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Flow Analysis in Water Distribution Network under Throttle State of Valves

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Abstract:- The main objective of a water distribution network is to supply water at a sufficient pressure level and quantity to all its users. One of the crucial components is throttle or control valves, which play a critical role in a water distribution system for subsystem isolation and flow or pressure control. Water supply rates from the reservoir(s) which is the source can fluctuate from time to time based on water availability. Therefore, percentage of valve openings has to be adjusted corresponding to the supply rate to maintain the efficacy of the distribution system and to prevent water losses and breakage of apparatuses. The most proficient grouping of valve openings has to be set up for various supply quantities from the reservoirs to maintain the resourcefulness of the network system, keeping equitable distribution among demand nodes as to be satisfied criterion. In addition to adjust valve settings, upholding the economical network configuration, number and position of valves has to be customized on the basis of source connectivity and path of expected higher flow rate and head loss. This paper focuses on obtaining near-Pareto-optimal solution of valve settings to be changed according to the degree of water supply from the reservoirs using differential evolution algorithm with the help of EPANET, Visual Basic embedded in MS Excel. Resilience and reliability parameters are taken as decisive factors for this procedure. This methodology can be used to derive the best set of valve operating conditions for different rates of water supply for every major water distribution network in India to prevent wastage and to reduce water scarcity.

Keywords— Differential Evolution Algorithm, Resilience, Reliability, Pareto-optimal solution, Simulation

1. INTRODUCTION

Administering adequate amount of water of applicable quality and quantity has been one of the most important predicaments in human history. Today, a water supply system consists of infrastructure that collects, treats, stores, and distributes apposite amount of sanitary water between water sources and consumers with sufficient pressure. Curtailed natural water sources and booming population has led to the need for innovative methods to efficiently manage a water supply system. Many exertions on the development of a water supply system have been made through for sustainable water supply. As demand of water raise increasingly on the existing water supply system, many studies are attempted to develop a general water supply system to assist decision makers to design more reliable system for a long-range operation period. These attempts also include the optimization of total system construction and operation cost under intricate circumstances. This study concentrates on flow analysis of water in distribution network for varying degrees of supply range from reservoirs by manoeuvring settings of valves. The main objective is to combine the concept of equitable distribution of available water and the ability of the system to overcome failures to a single parameter. This parameter is termed as common factor and is optimized using Differential Evolution. EPANET2 and macro enabled Microsoft Excel are linked together to search out of optimal valve operations for different percentage of water supply.

The distribution network includes all parts of the water system past treatment. Typical components of the distribution network are storage tanks, reservoirs, pipes, valves, and hydrants. Generally, valves are used to isolate equipment, buildings, and other areas of the water system for repair as well as to control the direction and rate of flow. They are used to drain the system for seasonal shutdown. There are mainly three kinds of valves used. Start/Stop valve only starts or stops the flow of water without controlling/guiding/directing the water flow to any particular direction. Throttle or control valve controls the flow through the supply/distribution system. Check valve checks on the direction of flow. It allows the flow of water through them only in one direction. Mainly, used for preventing backflow to the system. Most valves serve two purposes namely, flow and pressure control and isolating subsystems due to breakage or contaminant containment. In this paper, valves are considered from the point of view of pressure head and controlling water supply. A common practice is to have minimum number of valves in a network as unity less than number of links. This necessitates for every cross-intersection there should be three valves and at every T-section there should be two valves in a network. However, valves suffer more from lack of use than from frequent use. Therefore, placement and configuration of valves is figured out based on source connectivity.

In a water distribution network, the hydraulic parameters, pressure (h) and demand (Q) at the nodes are essential for hydraulic analysis. Equations of Q and h are obtained from conservation of mass or continuity equation and Work- energy principle based either on Darcy-Weisbach or Hazen-Williams equation. Analytical method of solving a network involves complexity because the equations are non-linear in nature. Therefore, several numerical methods such as Hardy - Cross Method, Newton- Raphson Method etc., were used in hydraulics to solve such equations in 19th century. The Evolution of computers had accomplished the task of doing large number of iterations with high speed and accuracy. This paved the way to hydraulic simulation of WDS. One of the approaches of hydraulic simulation is Demand-Driven Analysis (DDA). DDA is carried out by assuming demand on each node in the network is always satisfied without

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considering the variation of flow with respect to nodal pressure. This drawback was overcome in Pressure-Driven Analysis (PDA) proposed first by Bhave [1]. Later several relations of nodal pressure and nodal flow were proposed.

