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Design of Optimal Water Supply Network and Its Water Quality Analysis by using WaterGEMS

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Abstract: ***Water supply network are costly infrastructure designed with an objective of minimizing the overall cost while meeting the water demand requirements in the sufficient quantity, quality and at satisfactory pressure i.e. finding out such an optimal geometrical layout which delivers known demands from source to all individual consumers for a long period. In this paper design of water supply network duly considering optimization in addition to the cost minimization, minimum head requirement and minimum chlorine requirement is presented. Gradient method is one in which the pipe discharges and nodal heads are taken as the basic unknowns in formulating the Q-H equations. The non linear Q-H equations for the pipe head loss are linearised and solved by Gradient method. WaterGEMS software algorithm is based on Gradient method gives optimal solution for the design of new as well as expansion of existing water supply network. The software also gives how the chlorine concentrations changes throughout the network. Water quality results are represented either using colour coding, tables or graphs and helps to discover what better initial values for chlorine concentration might be set in the network. Decision variables involves are pipe diameter, reservoir elevations and reservoir capacity etc. with flow as primary variable. A design is obtained duly considering minimum and maximum head and velocity criteria in order to determine the actual supply form each node to all consumers. In this paper a part of Aurangabad city is designed and its water quality (chlorine) analysis is done by WaterGEMS software.***

Keywords: WaterGEMS Software, Gradient method, Water supply network, Optimization, Water Quality Analysis

1. Introduction

A water supply network is an essential hydraulic costly infrastructure which is a part of the water supply system consists of a set of pipes, hydraulic devices and storage reservoirs. Water supply network systems are designed to deliver water from a source in the sufficient quantity, quality and at satisfactory pressure to all individual consumers. A supply network may have either branched, looped or combination of above type of configurations depending upon the layout of the existing area.

The aim is to design such an optimal geometrical layout which delivers known demands from source to all consumers for a long period of time. A design is obtained duly considering minimum and maximum head and velocity criteria in order to determine the actual supply form each node to all individual consumers. Decision variables involves are pipe diameter, reservoir elevations and reservoir capacity etc. with flow as primary variable. Water supply network must be designed based on least-cost considerations and not just to satisfy functional requirements.

Various investigators have worked on this area and proposed various models for the analysis and optimal design of water supply network (e.g. Saleh, H. A., and Tanyimboh, T. T. (2014), Taher, S. A., and Labadle, J. W. (1996), Alperovits, E. and Shamir, U. (1977)). Various researchers have proposed the use of mathematical programming techniques such as Linear programming gradient, Linear programming, Non linear programming, (e.g. Varma, et. al. (1997), Chiplunkar, A., and Khanna, P. (1983), Bhave, P. R. (1983),). Presently, researchers are designing water supply network using various softwares or Toolkit based on different analysis methods such as Gradient method, Hardy-Cross method, Newton-Raphson method, linear theory (e.g. Saleh, H. A., and Tanyimboh, T. T. (2014),. Vasan, A. and Simonovic, P. (2010)).

WaterGEMS software is developed for design and analysis of water supply network. The software is also used for expansion of existing water supply network. The software provide required standard and economical platform for design, analysis and troubleshooting of new and existing supply network with accuracy and minimum time duration. WaterGEMS software gives optimal solution of all type of network. The property of WaterGEMS software is that, it can be used to accurately simulate network before it has been built or modified. While simulation of network problems can be easily identified and removed them so that expensive error can be avoided.

In this paper the proposed method is illustrated through an application. Design of water supply network duly considering optimization in addition to the cost minimization, minimum head requirement and minimum residual chlorine requirement is presented. The software also gives how the chlorine concentrations changes throughout the network. Water quality results are represented either using colour coding, tables or graphs and helps to discover what better initial values for chlorine concentration might be set in the network i.e. water quality (Chlorine) analysis to check the minimum chlorine criteria at each node. In this paper a part of Aurangabad city is designed and its water quality (chlorine) analysis is done by WaterGEMS software.

