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Economic Design of Water Distribution Networks

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***Abstract* - Water Distribution Networks represent a major economic investment of the total cost of water supply systems. Pipe cost optimization is usually considered as a prime objective. However, minimizing the capital cost of the pipeline alone may result in increasing the cost of pumping, so the balance between pipe cost and pumping cost is a vital issue. In this study, an empirical model is formulated to select the economic pipe diameter based on capital and operation costs. A new Diameter Optimization Ratio DOR is developed to evaluate the economic optimality, which equals to 1.0 at optimal design, when rate of increase/decrease of pipe cost equals rate of decrease/increase of pumping cost. A new mathematical models are developed to calculate optimum diameter, velocity, hydraulic gradient slope for a given flow rate under given cost data assumptions. Optimum diameter does not depend on pipe length. After applying the mathematical model on this case study, the economic optimality indicator can be raised from 57.2 % to 90.6 %, and the total cost decreased by 38.8% by selecting optimum pipe diameter. After applying the mathematical model on this case study, the economic optimality indicator can be raised from 57.2 % to 93.6 %, and the total cost decreased by 36.4% by selecting optimum pipe diameter. A new Cost Optimality Factor R for each pipe and for the whole network can be defined. A case study is considered to illustrate the application of proposed methodology.**

Keywords: Network optimization, Economic Optimality, Environmental Optimality, Economic performance indicator, Environmental performance indicator, Capital cost.

I. INTRODUCTION

Water Distribution Networks (WDNs) are made up of a variety of components, including tanks, valves, pumps, pipes, and reservoirs. WDN accounts for over 80% of all water supply project costs [1], one of the most important factors in WDN is the cost of energy used to pump water, which accounts up to 30% of total WDN operating costs[1], and hence the research in the subject of economic optimality of WDN is very vital. Numerous scholars have put forth numerous approaches throughout the years for finding the best solution to the WDN optimization challenge.

(Cross H, 1936) Outlined the construction of a dependable, efficient, and affordable distribution network as meeting the necessary water needs while keeping adequate pressure heads as the optimality of WDN. [2]

(Sonowal A, 2016) Discussed the economic optimality given that increasing conduit diameter results in higher annual capital expenses and lower operational costs. Therefore, choosing the best pipe diameter for a given flow will be a crucial economic choice. The designer may use a small diameter pipe to save money when water needs to be pumped over a lengthy pipeline at a predetermined pace, but this typically leads to high pumping costs due to significant friction loss in tiny size pipes.[3]

(Sangroula U, 2022) Determines the ideal pipeline diameters in a WDN with a predefined layout. [4]

Moreover, as minimizing energy costs during pumping must also be taken into consideration with construction expenses, several studies have thought about operational optimization of WDNs. One of the largest marginal costs for water utilities is the consumption of electricity during operation. [5, 6, 7]

(Suribabu CR, 2017) Combining two goals minimizing capital costs as the primary goal and maximizing the configuration's resilience measure as the secondary goal. The design's numerical outcomes highlight the significance of sizing pipes telescopically along the shortest path of flow for improved resilience indices.[8]

(Cimellaro GP, 2015) Generated a developed optimization model that chooses the shortest route to the

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demand node and gives all en-route pipes to that node and other demand nodes a least-dimensional pipe size.[9]

(Wang Q, 2014) Used 12 benchmark networks from the literature to test multi-objective evolutionary algorithms. According to study findings, the most promising method for tackling two-objective WDN issues is the non-dominated sorting genetic algorithm-II (NSGAII).[10]

(Lansey K, 1989) Presented a technique to reduce the cost of WDN design. Their suggestion highlights the demands, pressure heads, and roughness coefficients uncertainty. [11]

(Makaya E, 2014) examined the indicators for evaluating water distribution systems and evaluated how well they applied to emerging nations. The primary metrics used globally are either financial or operational. [12]

It was mentioned that as the water distribution system's retention time increases, the quality of the water will decrease, leading to issues including the production of disinfection byproducts, the decay of disinfectants, corrosion, taste, and odor. [13, 14, 15]

(Menelaos P, 2020) Mentioned that water age is a key factor in determining the water quality of a water distribution system, and that this factor is largely influenced by the system's design and requirements. [16]

(Song W, 2019), and (Xu Z, 2020) Achieved optimization of water distribution systems through choosing pipe diameter according to required flow, and achieving balance between pipe cost, and pumping cost. [17, 18]

For any pipe flow network system, the Life-Cycle Cost Analysis (LCCA) model is widely acknowledged as the suggested standard technique to estimate the ideal pipe size.

This research focuses on analyzing and improving the urban water supply system to guarantee long-term access to water of the proper quality as well as ensuring the city's water supply stays secure, dependable, and affordable.

In this study, a mathematical model is created to calculate capital and operational costs dependent on several physical characteristics including flow rate, electricity cost, and length in order to establish the ideal diameter. Along with evaluating WDN using an economic optimality indicator, which ranges in value from 0 to 1, and comparing the total cost before and after optimization.

II. METHODOLOGY

The flow chart shown in Figure 1 breaks down the process into four basic steps.

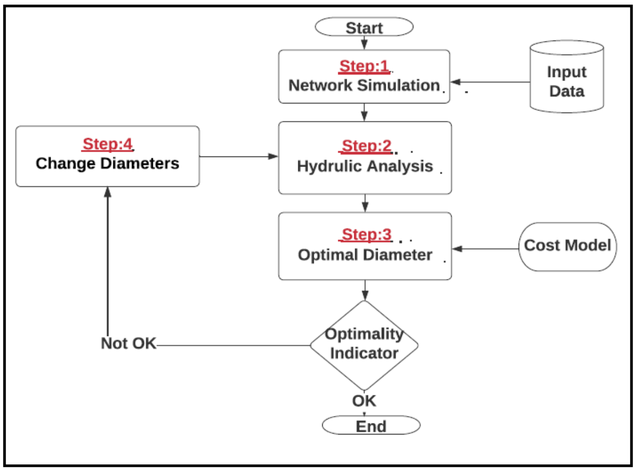

Figure 1: Flowchart of the Adopted Water Network Economic Optimality Methodology

Step 1: includes modeling the WDN using physical network data, such as information on pipes, junctions, pumps, and valves. The model structure is the step's output.

Step 2: includes hydraulic analysis of WDN by one of approved analysis programs. Actual flow in each pipe of the WDN is calculated in this step.