EPANET2 is open software used for hydraulic simulations developed by Rossman [2] based on the global gradient algorithm of DDA suggested by Todini and Pilati [3]. One of the techniques to perform PDA model in EPANET2 is to insert artificial elements to all demand nodes. It does not require the need to use of programmer's toolkit. Series of Artificial Elements, suggested by Paez et al. [4], containing FCV-TCV-CV-RES arrangement with has been employed. Parameters of all elements are fixed as suggested. Wagner's [5] relationship of flow-pressure is the key principle adopted. Flow Control Valve (FCV) is placed to make sure that flow is not exceeding demand of node. Adding Throttle Control Valve (TCV) is to determine the flow when the nodal pressure is less than minimum pressure. It is achieved by adjusting Minor loss coefficient (k) of TCV. k is calculated based on the following formula.

$$k = \frac{2h_{min}gA^2}{Q^2} \tag{1}$$

Where, A is area of cross section of TCV, h_{min} is minimum required pressure at each node, Q is discharge through TCV, g is acceleration due to gravity. Reservoir in the series is to quantify flow. When nodal pressure is a negative real number or zero then flow may occur from artificial reservoir (RES) to the node in simulation. Hence TCV and RES are connected via a Check Valve (CV). The arrangement encompasses of two dummy nodes to link the valves and reservoir. Elevation of dummy nodes and reservoir head are kept as same as the demand node to which they are affixed.

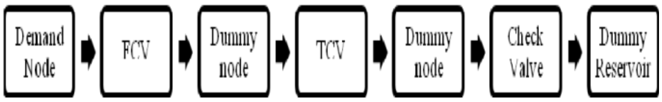

Fig. 1 Alignment of Artificial elements

The term Resilience Index, coined by Todini [6], relates nodal pressure and demand to address the intrinsic capacity of system to overcome failures.

$$ResilienceIndex = \frac{\sum_{i=0}^{n=13} Q_i * (p_i - p_{\min})}{\sum_{i=0}^{n=2} Q_{Res_i} * p_i - \sum_{i=0}^{n=13} Q_i * p_{\min}} \tag{2}$$

Where, Qi is the demand at each node, p_{min} is the minimum pressure required at each node, $QRes_i$ is the quantity of water supplied from reservoir. pi is pressure at each demand node.

Reliability of a water distribution network can be defined as the probability that the given demand nodes in the distribution system receive sufficient supply with satisfactory pressure head. Proper usage of weightage has made it easier to merge Resilience Index and Reliability into a sole element called common factor (CF).

Differential Evolution (DE), a meta-heuristics optimization method, is deployed here to maximize Common Factor for various percentages of water supplies. In general, any evolutionary method mimics the process of gene formation in nature. It is an iterative procedure involving crossover and mutation. DE, is one such method, applies crossover and mutation by means of factors to the generated matrix pool in consecutive sets.

Microsoft Excel is a spreadsheet which features calculation, graphing tools, pivot tables and a macro-enabled programming language called Visual Basic for Applications having an Integrated Development Environment (IDE). This utility can be used to incorporate the EPANET Toolkit. Its library has many functions that help us to retrieve and modify certain parameters of a network model before and after carrying out a hydraulic simulation. This permits us step-by-step control of its simulation process. Visual Basic module (epanet2.bas) and application extension file known as dynamic link library (epanet2.dll) are supplemented to enable access to the header file containing definitions of EPANET in-built functions.

2. LITERATURE REVIEW

This section presents the background to the methodology adopted and source for deciding on analysing dynamics of water flow in distribution network.

Suribabu [7] used Differential evolution algorithm for optimal design of water distribution networks. This paper deals with the application of one of the evolutionary methods to solve non-linear problems which is differential evolution algorithm. This paper gives an insight on how a simulation model of DE is created with the help of VISUAL BASICS to optimize the cost of network by selecting suitable measure for pipe diameter. The simulation is carried out for different sets of weightage factors and crossover probabilities and the results are compared to get best optimized value. Then model is illustrated with Hanoi network. Paez et al. [4] developed a Method for Extended Period Simulation of Water Distribution Networks with Pressure Driven Demands. This paper illustrates a simple way to carry out Pressure-Driven Analysis in EPANET-2 by introducing artificial elements in all demand nodes of the network. These artificial elements are created based on the Wagner's relationship between the flow and pressure. The method works both for single period simulation and extended period simulation.