2. Objectives

Water supply network are designed with an objective of minimizing the overall cost of network while meeting the water demand requirements at sufficient pressures for specified maximum discharge over a long period of time and also to provide possible overall minimum length network so as to have its operation and maintenance low and economical. Another objective is to perform water quality (Chlorine) analysis to check the minimum chlorine criteria at each node.

3. System Development

WaterGEMS software algorithm is based on Gradient method gives optimal solution. The software creates the network and by use of Model Builder transfers existing data on network then applies elevation data with Trex and take the demand using Load Builder and lastly goes for simulation of network for giving optimal design of water supply network.

Description of the Network Solution Algorithm used by WaterGEMS

The set of linearised equations for different pipes, Equation ${}_{t+1}H_i - {}_{t+1}H_j - (n\ R_{ox}\ |{}_tQ_{ox}|^{n-1})\ {}_{t+1}Q_x = (1-n)R_{ox}\ {}_tQ^n{}_{ox}$, $x = 1, \ldots, X$ (1) and the set of linear equations at the nodes of unknown HGL, Equation $\sum "x" connected\_to" j"\ {}_{t+1}Q_x + q_{o\,j} = 0$, $j = M + 1, \ldots, M + N$ (2) can be represented in matrix form as

$$\mathbf{A} \cdot \mathbf{B} = \mathbf{C} \quad (1)$$

In which **A** = coefficient matrix ($X + N$, $X + N$); **B** =column matrix of unknown parameters ($X + N$, 1); and **C** = column matrix ($X + N$, 1) showing the right hand side of Eq. (1) and Eq. (2).

Solution of Eq. (1) is

$$\mathbf{B} = \mathbf{A}^{-1} \cdot \mathbf{C} \quad (2)$$

In which $\mathbf{A}^{-1}$ = inverse of matrix A. this involves solution of a matrix of size ($X + N$, $X + N$)

Consider a network of one source and three demand nodes as shown below. Let H_{01} be the known HGL at source node 1; q_{02}, q_{03} and q_{04} be the demands at nodes 2,..4, respectively; and R_{01}, R_{02}, R_{03} and R_{04} be the resistance constraints constants of pipes 1,..4, respectively. Pipe discharges Q_1,..Q_4 and heads at demand nodes H_2, H_3 and H_4 are the unknown. The head loss in pipe is given by $R\ Q^n$.

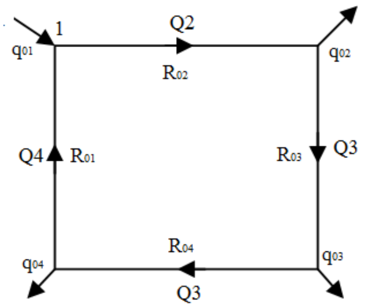

Figure 1: A one-source three demand node network

Linearised *Q-H* equations for pipes 1,..4 using Eq.(1) and after transferring unknown parameters on the left hand side and the known parameters on the right hand side, division by -1, and dropping the prefixing subscripts are

$$H_4 + nR_{01}\ |Q_{01}|^{n-1}\ Q_1 = H_{01} + (n-1)\ R_{01}\ |Q_{01}|^n \quad (3)$$
$$H_2 + nR_{02}\ |Q_{02}|^{n-1}\ Q_2 = H_{01} + (n-1)\ R_{02}\ |Q_{02}|^n \quad (4)$$
$$-H_2 + H_3 + nR_{03}\ |Q_{03}|^{n-1}\ Q_3 = (n-1)\ R_{03}\ |Q_{03}|^n \quad (5)$$
$$-H_3 + H_4 + nR_{04}\ |Q_{04}|^{n-1}\ Q_4 = (n-1)\ R_{04}\ |Q_{04}|^n \quad (6)$$

The node flow continuity equations for nodes 2,…4 are, respectively,

$$Q_2 - Q_3 = q_{02} \quad (7)$$
$$Q_3 - Q_4 = q_{03} \quad (8)$$
$$Q_1 + Q_4 = q_{04} \quad (9)$$