Step 3: includes determination of optimal pipe diameter using developed cost models. Optimality indicator is calculated as the ratio between optimized (minimum), which is calculated from cost model, and actual costs of WDN.

Step 4: The WDN is upgraded to increase its economic optimality through changing pipe diameters to be as near as possible to optimum pipe diameters.

III. COST MODELS

Physical analysis alone does not guarantee economic design, economic analysis achieves balance between capital and operating cost of WDN.As the pipe diameter increases capital cost increases and pumping cost decreases. Pipe diameter is optimal when total cost is minimum.

As suggested in (Arumugam A, 2021), the following section will describe Life-Cycle Cost Analysis (LCCA), an often suggested model for determining the ideal diameter for every given flow.

$$C = CC.A + OC \qquad (1)$$

Where:

C Annual worth value (EGP/yr)
CC the capital cost (EGP)
OC the operating cost (EGP/yr)
A the annual worth factor (1/yr)

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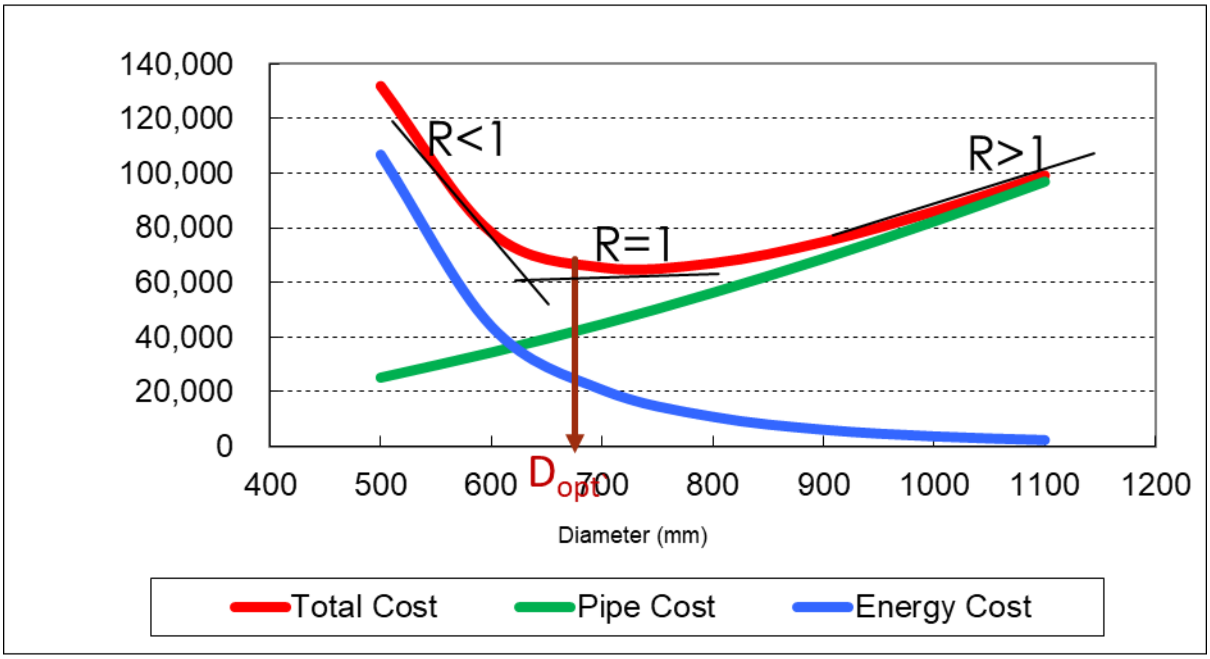

Figure 2: Relation between costs and pipe diameter [19-20-21]

$$C_T = C_P + C_M \tag{2}$$

$$C_P = f1(D), \quad C_P' = dC_P/dD \tag{3}$$

$$C_M = f2(D), \quad C_M' = dC_M/dD \tag{4}$$

The optimal diameter occurs at minimum total cost where,

$$dC_T/dD = 0, \quad \text{or} \quad C_P' = - C_M' \tag{5}$$

A new cost optimality factor R can be defined

$$R_{\text{for pipe}} = C_P'/-C_M' \tag{6}$$

$$R_{\text{for network}} = \frac{\sum_{i=1}^{m} R_i * L_i}{\sum L} \tag{7}$$

Where:

C_T Total cost of pipe and pumping (EGP/yr)

C_P Pipe cost (EGP/yr)

C_M Pumping cost (EGP/yr)

m No of pipes

R: Diameter Optimality Factor

R = 1.0 for optimal diameter

R > 1.0 for oversized diameter

R < 1.0 for undersized diameter

3.1 Pipe Cost Model

The first cost component is the capital cost of pipes calculated by the following formula:

$$C_P = CC_P.\ A_P = a.\ D^b.\ L.\ A_P \tag{8}$$

$$A_P = \frac{i.(1+i)^n}{(1+i)^n - 1} \tag{9}$$

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On differentiation with respect to D

$$C'_P = a.\ b.\ D^{b-1}.\ L.\ A_P = X_p.D^{b-1}.\ L \quad (10)$$

$$X_p = a.\ b.\ A_P \quad (11)$$

Where:

C_p Annual worth cost of pipe (EGP/yr)

CC_p Capital cost of pipe (EGP)

i Interest rate (%)

n Pipe lifetime (yr)

L Length of Pipe (m)

D Diameter of Pipe (m)