3. METHODOLOGY

3.1 General

This paper presents a procedure to generate percentage opening of valves in a water distribution network for varying degrees of supply range from reservoirs without compromising resilience of the system. The simulation model can be applied to any water distribution network.

The method proposed here adds,

- Selection of a water distribution network, develop it as a prototype and benchmark it under generic conditions.
- Fixation of Position and number of throttle control valves based on source connectivity. Extraction of

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Loss coefficient of values for different percentage openings of the valve from the designer of valve.

- Insertion of artificial elements to all demand nodes in the network to carry out PDA in EPANET.
  Parameters of artificial elements to be entered are as follows,
- For FCV: Diameter = 1000mm, Setting = Demand of node
- For TCV: minor loss coefficient = k
- For CV: Diameter =1000 mm and Length = 0.001mm
- Addition of connection of flow control valve to all reservoirs to control the supply of water to the network.
- Incorporation of EPANET2.0, VISUAL BASIC FOR APPLICATIONS, AND MS EXCEL to compute desired values for different degrees of water supply.
- Application of Differential Evolution Algorithm. Set mutation factor (mf), cross-over probability (cr), number of trials and population size.
- Calculation of resilience, reliability of each demand node, percentage of total water supply and their ratio 'M'.
- Allocation of suitable weightages to different M values to achieve equitable distribution of the supplied quantity of water to all demand.
- Obtaining the product of sum of weightages and resilience as corresponding Common Factor for each set of valves operations.
- Finding the near-Pareto-optimal common factor for the given percentage of water supply from reservoirs.

3.2 Equations involved in calculating common factor

$$Reliability = \frac{Q}{Q_D} \quad (3)$$

Where, Q is the actual quantity of water supplied to the node. QD is theoretical design demand of the node.

$$Q_p = \sum_{i=0}^{n} x_i * Q_i \quad (4)$$

$$Q_R = \frac{Q_p}{Q_{total}} * 100 \quad (5)$$

Where, Q_i is designed supply of water supplied from i^{th} Reservoir. x_i is the percentage of supply of water from the respective Reservoir. Q_{total} is the total designed supply of water from all the reservoirs.

$$M = \frac{Reliability}{Q_R} \quad (6)$$

Weightages for categorizing 'M' factor is used to make the ratio to approach unity so that equitable distribution is mathematically achieved. For example, maximum weightage is given to unity and the weightage value decreases as 'M' factor moves away from unity.

$$CF = W * Resilience \quad (7)$$

Where, CF is Common Factor used to compile W factor and resilience.

International Journal of Engineering Research & Technology (IJERT)
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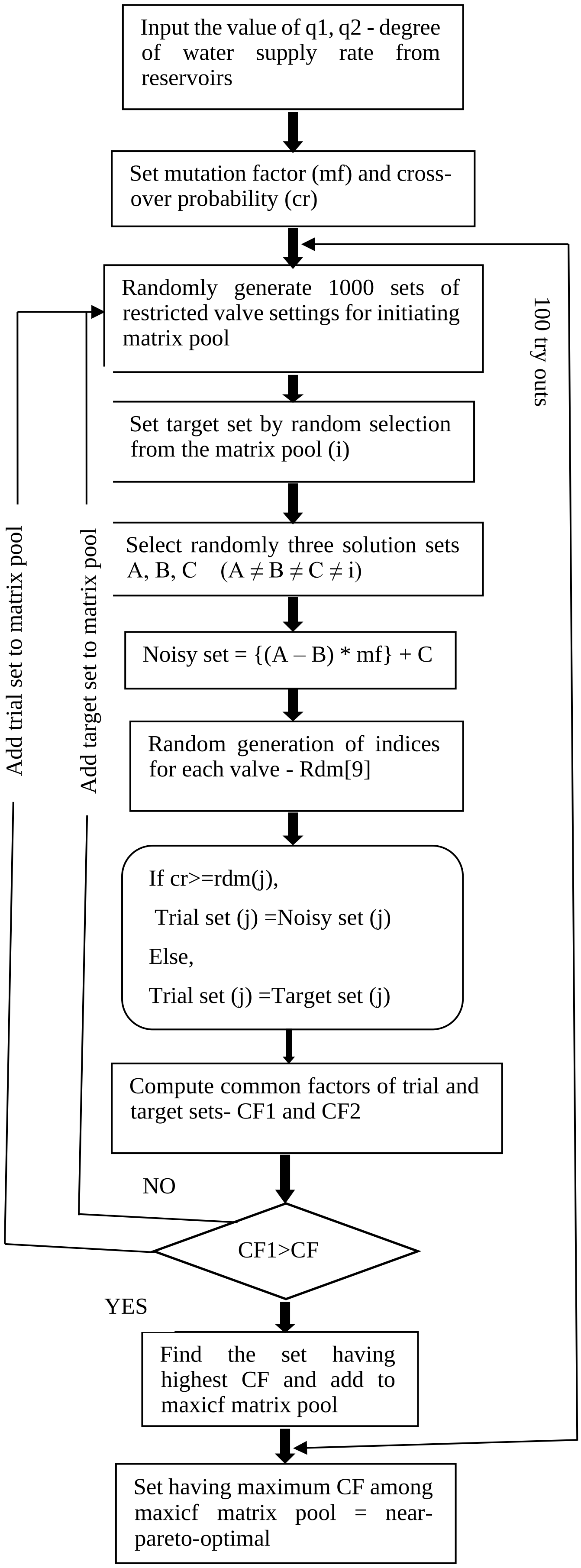
3.2 Differential Evolution Algorithm