In a matrix form Eqs. (3) to (9) are

$$\begin{bmatrix} nR_{01}|Q_{01}|^{n-1} & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & nR_{02}|Q_{02}|^{n-1} & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & nR_{03}|Q_{03}|^{n-1} & 0 & -1 & 1 & 0 \\ 0 & 0 & 0 & nR_{04}|Q_{04}|^{n-1} & 0 & -1 & 1 \\ 0 & 1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} Q_1 \\ Q_2 \\ Q_3 \\ Q_4 \\ H_2 \\ H_3 \\ H_4 \end{bmatrix} = \begin{bmatrix} H_{01} + (n-1)R_{01}Q_{01}^n) \\ H_{01} + (n-1)R_{02}Q_{02}^n) \\ (n-1)R_{03}Q_{03}^n \\ (n-1)R_{04}Q_{04}^n \\ q_{02} \\ q_{03} \\ q_{04} \end{bmatrix} \quad (10)$$

Comparing Eq. (10) with Eq. (1), matrices **A, B** and **C** are find out.

By multiplying inverse of coefficient matrix **A** with **C**, we get **B** which provides the values of the unknown Q_1,..Q_4; and H_2, H_3 and H_4.

Matrices **A** ($X + N$, $X + N$), **B** ($X + N$, 1) and **C** ($X + N$, 1) are divided as

$$A = \begin{bmatrix} NA_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix},\ B = \begin{bmatrix} Q \\ H \end{bmatrix},$$

$$C = \begin{bmatrix} -A_{10}H_0 - A_{11}Q_0 + NA_{11}Q_0 \\ q_0 \end{bmatrix}$$

in which **N** and $\mathbf{A_{11}}$ = diagonal matrices of size (X,X); $\mathbf{A_{12}} = \mathbf{A_{21}}^{\mathbf{T}}$ = unknown-head node incidence matrix of size (X,N) ; $\mathbf{A_{22}}$ = 0, a null matrix of size (N,N); **Q** = column matrix of unknown pipe discharges of size (X,1); **H** = column matrix of unknown nodal heads, of size (N,1); $\mathbf{A_{10}}$ = known-head incidence matrix of size (X,M); $\mathbf{H_0}$ = column matrix of size (X,1); $\mathbf{q_0}$ = column matrix of known nodal demands of size (N,1).

The non-diagonal term in **N** and $\mathbf{A_{11}}$ is 0; and the diagonal term in **N** is n and that in $\mathbf{A_{11}}$ is $n\ R_{ox}\ |{}_tQ_{ox}|^{n-1}$. Elements in $\mathbf{A_{12}}$ and $\mathbf{A_{10}}$ are obtained using assumed flow direction in pipes. Flow direction in pipes connected to the source nodes should always be assumed from a source node to a demand node. Elements $\mathbf{A_{12}}$ (i,j) or $\mathbf{A_{10}}$ (i,j) = 1, if flow in pipe i enters node j; $\mathbf{A_{12}}$ (i,j) or **A10** (i,j) = 0, if pipe i is not connected to node j; and $\mathbf{A_{12}}$ (i,j) or $\mathbf{A_{10}}$ (i,j) = -1, if flow in pipe i leaves node j.

Substituting **A, B** and **C** in Eq. (1),

$$\begin{bmatrix} NA_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}\begin{bmatrix} Q \\ H \end{bmatrix} = \begin{bmatrix} -A_{10}H_0 - A_{11}Q_0 + NA_{11}Q_0 \\ q_0 \end{bmatrix} \quad (11)$$

Therefore,

$$\begin{bmatrix} Q \\ H \end{bmatrix} = \begin{bmatrix} NA_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}^{-1}\begin{bmatrix} -A_{10}H_0 - A_{11}Q_0 + NA_{11}Q_0 \\ q_0 \end{bmatrix} \quad (12)$$

or,

$$\begin{bmatrix} Q \\ H \end{bmatrix} = A^{-1}\begin{bmatrix} -A_{10}H_0 - A_{11}Q_0 + NA_{11}Q_0 \\ q_0 \end{bmatrix} \quad (13)$$

Matrix equation, Eq. (13) is simplified for **Q** and **H** bearing in mind the following: (1) nowhere the inverse of non-square matrix is obtained; (2) $\mathbf{NA_{11}}$ = a diagonal matrix of size (X,X) in which diagonal element is $nR_{ox}|Q_{ox}|^{n-1}$; and (3) $\mathbf{A_{21}(NA_{11})^{-1}A_{12}}$ = a symmetrical matrix of size (N,N), whose diagonal element (j,j) is positive summation of $\mathbf{(NA_{11})^{-1}}$ for all pipes connected at the unknown-head nodes j, and non-diagonal element (j,jj) is negative summation of for all pipes connecting node j with other unknown- head node jj.

