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Effect of Booster Disinfection on Water Quality Behaviour in Distribution Networks

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***Abstract*: The analysis of hydraulic behaviour of water distribution networks (WDNs) is prime part of the planning and augmentation of any water supply projects. In addition to the hydraulic behaviour, water quality analysis is also essential to safeguard the consumer from the water-borne diseases. The quality of water varies from the treatment plant to the consumer's tap due to physical, chemical and biological phenomena. Due to low cost and effectiveness, chlorine is a chemical choice as disinfectant in many countries including India. Chlorine residuals decreases from water treatment plant to the consumer's tap due to various reasons including bulk decay of chlorine, wall decay, coliform regrowth or potential for biofilm formation within the system. It is found that there are higher and lower residual chlorine concentrations of water to the nearby and far-off nodes respectively from the reservoir. So the booster locations are identified and introduced to maintain the desired residual chlorine concentrations of water to all nodes and at different times. It also reduces the total amount of chlorine required for the disinfection. In this study, the amount of chlorine required for disinfecting the water supply without and with booster stations are analyzed. Incorporation of the booster station further reduces the amount of chlorine required for variable demand pattern as compared to constant demand pattern. It is found that the variable demand pattern has significant advantages over constant demand pattern.**

Keywords:chlorine, disinfection, EPANET, variable demand pattern, water distribution network, water quality

I. INTRODUCTION

The analysis of hydraulic behaviour of water distribution networks (WDNs) is prime part of the planning and augmentation of any water supply projects. In addition to the hydraulic behaviour, water quality analysis is also essential to safeguard the consumer from the water-borne diseases. The quality of water may be different from the treatment plant to the consumer's tap due to physical, chemical and biological phenomena. Water distribution systems frequently draw water from multiple sources, such as a combination of wells, or different surface sources, or both. Mixing of water from different sources take place within the distribution system, and is a function of complex system hydraulics. For these reasons the quality of delivered water to the consumer may vary spatially and temporally within the distribution system [1].

Occurrence of water-borne diseases in India is mainly due to contamination of drinking water with municipal sewage and industrial waste at different points of the water distribution network and lack of water disinfection practices and water quality monitoring at treatment plants.

In India, chlorination is practiced at most of the filtration plant as means of water disinfectant, and it is supplied to the public via distribution network. The maintenance of chlorine residue is needed at all points in the distribution system supplied with chlorine as disinfectant [2]. Chlorine residuals of drinking water have long been recognized as an excellent indicator for studying water quality in the distribution network ([3], [4]). Chlorine decay in distribution systems is generally considered to be composed of two components. One component is wall decay and the other is associated with decay in the bulk phase of water [5].

Chlorine residuals decreases from water treatment plant to the consumer's tap due to various reasons including bulk decay of chlorine, wall decay, coliform regrowth or potential for biofilm formation within the system. A mass-transfer based model for predicting chlorine decay in water distribution networks that applies to unsteady flow under both turbulent and laminar conditions. This model considers the first order reactions of chlorine to both in the bulk and wall decay [6].

Chlorine is used to minimize the risk from micro-biological contamination. However, chlorine or other disinfectants interact with the natural organic matter in treated water to form disinfection by-products (DBP). Raising the pH of treated water may assist in controlling the corrosion but will increase the formation of tri-halomethanes (by products of chlorine disinfectant). Since the THMs are carcinogenic, this is not desirable. There is a trade-off between providing enough residual to ensure the micro-biological safety of the water supplied, and adding too much disinfectant, which can lead to taste, odour, or by-product problems.

Long retention times are very significant with regard to the concentrations of various contaminates and substances as they propagate through the system. For example, it is well known that tri-halomethanes (THM) increase with time and that chlorine decays over time. Clark et al. [7] suggested from their study that potential degradation of water quality due to long residence time associated with storage tanks and highlighted the importance of tank design and operation in affecting water quality.

Chlorine reacts with organic and inorganic compounds. In addition to minimize the microbial regrowth and to provide protection against pathogen intrusion, a chlorine residual of at least 0.2 mg/l needs to be maintained in the distribution system. Therefore, the disinfection dose must meet the demand in the treated water in order to provide protection against microbial infection and simultaneously minimize the protection of DBPs.