4. Case Study

A benchmark Network with two reservoirs (Fig.2) is selected to perform desired experimentation. This particular network has 21 pipes linking and 13 nodes. Basic inputs such as properties of links, nodes are assigned as given in Table 2 and Table 3. Here gate valve is used as TCV and its loss coefficient corresponding to percentage opening is provided in Table 4. Allocation of weightages to 'M' factor is done as demonstrated in Table 1. Minor loss coefficients of TCV in series of artificial elements are calculated and the values with corresponding valve ID are listed in Table 7. To alter the supply from reservoirs percentage openings of FCV are discretized from a range of values to list of numbers. It is illustrated in Table 5 and 6. Mutation factor (mf) and cross-over probability (cr) are taken as 0.8 and 0.4 respectively. Differential Evolution is carried out by keeping 100 as the number of trials and 1000 as population size. . These data are fed to the program and near-Pareto-optimal CF is obtained. Table 8 is formatted to show optimized setting of valves for different combinations of degree of supply and corresponding CF.

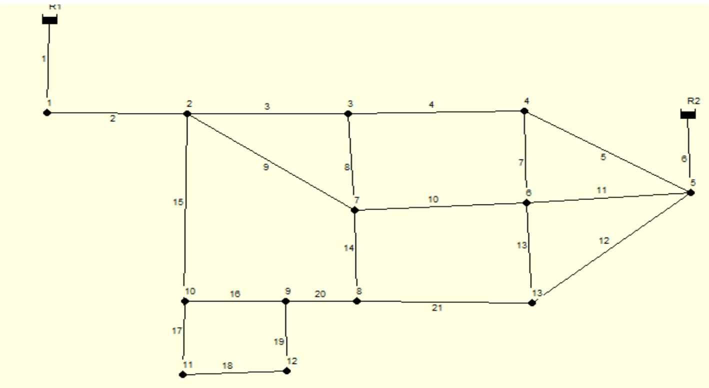


Fig .2 Benchmark Network

Table-1: Weightage Value corresponding to the range of 'M' factor

WEIGHTAGE ASSIGNED ' W'	RANGE OF M
0	0
	(17-37]
0.5	(10-17]
0.75	(8-10]
1	(6-8]
1.2	(4-6]
1.5	(2-4]
2	(0-0.2]
	(1.8-2]
3	(0.2-0.4]
	(1.6-1.8]
4	(0.4-0.6]
	(1.4-1.6]
5	(0.6-0.9]
	(1.1-1.4]
6	(0.9-1.1]
	(1-1.1]
7	1

Table – 2: Pipe Characteristics

Pipe ID	Length, m	Diameter, mm	Roughness Coefficient, H-W
1	609.60	762	130
2	243.80	762	128
3	1524.00	609	126
4	1127.76	609	124
5	1188.72	406	122
6	640.08	406	120
7	762.00	254	118
8	944.88	254	116
9	1676.40	381	114
10	883.92	305	112
11	883.92	305	110
12	1371.60	381	108
13	762.00	254	106
14	822.96	254	104
15	944.88	305	102
16	579.00	305	100
17	487.68	203	98
18	457.20	152	96
19	502.92	203	94
20	883.92	203	92
21	944.88	305	90