Now obtaining $\mathbf{A^{-1}}$ separately using matrix property $AA^{-1} = I$

$$\begin{bmatrix} NA_{11} & A_{12} \\ A_{21} & 0 \end{bmatrix} A^{-1} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \quad (14)$$

Let us assume $\mathbf{NA_{11} = D^{-1}}$, therefore $\mathbf{DA_{11} = N^{-1}}$. Modifying Eq. (14) by replacing $\mathbf{NA_{11}}$ by $\mathbf{D^{-1}}$

$$\begin{bmatrix} D^{-1} & A_{12} \\ A_{21} & 0 \end{bmatrix} A^{-1} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

Multiplying first row by **D**

$$\begin{bmatrix} 1 & A_{12}D \\ A_{21} & 0 \end{bmatrix} A^{-1} = \begin{bmatrix} D & 0 \\ 0 & 1 \end{bmatrix}$$

Multiplying first row by $\mathbf{A_{21}}$ and subtracting it from the second row

$$\begin{bmatrix} 1 & A_{12}D \\ 0 & -(A_{12}DA_{21}) \end{bmatrix} A^{-1} = \begin{bmatrix} D & 0 \\ -(DA_{21}) & 1 \end{bmatrix}$$

Multiplying second row by $\mathbf{-(A^{12}DA^{21})^{-1}}$

$$\begin{bmatrix} 1 & A_{12}D \\ 0 & 1 \end{bmatrix} A^{-1} = \begin{bmatrix} D & 0 \\ (DA_{21})(A_{12}DA_{21})^{-1} & -(A_{12}DA_{21})^{-1} \end{bmatrix}$$

Multiplying second row by $\mathbf{A_{12}D}$ and subtracting it from the first row

$$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} A^{-1} = \begin{bmatrix} D-(DA_{21})(A_{12}DA_{21})^{-1}(A_{12}D) & (A_{12}DA_{21})^{-1}(A_{12}D) \\ (DA_{21})(A_{12}DA_{21})^{-1} & -(A_{12}DA_{21})^{-1} \end{bmatrix}$$

Eliminating identity matrix

$$A^{-1} = \begin{bmatrix} D-(DA_{21})(A_{12}DA_{21})^{-1}(A_{12}D) & (A_{12}DA_{21})^{-1}(A_{12}D) \\ (DA_{21})(A_{12}DA_{21})^{-1} & -(A_{12}DA_{21})^{-1} \end{bmatrix}$$

Substituting A^{-1} in Eq. (13)

$$\begin{bmatrix} Q \\ H \end{bmatrix} A^{-1} = \begin{bmatrix} D-(DA_{21})(A_{12}DA_{21})^{-1}(A_{12}D) & (A_{12}DA_{21})^{-1}(A_{12}D) \\ (DA_{21})(A_{12}DA_{21})^{-1} & -(A_{12}DA_{21})^{-1} \end{bmatrix} \begin{bmatrix} -A_{10}H_0 - A_{11}Q_0 + NA_{11}Q_0 \\ q_0 \end{bmatrix} \quad (15)$$

Simplifying Eq. (15) for unknowns, **Q** and **H**, substituting $\mathbf{D= NA_{11}^{-1}}$ and reintroducing prefixing subscript,

$$_{t+1}\mathbf{H} = -[\mathbf{A_{21}(NA_{11})^{-1}A_{12}}]^{-1} . [\mathbf{A_{21}(NA)^{-1}}](\mathbf{A^{11}}\,_{t}\mathbf{Q} + \mathbf{A_{10}H_0}) - (\mathbf{A_{21}}\,_{t}\mathbf{Q} - \mathbf{q_0})] \quad (16)$$

$$_{t+1}\mathbf{Q} = (\mathbf{I-N^{-1}})_t\,\mathbf{Q} - [\mathbf{N^{-1}}\,\mathbf{A_{11}^{-1}}(\mathbf{A_{12}}\,_{t+1}\mathbf{H} + \mathbf{A_{10}H_0})] \quad (17)$$