Booster disinfection is the addition of disinfectant at locations distributed throughout water distribution systems. Such strategy can reduce the amount of disinfectant required to maintain a detectable residual at points of consumption in the distribution systems, which may lead to reduced formation of disinfectant by-products in particular in tri-halomethanes. The booster disinfection can reduce the amount of disinfectant required to satisfy concentration constraints, when compared to conventional disinfection only at the source. Optimal booster schedule reduces the average disinfectant concentration within the distribution system and, in some cases, the variability of these concentrations.

II. LITERATURE REVIEW ON WATER QUALITY MODELLING

EPANET model developed by Rossman [6] determines the unsteady chlorine concentrations in the distribution systems. It performs both extended period hydraulic and water quality simulations on complex pressurized pipe networks. Rossman et al [8] presented in their paper how EPANET can be used to calibrate the model to field observation and its ability to match measured changes in chlorine levels throughout the system over time.Also they observed that the overall rate of the wall reaction is a function of the rate of mass transfer of chlorine to the wall and is therefore dependent on pipe geometry and the flow regime. It was explained by field observations that higher chlorine decay rates associated with smaller pipe sizes and higher flow velocities. Similarly, Clark et al. [5] showed how chlorine residuals can vary throughout the day at different locations in a distribution system depending on the flow path and residence time of the water reaching a location. The chlorine residual losses were predicted and problems of maintaining chlorine residuals were verified by field study. It shows chlorine residual loss is influenced by pipe wall demand, residence time, velocity, pipe radius, and bulk water demand [9]. A model proposed to simulate fluoride and chlorine propagation in a real network for which published data of field measurements and simulation with EPANET advection-dispersion model [10]. Comparisons are presented which show that, while for high and medium pipe-flow velocities the two models give similar results, for low pipe velocities the new advection-dispersion model predicts more closely the concentration evolution, provided an appropriate value for the dispersion coefficient.

A computer model was presented by Islam and Chaudhry [11] to directly calculate the chlorine concentrations needed at source(s) to have specified residuals at given locations in a pipe network in unsteady flow conditions by using an inverse method. To maintain safe levels of chlorine, higher amounts of chlorine at the source is required. This may be undesirable due to bad taste and odour and even cause to carcinogenic.

Clark and Sivaganesan [12] formulated a model that predicts both the total tri-halometanes (TTHMs) and chlorine residuals based on the consumption of chlorine and can be used to assist in evaluating complex balance between microbial and DBPs risks associated with disinfecting drinking water with chlorine.

Boccelli et al. [13] developed a matrix generator code to interface with EPANET to determine the optimal schedule of booster disinfection. Tryby et al. [14] extended the model proposed by Boccelli et al. [13] treating the booster locations as variables and solving a mixed-integer linear programming (MILP) problem.

Munavalli and Mohan kumar [15] illustrated the usefulness of the inverse model to identify appropriate reaction kinetics and its capability to estimate the corresponding unknown wall reaction parameters. Further, Munavalli and Mohan kumar [16] formulated a non-linear optimization problem and solved using a genetic algorithm (GA) to estimate the source dosage for any combinations of water quality sources such that the resulting nodal chlorine concentrations are nearest to the specified minimum value at all monitoring nodes at all times.

Multi-objective genetic algorithm (MOGA) called elitist non-dominated sorting genetic algorithm (NSGA-II) were used by Prasad et al. [17] to minimize the total disinfectant dose and maximization of the volumetric demand within specified residual limits. The model utilizes the theory of linear super position in water quality modelling (EPANET) for concentration profiles at network nodes. EPANET combined with genetic algorithm (GA) to study booster disinfection dosing problem, including daily pump scheduling, for a real system [18].

Literature review shows the need of appropriate dose and location of chlorination injection. Hence this study attempts in finding the amount of chlorine required for disinfection with and without the booster station in order to maintain the desired level of residual concentration at different locations. However, the booster locations are identified based on the availability of residual chlorine and practical consideration.

III.ASE EXAMPLE

An existing WDN of Itanagar is selected to evaluate the performance of the water quality behaviour with and without booster station under constant and variable demand pattern. Itanagar is the capital city of Arunachal Pradesh in the North East State of India. It is situated at coordinates of 27°06'00" North latitude and 93°37'12" East longitude and at an average altitude of 440 metres above MSL. The location of the Itanagar city is shown in Fig.1. The augmentation of water supply for Itanagar-township is implemented in two phase's viz. Phase I and Phase II. The total augmentation of water supply combining Phase I (7MLD) and II (11MLD) project is 18 MLD inclusive of 15% unaccounted for water (UFW) for the population of 1,41,619 to be fed till design period of 2023. The net quantity of water supplied from the both phases is to be 1,56,52,174 L/day (181.158 L/s).

