraq) using software WaterCAD V8i. To achieve the goal, it is necessary to solve the following tasks:

1) Layout a tracing scheme for water supply through pipelines laid underground;
2) Choose the optimal diameter and material of pipelines;

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3) Ensure uninterrupted supply of treated wastewater.

The method of transporting water through an open canal was disadvantageous due to the climatic conditions of the region, because a significant part of the water was lost by evaporation. When transporting water through pipes, we considered two options:

1) At a flow rate =1.16 m3/s, pipe diameters from 800 to 1200 mm,

2) At a flow rate =4.63 m3/s, pipe diameters from 1600 to 2000 mm. At present, treated wastewater is discharged from the old treatment facilities with a flow rate of 1.16 m3/s. New wastewater treatment plants are being built in the city, which will discharge treated wastewater at a rate of 4.63m3/s. Then the water consumption from new and old wastewater treatment plants together will be 5.79m3/s. In this regard, our options include the existing and projected costs of discharging treated wastewater.

The WaterCAD software that we use in this article is designed to design and analyze the operation of a water supply network. This software product provides the choice of optimal operating conditions for the piping system when designing in normal and emergency situations. The WaterCAD software algorithm is based on the gradient method. WaterCAD software offers optimal solutions regardless of the type of network, i.e. the network can be branched, closed, or a combination of branched and closed [7, 12]. In [11], the goal of the authors is to optimize the designed water distribution system in the city of Voukro using the WaterGEMS model. Darwin Designer at WaterGEMS was used to find the optimal pipe diameter to deliver the required amount of water at a satisfactory pressure to end users. The results showed that the maximum pressure before optimization was 31.1 m and after optimization it was 38.1 m. The minimum pressure is 7.9 m and during peak load reaches 16 m. The results of this study showed that the WaterGEMS model is a promising approach for optimal pipe sizing in the design of water distribution networks and pumping schedules. In [12], the authors used the WaterCAD and waterGEMS software for a comparative assessment of the performance of the water distribution system of the Federal Agricultural University of Makurdi. A stationary analysis was also carried out to determine hydraulic parameters such as pressure, velocity, head loss and flow rate. The result of the statistical analysis showed that both simulators could be used interchangeably as there were no statistical differences. In our case, we consider the backbone network, which is also solved using the above software product. In addition, the calculations used Darwin Designer, a more advanced tool in WaterCAD, which allows you to find projects with a minimum cost. Since the tool is available in WaterCAD, it includes optimization mechanisms for automatic calibration, design and restoration of the piping system [4].

2 Materials and methods

The research in this article is based on data from the Water Resources Authority and the Sewerage Authority in Kerbala Province. These data were used to build a simulation model using the WaterCAD V8i program. The basis for modeling the transport of purified water for supply to irrigation systems is the simulation of the processes of water movement in main pipelines. To ensure the transport of water in pressure systems, it is necessary to take into account the head loss, which determines the energy costs for pumping water by pumping equipment.

Various equations are known in the literature for determining head losses in pipes. The most widely accepted in fluid mechanics is the Darcy-Weisbach formula due to its proven accuracy compared to other equations [8]. The Darcy–Weisbach equation is traditionally considered as the most accurate method for modeling friction losses in the following form:

$$h_f = f\ \frac{L}{D}\frac{V^2}{2g} \qquad (1)$$

Where h_f - head loss (m), f - hydraulic resistance coefficient (Darcy-Weissbach friction coefficient), D - Pipe diameter (m), L - pipe length (m), V - flow velocity (m / s), g - constant of gravitational acceleration (m / s^2).

We denote

$$f = 2f\left(Re, \frac{\Delta}{d}\right), \quad (2)$$

$$R_e = \frac{\rho v d}{\mu}. \quad (3)$$

Where R_e: Reynolds numbers (dimensionless), $\boldsymbol{\rho}$ - flow density ($\boldsymbol{kg}$ / $\boldsymbol{m3}$), $\boldsymbol{V}$ - average flow rate ($\boldsymbol{m}$ / $\boldsymbol{s}$), d - length index or pipe diameter (m), $\boldsymbol{\mu}$ - dynamic viscosity ($\boldsymbol{kgm}$ /$\boldsymbol{s}$), Δ - wall roughness ($\boldsymbol{m}$).