Table – 3: Node Characteristics

Node ID	Elevation, m	Demand, CMH
1	27.43	0.0
2	33.53	212.4
3	28.96	212.4
4	32.00	640.8
5	30.48	212.4
6	31.39	684.0
7	29.56	640.8
8	31.39	327.6
9	32.61	0.0
10	34.14	0.0
11	35.05	108.0
12	36.58	108.0
13	33.53	0.0
RES1	60.96	NA
RES2	60.96	NA

Table -4: Loss coefficient value VS valve opening

% Opening	Loss Coeffficient
0	CLOSED
5	120
10	100
15	50
20	26
25	15
30	12
35	9
40	7
45	6
50	5.5
55	5
60	4.5
65	4
70	4
75	4
80	4
85	4
90	4
95	4
100	4

Table - 5: Discharge of water from Reservoir 1 per % of supply

% of Water Supply	Discharge, CMH
0	0
10	224.49
20	448.98
30	673.47
40	897.96
50	1122.45
60	1346.94
70	1571.43
80	1795.92
90	202.41
100	2244.9

Table – 6: Discharge of water from Reservoir 2 per % of supply

% of Water Supply	Discharge, CMH
0	0
10	89.177
20	178.354
30	267.531
40	356.708
50	445.885
60	535.062
70	624.239
80	713.416
90	802.593
100	891.77

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Vol. 10 Issue 04, April-2021

Table – 7: Head loss coefficient values corresponding to Demand

Valve ID	Demand, CMH	K value
23	212.4	26
25	212.4	26
27	640.8	2
29	212.4	26
31	684.0	2
33	640.8	2
35	327.6	11
37	108.0	102
39	108.0	102

5. RESULTS AND DISCUSSION

Proper working of Differential Evolution algorithm is verified by plotting graph between trial number and highest value of Common Factor of the set among 1000 sets in the matrix pool for 20-30 combo (20% supply from Reservoir 1 and 30% supply from reservoir 2). The profile of obtained graph was a reasonable increasing curve. This also proves that the program set for running is working properly according to the formulated procedure.

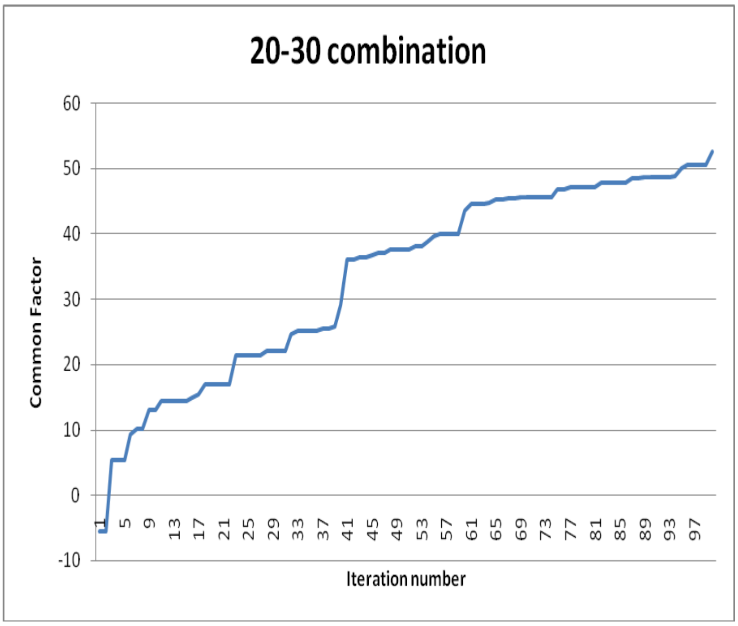

Fig 3 Graph between iteration number and Common Factor for 20-30 combination

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Table – 8: Near-Pareto-optimal solutions for different combinations of degree of supply