X_p, a, and b are pipe cost coefficients depending on pipe material

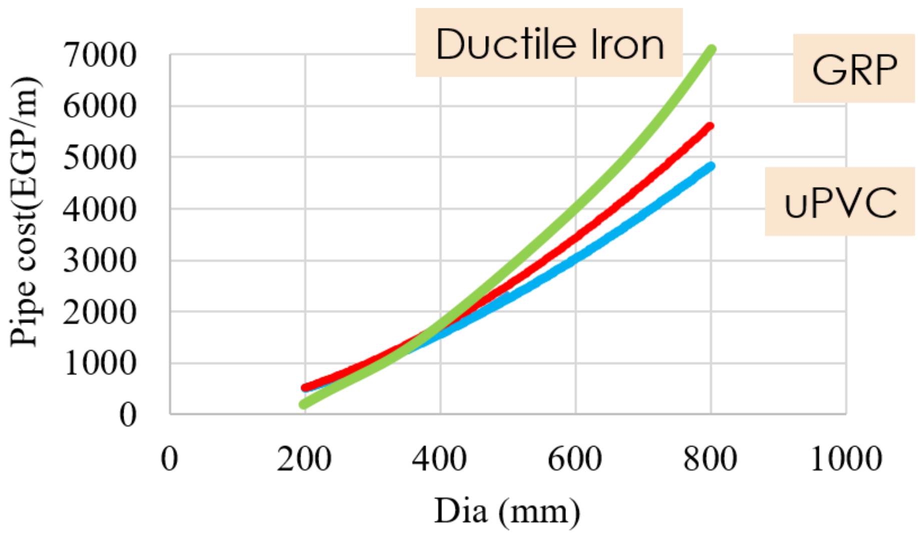

Figure 3: Pipe Cost Models for Different Pipe Materials [20]

3.2 Pump Cost Model

Pump cost component includes the capital cost of pumps.

$$C_{pump} = CC_M.A_M = c.\ P.\ A_M \quad (12)$$

$$A_M = \frac{i\,.\,(1+i)^m}{(1+i)^m - 1} \quad (13)$$

Where:

C pump	Annual worth cost of pump	(EGP/yr)
CC_M	Capital cost of pump	(EGP)
P	Power	(watt)
m	Lifespan of pump	(yr)
c	Pump capital cost linear coefficient	(EGP/kw)

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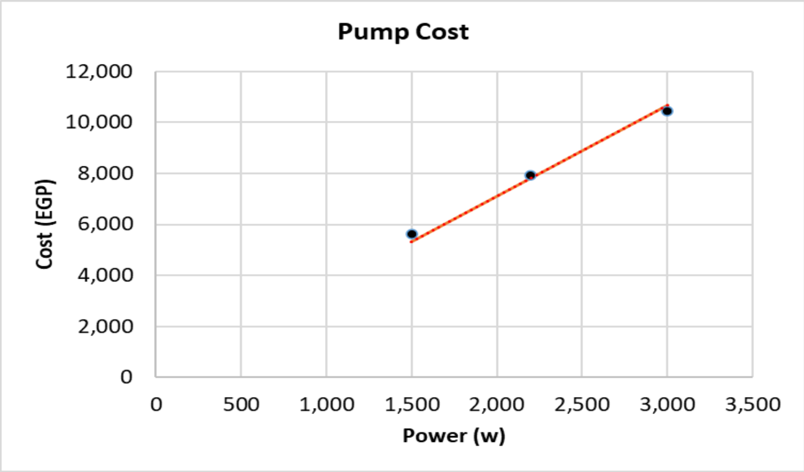

Figure 4: Pump Cost Model [21]

3.3 Pumping Cost Model

Pumping cost includes the annual operation cost of power consumed to overcome friction losses in pipes. Calculation does not include the power consumed to overcome static and residual heads which is considered a fixed cost in the optimization problem.

$$C_{Pumping} = P.\, t.\, C_E \qquad (13)$$

$$P = \frac{w.Q.H}{E} = \frac{1000.g.Q.H}{E} \qquad (14)$$

Where:

$C_{Pumping}$	Annual worth cost of pumping	(EGP/yr)
C_E	Cost of electricity	(EGP/Kwh)
t	Pump use	(hr/yr)
P	Power consumed to overcome friction losses	(kw)
Q	Flow rate in pipe	(m^3/s)
H	Friction head losses in pipe section L	(m)
E	Combined pump and motor efficiency	(%)

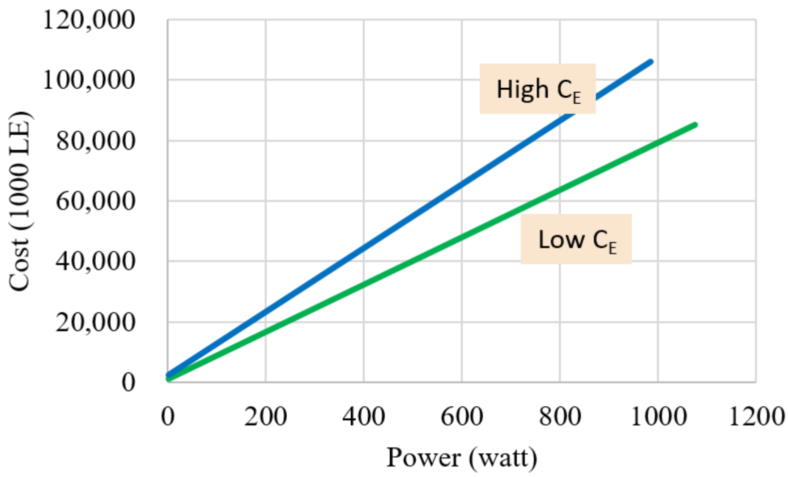

Figure 5: Pumping Cost Model [21]

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3.4 Pump and Pumping Cost Model

The operating cost is the pumping cost which includes the capital cost of pumps and the annual operation cost of power consumed to overcome fixed and friction losses in pipes. Fixed head include the power consumed to overcome static and residual heads which is considered a fixed cost in the optimization problem.

$$C_M = Pump\ Cost + Pumping\ Cost = CC_M . A_M + OC_M = c.\ P.\ A_M + P.\ t.\ C_E = (c.\ A_M + t.\ C_E)\ P = X_M . P \quad (15)$$

$$X_M = c.\ A_M + t.\ C_E \quad \text{and} \quad A_M = \frac{i.(1+i)^m}{(1+i)^m - 1}$$

$$P = \frac{w.Q.H}{E} = \frac{1000.g.Q.H}{E} \quad \text{and} \quad H = H_o + H_f$$

On substituting the value of friction losses from Darcy's Equation,

$$H_f = \frac{f.L.V^2}{2.g.D} = \frac{8.f.L.Q^2}{\pi^2.g.D^5}$$

$$\text{Then} \quad P = \frac{1000.g.Q.H}{E} = \frac{8000.f.L.Q^3}{\pi^2.E.D^5} = K.\frac{Q^3}{D^5}.L \quad K = \frac{8000.f}{\pi^2.E}$$

$$C_M = X_M . K.\frac{Q^3}{D^5}.L \quad (16)$$

On differentiation with respect to D

$$C'_M = -6.\ X_M.\ K.\ \frac{Q^3}{D^6}.L \quad (17)$$

Where:

C_M	Annual worth cost of pump and pumping	(EGP/yr)
CC_M	Capital cost of pump	(EGP)
OC_M	Operating cost of pumping	(EGP/yr)
C_E	Cost of electricity	(EGP/Kwh)
t	Pump use	(hr/yr)
m	Lifespan of pump	(yr)
c	Pump capital cost linear coefficient	(EGP/kw)
P	Power consumed to overcome friction losses	(kw)
Q	Flow rate in pipe	(m^3/s)
H	Friction head losses in pipe section L	(m)
E	Combined pump and motor efficiency	(%)
f	Darcy's coefficient of friction	
g	Gravity acceleration	(m^2/s)
k	Lumped Power Cost Factor	

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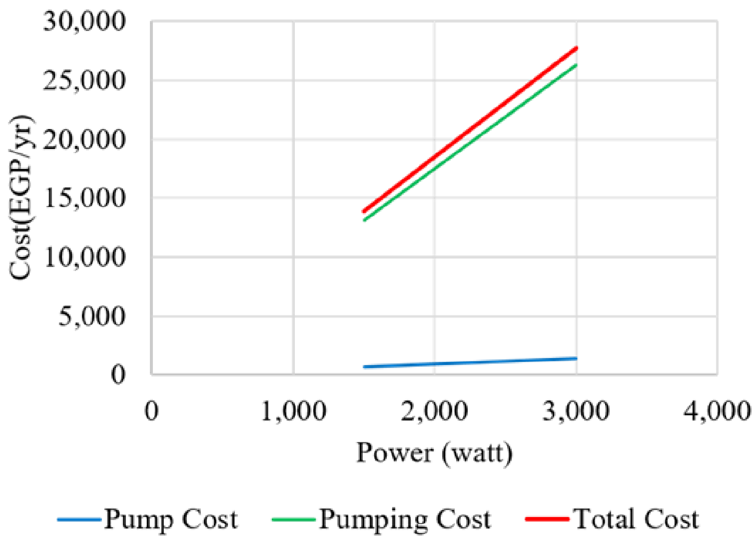

Figure 6: Pump and Pumping Cost Model [24]

3.5 Optimal Diameter, Velocity, and Hydraulic Slope Calculation

Depending on the pipe's diameter, length, and flow rate, the total cost of any pipe in a WDN is the sum of its capital and operating costs.

$$C_T=C_P+C_M = a.\ D^b.\ L.\ A_P + X_M.\ K.\frac{Q^3}{D^5}.L \qquad (18)$$

$$C'_T=C'_P+C'_M = X_P\ D^{b-1}.\ L - 6\ X_M.\ K.\ \frac{Q^3}{D^6}.L \qquad (19)$$

At minimum total cost,

$$C'_P = C'_M$$

$$X_P\ D^{b-1}.\ L =6\ X_M.\ K.\ \frac{Q^3}{D^6}.L$$

$$D^{5+b}=6\ X_M.\ K.\ \frac{6.X_M.K}{Xp}.Q^3 \qquad (20)$$

$$D_{opt}=X\ .Q^Y \qquad (21)$$

$$V_{opt}=\frac{4.Q^{1-2Y}}{\pi X^2} \qquad (22)$$

$$S_{opt}=\frac{8.f.Q^{2-5Y}}{\pi^2.g.X^5} \qquad (23)$$

Where:

$$X=\ (\frac{6.Xm.K}{Xp})^{\frac{1}{5+b}} \qquad (24)$$

$$Y=\frac{3}{5+b} \qquad (25)$$

3.6 Economic Performance Evaluation

After calculating optimum diameter for each pipe, the total cost of the network calculated.

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Calculation the total cost of actual diameters in case of existing network. Actual diameters are the available commercial diameters nearest to values of optimum diameters calculated from cost model according to actual flow in pipes. Calculate WDN optimality ratio from the following formula

$$WDN\ Optimality\ Ratio = \frac{Minimum\ Cost}{Actual\ Cost} \quad (ranges\ for\ 0\ to\ 100\%) \qquad (26)$$

A new Cost Optimality Factor R for each pipe and for the whole network can be defined

$$R_{Pipe} = \frac{C'_P}{C'_M} = \frac{a.b.Db^{-1}.L.AP = Xp.Db^{-1}.L}{-6.XM.K.Q^{3}/D^{6}.L} \qquad (27)$$

$$R_{Network} = \frac{\sum_{i=1}^{m} R_i * L_i}{\sum L} \qquad (28)$$

IV. CASE STUDY AND RESULTS

Water network consists of 30 pipes, 22 nodes, and 9 loops. The network is fed by a single pump of Q= 206 L/s. The minimum head limitation for this network is 2.5 bar above ground level. The details of the distribution are described below, and illustrated in Figure 7.

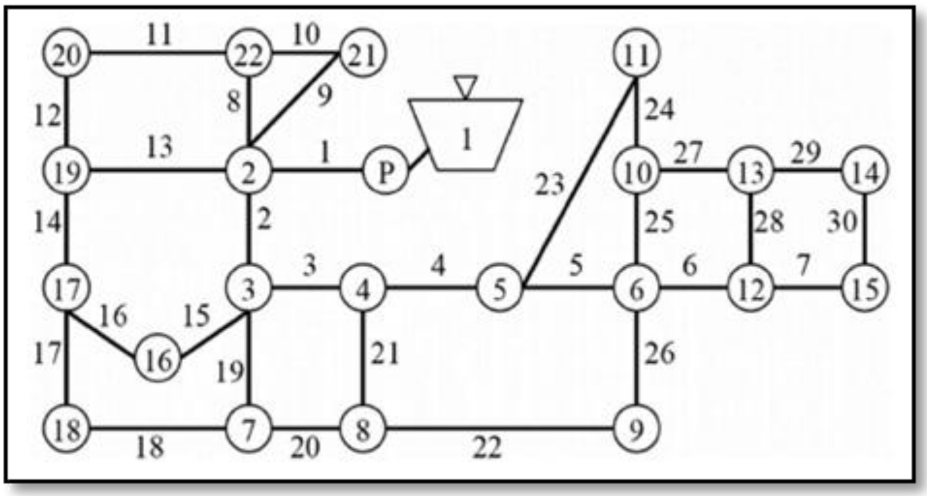

Figure 7: Layout of Case Study [22]