2.1 Fixed and operating costs

The fixed cost (C_f) of the pipeline, L is expressed as [7]

$$C_f = P \times L \frac{i(1+i)^n}{(1+i)^n - 1}, \quad (4)$$

where $C_f -$ is a fixed cost, \$/year; P – is the price of the pipe \$; L– is the pipe length, m; i – interest rate; n– is the service life of the pipe, years.

The cost of operation (C_o) also depends on the following factors:

$$C_o = f(d, Q, h_f, t, c_e, \eta). \quad (5)$$

The annual operating costs for overcoming friction are:

$$C_o = \frac{0.746 \rho g Q h_{f \times C_e} \times t}{75 \eta} \quad (6)$$

When substituting the velocity value in the equation (1), $h_f = \frac{8 \lambda l Q^2}{\pi^2 g d^5}$

$$C_o = \frac{8.103 \times 10^{-4} \times \rho \times Q^3 \times l \times \lambda \times C_e \times t}{\eta \times d^5} \quad (7)$$

The annual power loss due to friction (PS) is calculated in kilowatt-hours as

$$PS = \frac{0.746 \times \boldsymbol{\rho g} \times Q \times h_{f \times t}}{75 \eta} \quad (8)$$

Thus, $C_t = C_f + C_o$

$$C_t = P \times L \frac{i(1+i)^n}{(1+i)^n - 1} + \frac{8.103 \times 10^{-4} \times \boldsymbol{\rho} Q^3 l h_f \times C_e \times t}{\eta d^5}, \quad (9)$$

where $C_t -$ is the total cost, \$/year; $C_f -$ fixed cost, \$/year; C_o – operating costs, \$/year; L is the pipe length, m; d –is the pipe diameter, m; Q – is the flow rate, m^3/s; hf –is head loss, m; t – is pump usage, hour/year; *Ce* – is the cost of electricity, \$/KWH; η – pump efficiency = 80%; ρ – is the specific gravity of water, kg/m^3; P – is the price per unit length of the pipe, \$/m; i – interest rate; n – is the service life of the pipe, years.

2.2 Piping system optimization

The advanced Darwin Designer tool in WaterCAD V8i was used to solve decision optimization problems.
For four types of pipe materials, different initial diameters were used in the range from 800–1200 mm and flow rate = 1.16 m^3/s for the first option, 1600–2000 mm and flow rate = 4.63 m^3/s for the second option when choosing the best diameters to reduce transportation costs wastewater in Kerbala. So, we need to solve the following tasks using Darwin Designer in WaterCAD V8i:
- Selection of the optimal pipe diameter;
- Reduction of energy consumption for water transportation.

$$\text{Minimize } C_t = C_f + C_o$$
$$C_t = \sum_{f=1}^{N_{PP}} C_f L_f + \sum_{t=1}^{N_{Pm}} C_0 L_t , \quad (10)$$

where C_t – is the total cost, \$/year; C_f – fixed cost, \$/year; C_o – operating costs, \$/year; with diameter D, mm; L_f – is the length of the i-th pipe, m; Npp –is the number of pipes; L_t – is the length of the t-th pipe, m, and Npm –is the type of pipe material.
For this study, pressure and velocity are limited: P is from 6 to 40 m, respectively, and V is from 0.6 to 3 m/s.

2.3 Calculation Pipe cost

The calculation uses the cost of a pipe per unit length for a different assortment of pipe material. The prices for pipes in the calculations correspond to the prices for the administrative district of Kerbala. In table 1 shows the price of a pipe diameter for 1 meter of length for each type of pipe material.

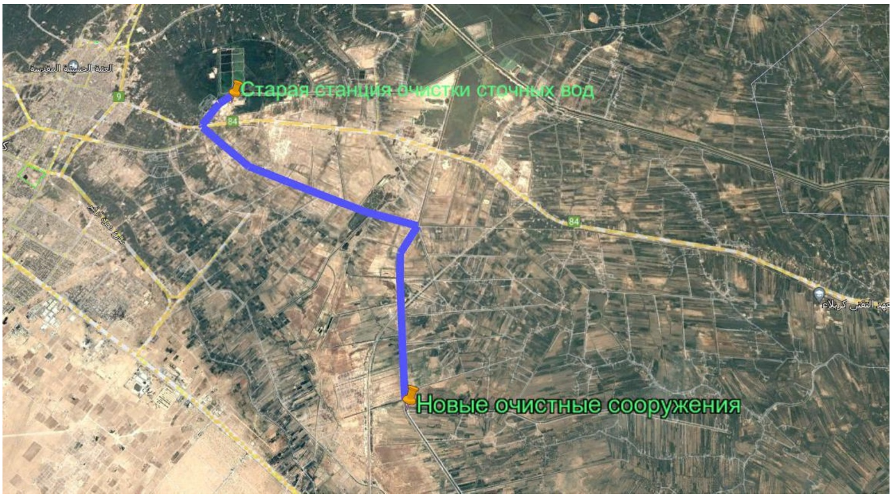
Table 1. The cost of pipes from different materials