Reservoir 1	**Reservoir 2**	**Valve 1**	**Valve 2**	**Valve 3**	**Valve 4**	**Valve 5**	**Valve6**	**Valve 7**	**Valve 8**	**Valve 9**	**CF**
0	10	30	100	100	50	30	10	100	60	100	37.852
0	20	50	40	70	100	90	50	50	50	40	41.235
0	30	70	90	100	70	50	50	20	0	10	8.800
0	40	90	90	90	90	100	70	60	50	80	52.676
0	50	90	30	90	30	90	100	30	80	60	47.176
0	60	80	60	80	80	20	0	30	10	90	42.727
0	70	50	60	20	20	70	40	100	60	20	38.497
0	80	70	90	100	70	50	50	20	0	10	44.000
0	90	50	90	40	100	30	50	20	0	100	39.759
0	100	50	40	70	100	90	50	50	50	40	45.817
10	0	20	70	90	20	50	30	60	90	60	2.635
10	10	70	50	10	0	30	20	30	40	90	16.036
10	20	90	30	90	30	90	100	30	80	60	47.176
10	30	80	60	80	80	20	0	30	10	90	42.727
10	40	40	30	50	70	70	70	80	20	40	38.072
10	50	50	60	20	20	70	40	100	60	20	38.497
10	60	70	90	100	70	50	50	20	0	10	44.000
10	70	50	90	40	100	30	50	20	0	100	39.759
10	80	50	40	70	100	90	50	50	50	40	45.817
10	90	100	90	30	80	60	20	10	80	70	45.604
10	100	10	100	70	0	60	10	10	80	30	25.250
20	0	70	50	10	0	30	20	30	40	90	40.090
20	10	10	100	70	0	60	10	10	80	30	25.250
20	20	70	50	10	0	30	20	30	40	90	40.090
20	30	90	90	90	90	100	70	60	50	80	52.676
20	40	90	30	90	30	90	100	30	80	60	47.176
20	50	40	60	70	40	90	80	50	60	80	44.713
20	60	80	60	80	80	20	0	30	10	90	42.727
20	70	70	90	100	70	50	50	20	0	10	44.000
20	80	50	40	70	100	90	50	50	50	40	45.817
20	90	100	90	30	80	60	20	10	80	70	45.604
20	100	70	50	10	0	30	20	30	40	90	40.090
30	0	70	50	10	0	30	20	30	40	90	40.090
30	10	90	90	90	90	100	70	60	50	80	52.676
30	20	90	30	90	30	90	100	30	80	60	47.176
30	30	90	90	90	90	100	70	60	50	80	52.676
30	40	90	30	90	30	90	100	30	80	60	47.176
30	50	70	90	100	70	50	50	20	0	10	44.000
30	60	50	40	70	100	90	50	50	50	40	45.817
30	70	100	90	30	80	60	20	10	80	70	45.604
30	80	90	90	90	90	100	70	60	50	80	52.676
30	90	90	30	90	30	90	100	30	80	60	47.176
30	100	80	60	80	80	20	0	30	10	90	42.727
40	0	70	90	100	70	50	50	20	0	10	44.000
40	10	50	40	70	100	90	50	50	50	40	45.817
40	20	100	90	30	80	60	20	10	80	70	45.604
40	30	90	90	90	90	100	70	60	50	80	52.676
40	40	90	30	90	30	90	100	30	80	60	47.176
40	50	40	60	70	40	90	80	50	60	80	44.713
40	60	70	90	100	70	50	50	20	0	10	44.000
40	70	50	40	70	100	90	50	50	50	40	45.817
40	80	100	90	30	80	60	20	10	80	70	45.604
40	90	70	50	10	0	30	20	30	40	90	40.090
40	100	90	30	90	30	90	100	30	80	60	47.176
50	0	40	60	70	40	90	80	50	60	80	44.713
50	10	80	60	80	80	20	0	30	10	90	42.727
50	20	70	90	100	70	50	50	20	0	10	44.000
50	30	50	40	70	100	90	50	50	50	40	45.817
50	40	100	90	30	80	60	20	10	80	70	45.604
50	50	70	50	10	0	30	20	30	40	90	40.090
50	60	90	90	90	90	100	70	60	50	80	52.676
50	70	90	30	90	30	90	100	30	80	60	47.176
50	80	40	60	70	40	90	80	50	60	80	44.713