For the assumed or known values of pipe discharges, Eq. (16) provides improved nodal heads, and corresponding improved pipe discharges for the improved nodal heads are obtained by Eq. (17). The maximum size of matrix involved is (X, X) against $(X+N, X+N)$ required in the solution of matrix equation, Eq. (1).

4. Results and Discussion

Present Water Supply Condition: The method is illustrated with an application to study the various design constraints. Aurangabad City is situated in central part of Maharashtra State. However, a part of water supply network of area from Aurangabad city is considered for optimal design purpose. The source for the study area is in the form of ESR which is located at N-8, Aurangabad with an average ground level of 595.43 m, staging height of 15 m and with a fixed capacity. Various pipe materials such as R.C.C., C.I., and Asbestos cement are laid in the city for the supply system and for feeding ESR.

Data collection:

The following data need to collect while finding out optimal design of water supply system;

Capacity and Location of ESR

Existing water supply network information

All Controlling levels of ESR

All Reduced levels of all components in supply network

Table 1: Daily Water Demand

Particulars	Present Stage Year 2015		Ultimate Stage Year 2045	
	Popul-ation	Qty MLD	Popul -ation	Qty MLD
Domestic Demand	7296	0.985	22645	3.057
Institutional Demand		0.148		0.459
Public Use Demand		0.099		0.306
Total Net Demand		1.231		3.821
Total Gross Demand with 15% Losses		1.449		4.496
Max.Design Demand (2.7 x Total Gross)		3.911		12.139

Rate of Lpcd is assumed as 135, Institutional Demand as 15%, Public Use Demand as 10%. Therefore, total per capita demand calculated comes equal to 200 lpcd.

Hazen William's formula for calculating head loss;

$V = 0.85C_H R^{0.63} S^{0.64}$

where,

C_H = Dimensionless Hazen Williams Coefficient

R = Hydraulic radius of the pipe in m

S = Slope of section

V = Flow velocity through pipe in m/sec

The WaterGEMS software also gives how the chlorine concentrations changes throughout the network. Water quality results are represented either using colour coding, tables or graphs and check the minimum chlorine criteria at each node so as to discover what better initial values for chlorine concentration might be set in the network.