Diameter, mm	Ductile iron, \$/m	GRP, \$/m	Concrete, \$/m	Plastic, \$/m
800	294	160	327	230
1000	326	227	488	345
1200	354	302	678	481
1600	405	473	1136	812
1800	427	569	1403	1006
2000	449	671	1696	1219

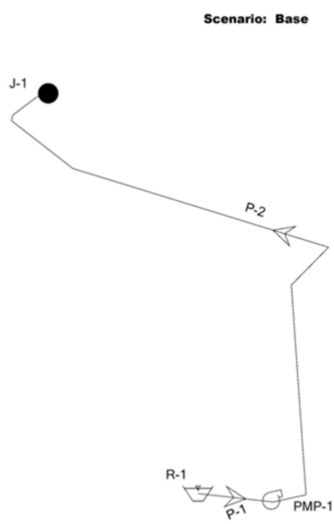
2.4 Building scheme for water transportation

The scheme for transporting treated wastewater between two stations in the city of Karbala was built using WaterCAD V8i software. The program contains a map of the area with all the marks and buildings. To ensure the transportation of water, a pressure pipeline system is adopted using pumping equipment. The selection and placement of pumping equipment was also carried out using the WaterCAD V8i software.

For four types of materials, different initial diameters were used in the range from 800–1200 mm and a flow rate =1.16 m^3/s for the first option, 1600–2000 mm and a flow rate =4.63 m^3/s for the second (Fig. 1).



a. Location of two stations



b. Model design

Fig. 1. Scheme of transporting treated wastewater between two stations in the city of Kerbala: R-1 is a water source representing a new treatment plant; P-1 from new station to pump; PMP-1 pump; P-2 - from the pump to the old station; J - node represents the flow of water from the old station.

3 Results

So, we made sure that a comparative assessment and selection of the optimal option for pipeline diameters, as well as the selection of pumping equipment, the determination of hydraulic resistance in these communications can be carried out by modeling methods.

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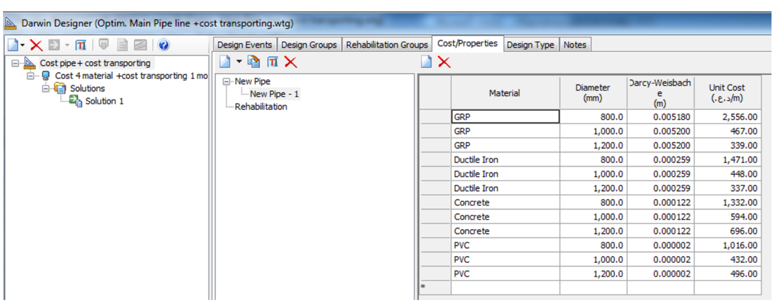
Using the WaterCAD V8i software-computer complex, we performed hydraulic calculations for pipes of different diameters and from various materials. The head loss in the system was calculated using the Darcy–Weisbach equation. Annual costs for wastewater transportation per 1 running meter of length for four pipe materials were calculated using formula (7). In table 2 shows the cost of operating costs of transporting water per 1 meter of pipeline for two options. The transmission distance between two stations is 8200 m.

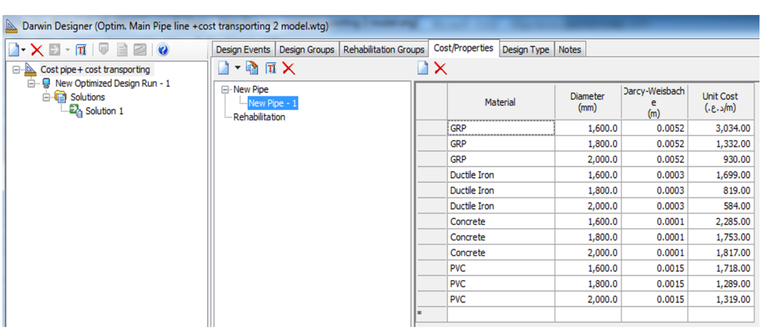
Table 2. The cost of operating pipes of different diameters and materials