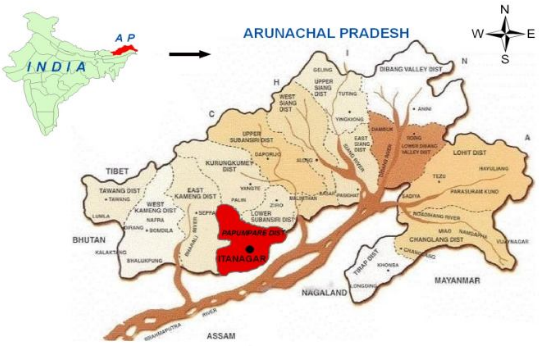

Fig. 1 Location map of Itanagar city

The entire Itanagar network area is divided into three zones viz., Zone I (Mowb II Zone), Zone II (Microwave Zone) and Zone III (R.K. Mission Zone). The schematic diagram of the Itanagar WDN is shown in Fig. 2. Three tanks are situated at Mowb II area receiving treated water supply from the two sumps tank of clear water reservoirs (CWRs). The bottom elevations of all the three tanks are 458.5 m. The elevations of the nodal junctions are varying from 225 m (node 31) to 506.75 m (Raj Bhawan area, node 24), above MSL. The total head of CWR node 49 and 50 is 294.71 m and 517 m respectively. The elevation level of all nodes including reservoirs, tanks are shown in Fig. 3. The pipe diameters varying from 100 mm to 400 mm are used to convey the water from the CWR to all junction nodes. They are made of ductile iron, mild steel and galvanised iron having Hazen William's roughness coefficient of 140,120 and 100 respectively. The water demands of Zone I, Zone II and Zone III are 100.372, 28.788 and 51.998 L/s respectively. Combined with three zones, the total water demand is 181.158 L/s.

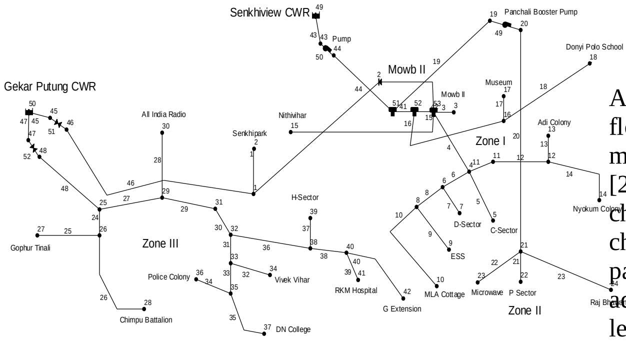

Fig. 2 Schematic of Itanagar water distribution network

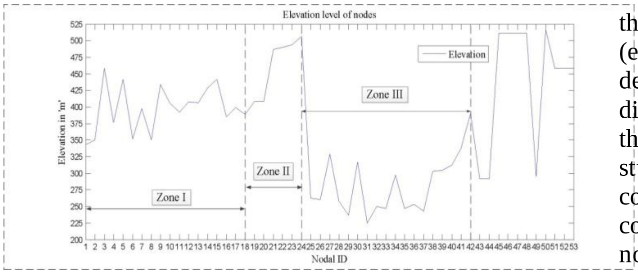

Fig. 3 Elevation level of nodes

Two flow control valves (FCV) are used to regulate the supply from CWR 50. The FCV 51 is adjusted to regulate the flow of 58.711 L/s to Zone I and FCV 52 is adjusted to regulate the flow of 51.998 L/s to Zone III. Likewise, the pump 50 also designed to discharge the supply of 70.451 L/s. These flows are maintained to equate the total inflow from both CWRs to meet all nodal demands. Though FCV will create the desired pressure drop [19], this procedure requires accurate measurement or computation of pressure at outlets. The Itanagar water supply system is operated by combined gravity and pumping system. The reservoir 49 has to supply 70.451 L/s as per design. So it is required to design the pump to meet specific flow as per EPANET [20]. Hence, a pump curve relationship is adopted between the head delivered by the pump as 197.26 m and the flow through the pump as 70.451 L/s for constant demand pattern of supply.