4.1 Network Simulation

Table (1) Junction Data [22]

Junction Label	Elevation (m)	$q\ (m^3/d)$
2	56.4	1,530
3	53.8	705
4	54.9	585
5	56	750
6	57	675
7	53.9	630
8	54.5	480
9	57.9	420
10	62.1	300
11	62.8	420
12	58.6	375
13	59.3	375
14	59.8	630

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15	59.2	4,455
16	53.6	1,080
17	54.8	795
18	55.1	555
19	54.2	1,185
20	54.5	1,245
21	62.9	315
22	62.8	315
Total		17,820

Table (2) Pipe Data [22]

Pipe No.	L (m)	D_1 (mm)
1	165	500
2	124	400
3	118	200
4	81	200
5	134	200
6	136	200
7	202	200
8	135	200
9	176	200
10	113	100
11	335	200
12	135	200
13	345	300
14	114	300
15	193	100
16	162	200
17	72	200
18	347	100
19	98	100
20	118	200
21	98	100
22	81	100
23	236	100
24	102	100
25	92	100
26	100	100
27	136	100
28	90	100
29	201	100
30	90	100
32	29	500

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4.1 Cost Model Assumptions

Cost models assumptions are presented below:

Pipe Cost Assumptions:

Table (3) Pipe Cost Model Assumption [23]

Item	Symbol	Value	Unit
Pipe Material		uPVC	
Pipe Lifetime	n_p	30	year
Interest Rate	i	10	%
Pipe Annual Worth Cost Factor	A_p	0.11	1/yr

Table (4) NOPWASD Prices (2022) UPVC [20]

D (m)	Cost (EGP/m)
0.200	550
0.225	650
0.250	760
0.315	1,100
0.355	1,350
0.400	1,650
0.450	2,080
0.500	2,450
0.560	3,000
0.630	3,800
0.710	4,700
0.800	5,800

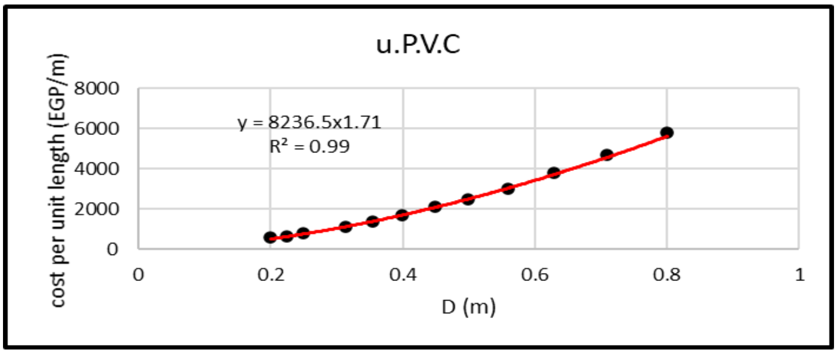

Figure 8: Empirical Model for uPVC Pipes [25]

Derived empirical relationship between cost and diameter of pipe for uPVC pipes can be expressed in the following relationship:

$$C_P = CC_P \,.\, A_P = a.\, D^b .\, L.\, A_P$$

In case study:

$$a=8236.5,\ b=1.71,\ A_p=0.11$$

$$C_P = 8,236 * D^{1.71} * L * 0.11 = 906 * D^{1.71} * L \qquad (29)$$

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Pump Cost Model Assumptions:

Table (5) Pump Cost Model Assumption [23]

Item	Symbol	Value	Unit
Combined Pump and Motor Eff.	E	75	%
Interest Rate	i	10	%
Pump Lifetime	n_M	15	year
Pump Annual Worth Cost Factor	A_M	0.13	1/yr

Table (6) KSB Prices (June_2022) [21]

Power (KW)	Power (W)	Cost (EGP)
1.500	1,500	5,630
2.200	2,200	7,925
3.000	3,000	10,440

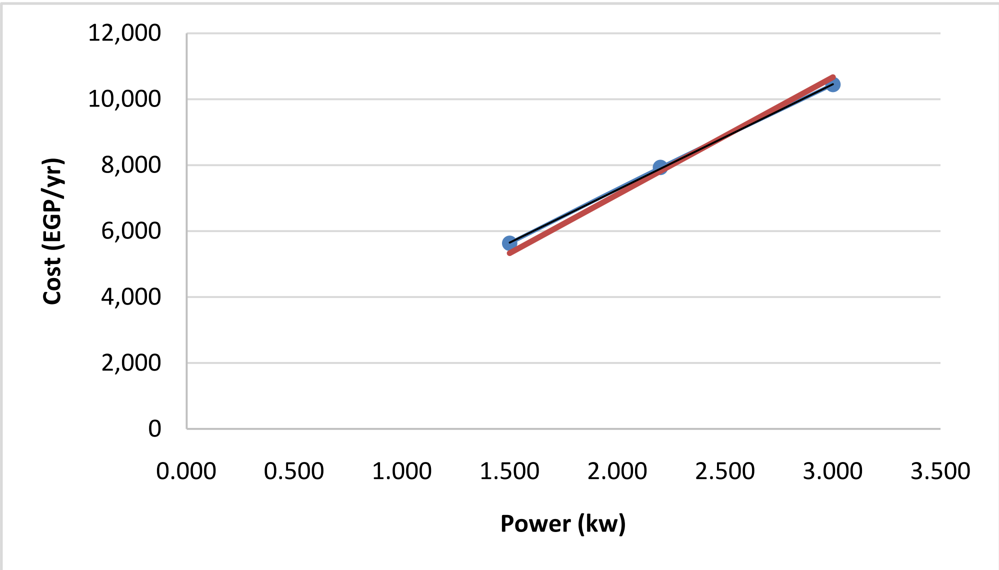

Figure 9: Pump Cost Model [21]

Derived empirical relationship between power in KW and pump cost in EGP/yr can be expressed in the following relationship:

$$C_{pump} = CC_M .A_M = c. P. A_M$$

In case study:

$$c=3.55, A_M=0.13$$

$$C_{pump} = CC_M .A_M =3.55* P* 0.13=460 P \qquad (30)$$

Pumping Cost Model Assumptions:

Table (7) Pumping Cost Model Assumption [23-24]