Diameter, mm	Ductile iron, $/m	GRP, $/m	Concrete, $/m	Plastic, $/m
First option				
800	1177	2396	1005	786
1000	122	240	106	87
1200	19	37	18	15
Second option				
1600	1294	2561	1149	906
1800	392	763	350	283
2000	135	259	121	100

In general, an increase in the annual cost of transporting water can be observed with a decrease in pipe diameter for both options due to head loss.
We used the data of tables 1, 2 to build a mathematical model for calculating the optimal diameter and type of pipe material in the water supply system. On fig. 2 shows the diameter, the price of the material of the pipe, indicating the transport costs per meter of length and the type of each pipe.



a. First option



b. Second option

Fig. 2. Type of material, diameter and cost per linear meter of pipes used in the WaterCAD V8i program for the first and second options

The model calculation results show that the optimal diameter for the first option was 1000 mm of plastic at a cost of 3,585,600 $ (pipe price and transportation cost per year). The results of the second option were 2000 mm for ductile iron costing 4,847,200 $. On fig. 3 shows the results of both options.

Darwin Designer (Optim. Main Pipe line +cost transporting.wtg): Cost 4 material +cost transporting 1 model

Design Group Results

Design Group	Pipe	Material	Darcy-Weisbach e (m)
Design Group - P-1	P-1	PVC	0.000002
Design Group - P-2	P-2	PVC	0.000002

Diameter (mm)	Cost (د.ع.)
1,000.0	43,200.00
1,000.0	3,542,400.00

Rehabilitation Group Results

Rehabilitation Group	Pipe	Design Rehabilitation Action	Cost (د.ع.)

Pressure Results

Design Event	Element	Required Minimum Pressure (m H2O)	Required Maximum Pressure (m H2O)
GRP, Duct.D800-1200 mm	J-1	6	40

Simulated Pressure (m H2O)	Violation (m H2O)
31	0

Velocity Results

Design Event	Element	Minimum Velocity (m/s)	Maximum Velocity (m/s)

Simulated Velocity (m/s)	Violation (m/s)

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a. First option

Darwin Designer (Optim. Main Pipe line +cost transporting 2 model.wtg): New Optimized Design Run - 1

Design Group Results

Design Group	Pipe	Material	Darcy-Weisbach e (m)
Design Group - P-1	P-1	Ductile Iron	0.0003
Design Group - P-2	P-2	Ductile Iron	0.0003

Diameter (mm)	Cost (د.ع.)
2,000.0	58,400.00
2,000.0	4,788,800.00

Rehabilitation Group Results

Rehabilitation Group	Pipe	Design Rehabilitation Action	Cost (د.ع.)

Pressure Results

Design Event	Element	Required Minimum Pressure (m H2O)	Required Maximum Pressure (m H2O)
GRP, Duct.D800-1200 mm	J-1	6	40

Simulated Pressure (m H2O)	Violation (m H2O)
27	0

Velocity Results

Design Event	Element	Minimum Velocity (m/s)	Maximum Velocity (m/s)

Simulated Velocity (m/s)	Violation (m/s)

Optim. Main Pipe line +cost transporting 2 model.wtg
11/08/2021

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b. Second option

Fig. 3. Optimized pipe diameter using WaterCAD V8i

The results also showed that pressure and velocities are within acceptable limits.

4 Conclusions

So, using the WaterCAD V8i software, we have designed the optimal system of main pipelines for transporting treated wastewater in the city of Kerbala (Iraq). The software made it possible to make the optimal choice of pipe diameter and materials, taking into account design constraints, i.e. pressure, velocity. In addition, with the help of the program, it was possible to calculate the cost of transporting water with various materials and pipe diameters and select the most optimal option.

As can be seen from the simulation results, the following indicators were obtained:

1. For the first option, the optimal pipe diameter at a flow rate = 1.16 m3/s made of plastic 1000 mm. The annual operating costs for transportation and the cost of the pipe for the first option are 3,585,600 $.

2. For the second option, the optimal pipe diameter at a flow rate of =4.63 m3/s was 2000 mm for ductile cast iron. The annual operating cost for transportation and the cost of the pipe for the second option was 4,847,200 $.

3. Determining the cost of transporting water is very important when choosing the optimal pipe diameter, since a small pipe diameter requires higher operating costs for transporting water flows than in larger diameter pipes.

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