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50	90	80	60	80	80	20	0	30	10	90	42.727
50	100	50	60	20	20	70	40	100	60	20	38.497
60	0	30	100	100	50	30	10	100	60	100	37.852
60	10	50	40	70	100	90	50	50	50	40	45.817
60	20	100	90	30	80	60	20	10	80	70	45.604
60	30	90	90	90	90	100	70	60	50	80	52.676
60	40	40	30	40	90	100	50	90	80	80	37.590
60	50	90	30	90	30	90	100	30	80	60	47.176
60	60	40	60	70	40	90	80	50	60	80	44.713
60	70	40	30	50	70	70	70	80	20	40	38.072
60	80	50	60	20	20	70	40	100	60	20	38.497
60	90	50	40	70	100	90	50	50	50	40	40.726
60	100	90	90	90	90	100	70	60	50	80	40.970
70	0	90	30	90	30	90	100	30	80	60	47.176
70	10	40	60	70	40	90	80	50	60	80	44.713
70	20	40	30	50	70	70	70	80	20	40	38.072
70	30	50	60	20	20	70	40	100	60	20	38.497
70	40	30	100	100	50	30	10	100	60	100	37.852
70	50	50	40	70	100	90	50	50	50	40	45.817
70	60	100	90	30	80	60	20	10	80	70	40.537
70	70	90	90	90	90	100	70	60	50	80	46.823
70	80	10	40	30	30	10	90	90	60	90	0.000
70	90	40	90	70	90	70	50	80	60	40	0.000
70	100	10	20	10	60	60	60	80	70	60	0.724
80	0	40	30	50	70	70	70	80	20	40	38.072
80	10	50	60	20	20	70	40	100	60	20	38.497
80	20	30	100	100	50	30	10	100	60	100	37.852
80	30	50	40	70	100	90	50	50	50	40	40.726
80	40	100	90	30	80	60	20	10	80	70	40.537
80	50	10	70	80	10	40	20	90	60	50	0.000
80	60	40	90	70	90	70	50	80	60	40	0.000
80	70	90	90	90	90	100	70	60	50	80	0.000
80	80	40	30	40	90	100	50	90	80	80	0.000
80	90	90	30	90	30	90	100	30	80	60	0.000
80	100	40	60	70	40	90	80	50	60	80	5.962
90	0	40	30	50	70	70	70	80	20	40	3.807
90	10	10	40	70	60	60	40	90	30	40	5.580
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90	40	30	100	100	50	30	10	100	60	100	37.852
90	50	50	40	70	100	90	50	50	50	40	45.817
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90	80	40	30	40	90	100	50	90	80	80	37.590
90	90	90	30	90	30	90	100	30	80	60	47.176
90	100	40	60	70	40	90	80	50	60	80	44.713
100	0	90	50	30	40	60	70	10	30	20	0.000
100	10	30	70	60	70	20	20	70	60	80	0.000
100	20	50	60	90	90	50	90	50	60	20	0.000
100	30	50	90	40	100	30	50	20	0	100	4.418
100	40	40	30	40	90	100	50	90	80	80	5.012
100	50	40	80	40	30	20	20	50	40	10	5.506
100	60	90	50	30	40	60	70	10	30	20	6.029
100	70	10	40	70	60	60	40	90	30	40	22.322
100	80	50	60	20	20	70	40	100	60	20	46.196
100	90	30	70	60	70	20	20	70	60	80	43.995
100	100	40	60	10	20	50	20	60	30	100	39.908

6. CONCLUSION

This paper gave an insight on how to deal with managing steady and convenient flow of water in water distribution network. Whenever there is a fluctuation in the water supply rates from the reservoir. This approach can be used to determine the value adjusting to be made for every prominent change in the water supply for water distribution networks. This ensures reduction in leakages and increase in the durability of apparatuses in the network as the resilience factor is controlled. Also, as the reliability factor is taken into account for justifiable distribution of water among all demand nodes, consumer satisfaction is enhanced. If the prevailing handlings such as gauge measurements and controls, valve/pump operations, of WDN are completely digitalized, manoeuvring of WDN can be done remotely monitored and controlled. Internet of Things (IOT) can be incorporated in the digitized system. This paves way for quick and smart response by the system itself. This reduces human error and their involvement in regulating water supply in distribution network. By these tactics, sustainable and effectual usages of withstanding water resources can be done to ensure their future availability. For further study and exploration, by the domain of Computational Engineering, multiple simulation models can be explored using different software tools, apt methodologies, complex WDN benchmark layouts and setup configurations. In this research article, combination of streams of water resource engineering and software programming was used which further denotes that mathematical models can be incorporated for numerical analysis of structures and design layouts with the help of software tools.

7. REFERENCES

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