Item	Symbol	Value	Unit
Pump Operation Time	t	8,760	h/yr
Combined Pump and Motor Eff.	E	75	%
Liquid Weight	w	1000	kg/m^3
Cost of Electricity	C_E	1.0	EGP/kwh
Darcy friction factor	f	.032	
Gravity Acceleration	g	9.81	m/s^2

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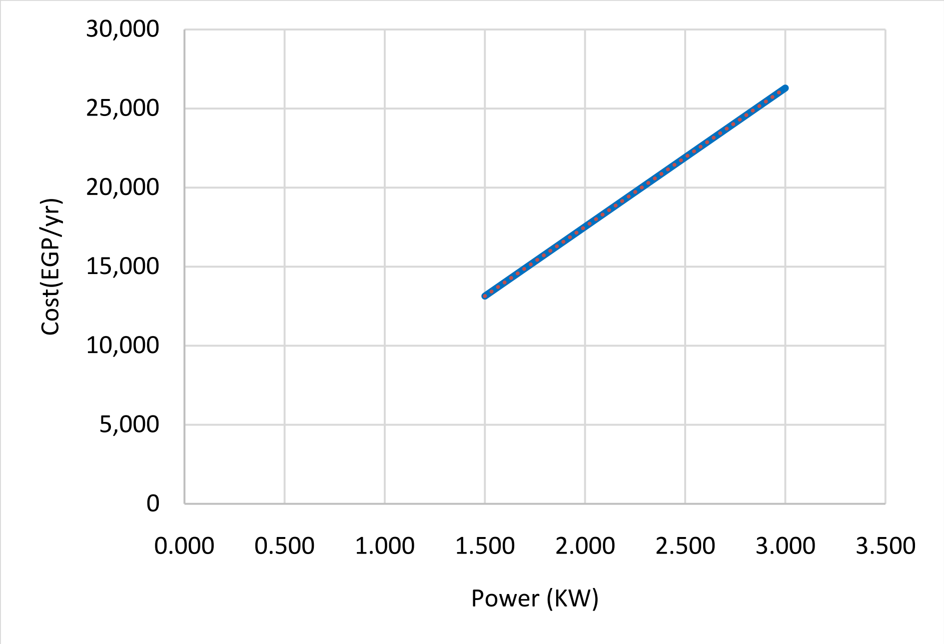

Figure 10: Pumping Cost Model [23-24]

Derived empirical relationship between power in KW and pumping cost in EGP/yr can be expressed in the following relationship:

$$C_{Pumping} = P.\ t.\ C_E$$

$$P = \frac{w.Q.H}{E} = \frac{1000.g.Q.H}{E}$$

$$C_{Pumping} = P.\ t.\ C_E = P*8,760*1 = 8,760\ P \qquad (31)$$

After comparison of pump cost, and pumping cost equations, Pump cost (EGP/yr) is about 5% of pumping cost (EGP/yr) , so pump cost can be ignored in optimum cost model.

4.3 Optimum Diameter, Velocity, and Hydraulic Gradient Slope Calculation

From previous assumption, optimal diameter, velocity, and Hyd. Grad Slope can be calculated from the following equations and shown in Figure 11.

$$\text{Optimal Diameter (m)} \qquad D_{opt} = X.Q^{Y} \quad , X = \left(\frac{6.Xm.K}{Xp}\right)^{\frac{1}{5+b}} \ , Y = \frac{3}{5+b}$$

$$\text{Optimal Velocity (m/s)} \qquad V_{opt} = \frac{4.Q^{1-2Y}}{\pi X^2}$$

$$\text{Optimal Hyd. Grad Slope} \qquad S_{opt} = \frac{8.f.Q^{2-5Y}}{\pi^2.g.X^5}$$

In case study:

X=1.04

Y=0.45

$$(D_{opt}) = =1.04 *Q^{0.45} \qquad (32)$$

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$$(V_{opt}) = \frac{4*Q^{0.1}}{\pi(1.04)^2} = 1.17*Q^{0.1} \qquad (33)$$

$$(S_{opt}) = \frac{8.f.Q^{-0.25}}{\pi^2.g.(1.04)^5} = 0.002*Q^{-0.25} \qquad (34)$$

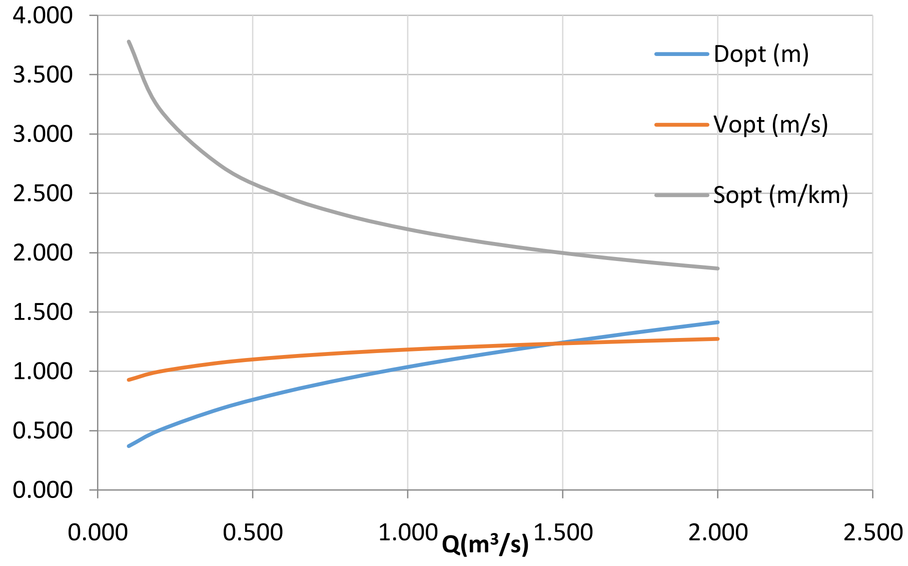

Figure 11: Relation between Q, D_{opt}, V_{opt}, and S_{opt} [23]

4.4 Economic Optimality Performance Evaluation

After hydraulic analysis and determination of flow in each pipe, optimum diameter for each pipe is calculated by Equation 32, as shown in Table 8.