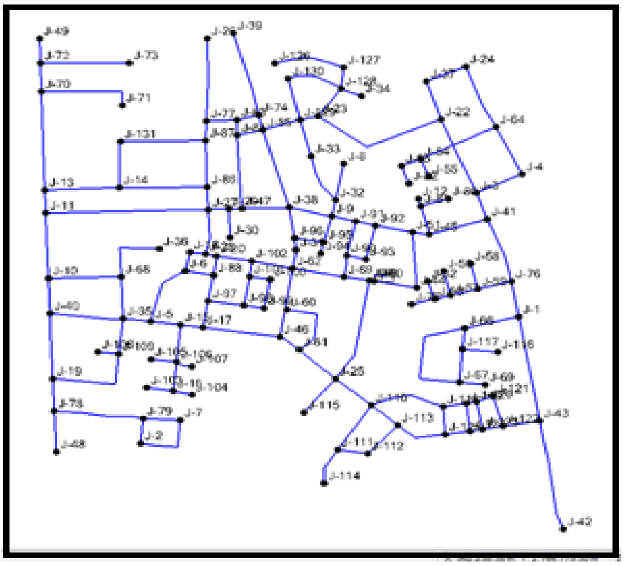

Figure 2: Real network showing all Nodes

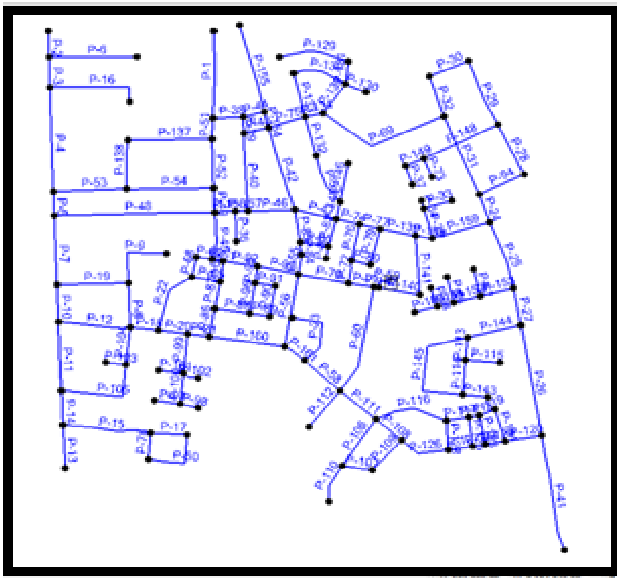

Figure 3: Real network showing all Pipe sections

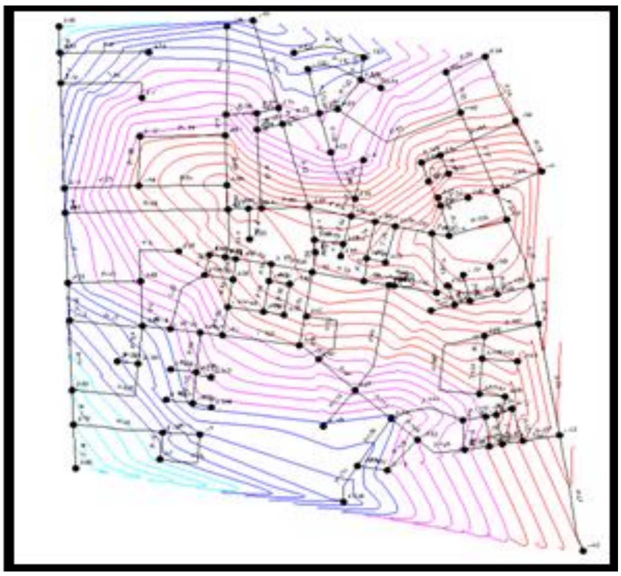

Figure 4: Real network showing Contour lines

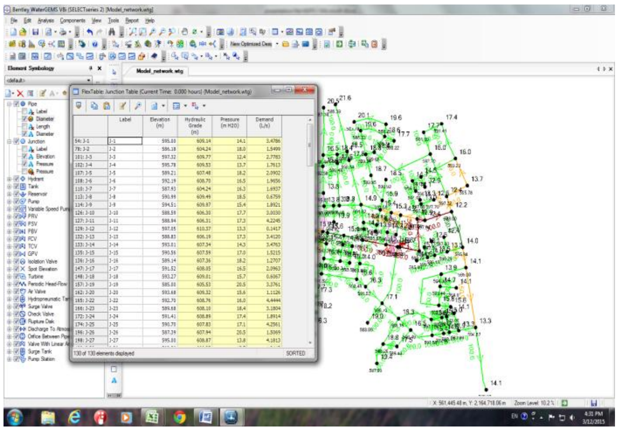

Figure 5: Optimal layout of network with Node data for DI pipe

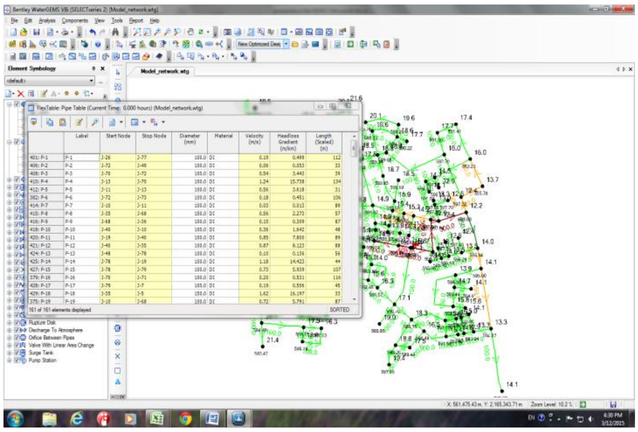

Figure 6: Optimal layout of network with Pipe section data for DI pipe

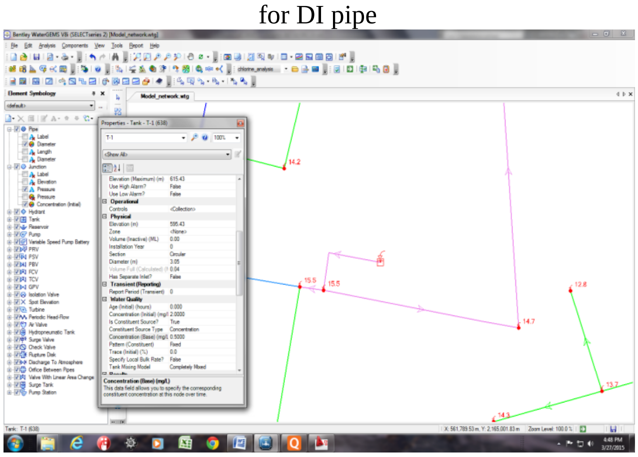

Figure 7: Tank's initial chlorine concentration for network

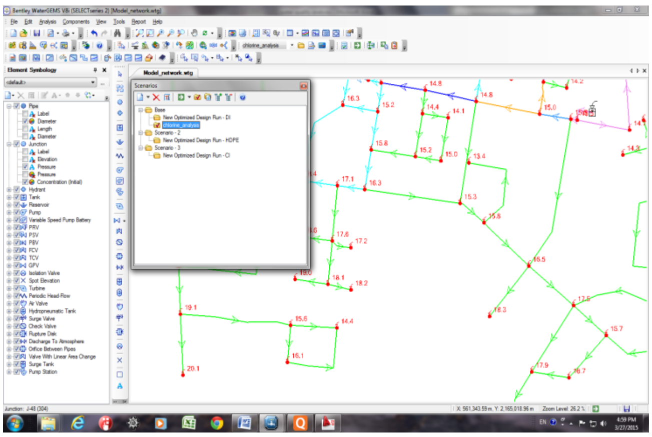

Figure 8: Water quality (Chlorine) Analysis of network

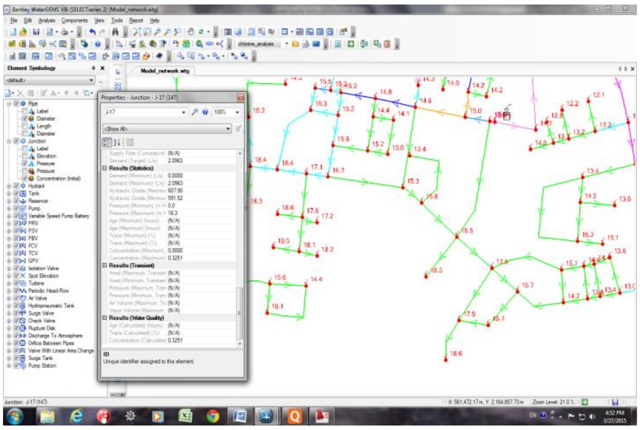

Figure 9: Calculated Chlorine (water quality) concentration at a Node

5. Conclusion

In this paper WaterGEMS software is used for obtaining optimal design of water supply network of a part of Aurangabad city. With the help of WaterGEMS software design of optimal water supply network and its water quality analysis (chlorine analysis) is done with achieving objective of minimizing the overall cost while meeting the water demand requirements at sufficient pressures for specified maximum discharge over a long period of time.

The software also gives different alternative optimal design solution considering pipe diameters, pipe material and roughness coefficient based on head dependent analysis. Mainly in water quality analysis, this software calculates the chlorine concentration with respect to the given initial concentration at all the nodes in water supply network and helps to discover what better initial values for chlorine concentration might be set in the network.

The WaterGEMS software provide required standard and economical environment for design, analysis and troubleshooting of new and existing supply network with accuracy and minimum time duration . The software is also used for solving problems in existing network and also in expansion of existing water supply network.

6. Acknowledgement

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