Table (8) Water Network Pipe Data before, optimum, and after upgrading [23]

Pipe	L (m)	D_1 (mm)	Q (L/s)	C_1 (EGP)	R_1	D_{opt} (mm)	C_{min} (EGP)	D_2 (mm)	C_2 (EGP)	R_2
1	165	500	206	52,280	0.85	510	53,750	500	52,270	0.97
2	124	300	121	26,218	0.15	395	29,293	400	24,571	0.96
3	118	200	93	59,480	0.02	365	23,508	400	27,783	0.96
4	81	400	86	33,886	2.04	357	14,063	350	14,600	0.95
5	134	300	74	39,887	0.50	330	21,525	300	20,051	0.95
6	136	400	59	25,123	6.35	301	18,654	300	18,364	0.95
7	202	200	51	112,06	0.11	275	23,134	300	25,252	0.94
8	135	300	15	7,765	13.0	202	8,021	200	8,078	0.93
9	176	300	6	9,810	14.6	141	3,897	150	6,104	0.91
10	113	200	2	1,956	28.0	120	1,245	100	1,925	0.89
11	335	200	13	19,213	0.53	218	18,317	200	19,278	0.93
12	135	200	1	7,524	3.44	164	3,190	150	4,601	0.91
13	345	200	47	42,407	0.43	224	26,721	250	31,077	0.94
14	114	200	33	13,159	0.33	233	7,115	250	10,214	0.93
15	193	100	3	3,440	5.96	21	28	100	3,987	0.80
16	162	100	9	9,210	0.07	145	6,189	150	5,658	0.92
17	72	100	14	4,136	0.05	154	1,180	150	2,714	0.90
18	347	100	8	9,800	0.30	118	2,790	100	5,912	0.89
19	98	100	16	10,695	0.12	136	5,679	100	2,805	0.92
20	118	100	17	7,052	0.10	140	2,613	150	4,021	0.91

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21	98	100	0	1,670	3.89	66	977	100	2,237	0.89
22	81	400	11	4,051	3.49	85	1,351	100	1,380	0.90
23	236	100	9	8,592	1.06	98	4,438	100	4,733	0.90
24	102	100	5	1,963	2.91	30	0	100	1,738	0.73
25	92	200	7	2,351	5.32	108	2,004	100	2,034	0.91
26	100	100	7	2,412	1.34	48	614	100	2,005	0.87
27	136	100	8	4,058	3.52	82	1,646	100	2,350	0.89
28	90	100	4	1,661	0.36	115	2,648	100	1,805	0.91
29	201	100	8	5,677	0.51	109	5,130	100	3,570	0.91
30	90	100	0	1,533	6.10	38	564	100	1,707	0.87
32	29	500	206	27,566	0.85	510	28,341	500	27,561	0.97
Total Cost (EGP)				556,682 (57%)	3.4%		318,627 (100%)		340,412 (90%)	

This step includes calculating economic optimality indicator by applying Equation 5-4, and checking if economic optimality is achieved or not.

$$\text{WDN Optimality Ratio before Upgrading} = \frac{\text{Minimum Cost}}{\text{Actual Cost}} = \frac{318{,}627}{556{,}682} = 57\%$$

$$R_{Network}\ \text{before upgrading} = \frac{\sum_{i=1}^{m} R_i * L_i}{\sum L} = \frac{13{,}915}{4{,}529} = 3.07$$

4.5 Network Upgrading

The WDN is upgraded by changing the pipe diameters to the most optimum taking in consideration the available commercial diameters as shown in Table 8.

After changing the pipe diameters to optimum diameters, the total cost of WDN decreased as shown in Table 8.

$$\text{WDN Optimality Ratio after Upgrading} = \frac{\text{Minimum Cost}}{\text{Actual Cost}} = \frac{318{,}627}{340{,}412} = 90\%$$

$$R_{Network}\ \text{after upgrading} = \frac{\sum_{i=1}^{m} R_i * L_i}{\sum L} = \frac{4{,}123}{4{,}529} = 0.91$$

It is noted after upgrading network, the total cost decreased by %38.8, so the economic optimality indicator increased from 57 to 90.6 %. And R (optimal diameter ratio) tends to 1.0, which $C_P' = C_M'$.

4.6 Summary of Economic Analysis Results

Table (9) Economic Analysis Results [23]

Item	Before Upgrading	Optimum Design	After Upgrading
Capital Cost (L.E/yr)	369,925	270,730	298,008
Running Cost (L.E/yr)	186,757	47,897	42,403
Total Cost (L.E/ yr)	556,682	318,627	340,411
Economic Optimality Indicator (%)	57.2	100	93.6
R (Diameter Optimality Ratio)	3.0	1.0	0.91

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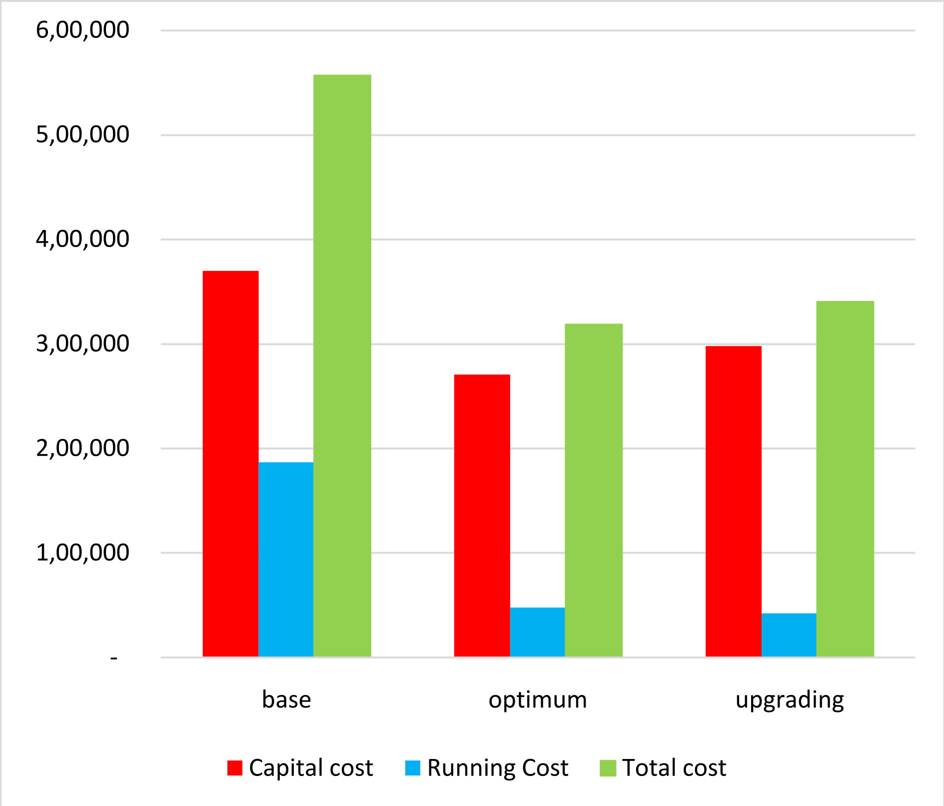

Figure 12: Economic Analysis Results [23]

VI. CONCLUSIONS AND RECOMMENDATIONS

Design of water distribution network usually follows national design criteria which set certain constraints on hydraulic parameters such as velocity, hydraulic gradient slope, and pressure.

However these design criteria do not necessarily produce optimal design. Cost minimization is usually overlooked in design codes. The target of this study is to produce safe and optimal design through diameter optimization (Economic Optimality). The economic optimality guarantees the balance between capital and running cost, such that the total cost is minimum.

A new 4-step methodology is proposed to achieve economic optimality of WDN as shown in Figure 1. Economic analysis is proposed for diameter optimization. New indicators are proposed to evaluate the economic performance of WDN.

A new Diameter Optimization Ratio DOR is developed to evaluate the economic optimality, which equals to 1.0 at optimal design, when rate of increase/decrease of pipe cost equals rate of decrease/increase of pumping cost.

R=1 for optimal diam, R>1 for oversized diam, R<1 for undersized diam.

A new mathematical models are developed to calculate optimum diameter, velocity, hydraulic gradient slope for a given flow rate under given cost data assumptions. Optimum diameter does not depend on pipe length.

After applying the mathematical model on this case study, the economic optimality indicator can be raised from 57.2 % to 90.6 %, and the total cost decreased by 38.8% by selecting optimum pipe diameter.

A new Cost Optimality Factor R for each pipe and for the whole network can be defined and it decreased from3.0 to 0.91.

REFERENCES

[1] Swamee PK. Design of Water Supply Pipe Networks. John Wiley & Sons: Hoboken, , NJ, USA, 2008.
[2] Cross H. Analysis of Flow in Networks of Conduits or Conductors. University of Illinois at Urbana Champaign, College of Engineering, Engineering Experiment Station: Urbana, IL, USA, 1936.
[3] Sonowal A. A mathematical model for the selection of an economical pipe size in pressurized irrigation systems. African Journal of Agricultural Research, 2016, India.

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https://doi.org/10.47001/IRJIET/2023.711010

[4] Sangroula U, H. K. Optimization of WDNs Using Genetic Algorithm Based SOP–WDN Program. Water, 2022, Basel, Swit-zerland.
[5] Mala Jetmarova H. Lost in optimisation of water distribution systems? A literature review of system operation. Environ. Model. 2017, Softw, 209–254.
[6] Brentan B.M. Near real time pump optimization and pressure management. Procedia Eng, 2017, 666–675.
[7] Jung D. Real-time pump scheduling for water transmission systems": Case study. KSCE J. Civ. Eng, 2015, 19, 1987–1993.
[8] Suribabu CR. Resilience-based optimal design of WDN. Appl Water Sci,2017, 4055–4066.
[9] Cimellaro GP. New resilience index for urban WDNs. J Struct Eng ASCE, 2015. doi: 10.1061/(ASCE)ST.1943-541X.0001433.
[10] Wang Q. Two-objective design of benchmark problems of a water distribution system via MOEAs: towards the best known approximation of the true Pareto front. Water Resour Plan Manag.2014. doi: 10.1061/ ASCE(WR).1943-5452.0000460.
[11] Lansey K. Optimization Model for Water Distribution System Design. Journal Hydraulic Div. Am. Soc.Civ.1989. Eng 115 (10), 1403.
[12] Makaya E. Water Distribution Systems Efficiency Assessment Indicators – Concepts and Application. International Journal of Science and Research (IJSR),2014, 219-228.
[13] Al-Washali T. Assessment of water losses in distribution networks: methods, applications, uncertainties, and implications in intermittent supply. Resour. Conserv. Recycle, 2020.
[14] Dai D. Optimal pressure management in water distribution systems using an accurate pressure reducing valve model based complementarity constraints PHAM. Water 13. 2021. (6).
[15] Kouchi D. Sensitivity of calibrated parameters and water resource estimates on different objective functions optimization algorithms. Water 9. 2017. (6).
[16] Menelaos P. Pressure regulation vs. Water aging in WDNs. Water, 2020, 12.
[17] Song W. Optimal Water Allocation Scheme in Integrated Water-Ecosystem-Economy System. 2019, 333-360.
[18] Xu Z. Urban water supply system optimization and planning: Biobjective optimization and system dynamics methods. Comput.2020. Ind. Eng. 142,106373.
[19] Lischer, Vance C. "Determination of Economical Pipe Diameters in Distribution Systems." Journal (American Water Works Association), vol. 40, no. 8, 1948, pp. 849–67. JSTOR, http://www.jstor.org/stable/41233042.
[20] National of Potable Water and Sanitation (NOPWASD) Price List (2022).
[21] Single Stage, End Suction & Inline Vertical & Horizontal Multistage Pressure Boosting Systems KSB Prices (June_2022).
[22] Arumugam A. Comparison and Validation of Models for the Design of Optimal Economic Pipe Diameters: A Case Study in the Anseba Region. Eritrea, Technologicas, 2021, Vol. 24, nro. 52, e1992.
[23] Mahmoud A. S, Naguib A.H, Abdelrazik M.H, Husssien H.M, "Criticality Analysis of Water Distibution Networks", P.hD, Thesis, Fac. of Engineering, Ain Shams Univ., Cairo, Egypt, 2023.
[24] Bagirov A.M., Barton A.F., An algorithm for minimization of pumping costs in water distribution systems using a novel approach to pump scheduling. Mathematical and Computer Modelling, 2013, Volume 57, Issues 3–4, Pages 873-886.
[25] Clark, Robert & Sivaganesan, Mano & Selvakumar, A. & Sethi, Virendra. Cost Models for Water Supply Distribution Systems. Journal of Water Resources Planning and Management. 128. 312-321. 10.1061/(ASCE)0733-9496(2002)128:5(312).

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