III. SIMULATION PARAMETERS FOR WATER QUALITY

A water quality source, where the quality of the source flow entering the network is defined as a concentration, mass booster, flow paced booster and set-point booster [20]. The term "water quality source" used here refers to chlorine source node. A concentration source maintains a chlorine concentration of specified value and a time pattern at the source node. A mass booster source always adds a specified mass flow rate (mg/min) to any water leaving the source node. A flow paced source adds the specified chlorine concentration of a certain time pattern to the concentration already resulting from incoming pipe flows at the node. A set-point booster source fixes the concentration of any flow leaving the node, as long as the concentration from all inflow to the node is below set-point. A set-point is the desired chlorine concentration to be maintained at that node at all times.

The concentration-type source is best used for nodes that represent source water supplies or treatment works (e.g., reservoirs or nodes assigned as negative demand).The booster type source is best used to model direct injection of a tracer or additional disinfectant into the network or to model a contaminant intrusion. In this study, water quality sources in CWRs are considered to be concentration type. The chlorine concentrations are added continuously in the range of 5 mg/L from each CWR node.

In this network, total duration of the simulation is taken as 24 hours with hydraulic time step of 1 hour and quality time step of 5 minutes for all scenarios of the simulation. Hydraulic time step determines how often a new hydraulic state of the network is computed. Quality time step is the time step used to track the changes in water quality throughout the network. It is normally taken as 1/10 of the hydraulic time step [20]. Pump efficiency is taken as 75%. The concentration of chlorine is assumed to be completely mixed within tanks. The bulk reaction parameters can be estimated by bottle tests, whereas the wall reaction parameters of each pipe are difficult to determine in the field [15].

Hence the global bulk decay coefficient is 0.55/d and global wall decay coefficient is 0.36 m/d for all pipes are used to model disinfectant decay reaction [16]. Generally it is reasonable to assume, first order kinetics for both bulk reaction and wall reaction for network modelling purposes [21].

V. RESULTS AND DISCUSSIONS

The accurate measurement of chlorination is a very important control tool for efficient and proper doses of chlorine. As per Indian drinking water quality standards, physcio-chemical parameters of water quality at consumer end must meet after conventional treatment followed by disinfection. The desirable limit of residual free chlorine is given as 0.2 mg/L [22]. A chlorine concentration level of 5 mg/L is maintained at the sump of CWRs. The desirable residual chlorine concentration should not be less than 0.2 mg/L at all nodes and at different times. After simulation, the desirable residual chlorine concentration was observed in Zone III except the distribution nodes of 30 and 42 after 3.00 hrs. Similarly, in Zone II the minimum residual chlorine concentration has been observed (except at distribution node 24 as 0.135 mg/L). But in Zone I, all nodal junctions receive residual concentration below 0.1 mg/L except the distribution node 15. Node 1, 2, 14, 16, 17and 18 has received residual chlorine of 0.00, 0.00, 0.197, 0.075, 0.073 and 0.00 mg /L after 7.00 hours starting of the simulation. The distribution node 2 has received water from the distribution main pipe line of 400 mm diameter ductile iron pipe which is connected with CWR node 50.

It shows that chorine concentration is consumed by bulk flow and wall reaction before to reach junction node 1. So, this will affect the residual chlorine level of Zone I network. It clearly shows that tank node 51, 52 and 53 having chlorine concentration level of 2.611, 1.366 and 0.368 respectively at 7.00 hrs. Node16, 17 and 18 have concentrations level 0.159, 0.154 and 0.00 mg/L respectively (below 0.2 mg/L) at 9.00 hrs. It is customary to adopt the booster disinfection location to get the desirable residual chlorine at node 18 and at all other nodes. Fig. 4 shows the residual chlorine concentrations for the different time periods. Among the three zones considered, Zone I network nodes have the least residual chlorine. This Zone is fully dependent on the out flow of CWR node 50 which is about 15 km away from the tank node 53. Tank node 53 receives water from tank node 52 at first three hours. All distribution nodes have the residual chlorine less than 2.63 mg/L. Fig. 5 shows the residual chlorine availability at selected nodes. In this Fig, node 25 is not a distribution node and is the first node to get water from CWR node 50 which is about 8.20 km away from source node. Hence, it gets the highest of residual chlorine of about 3 mg/L available among all nodes.

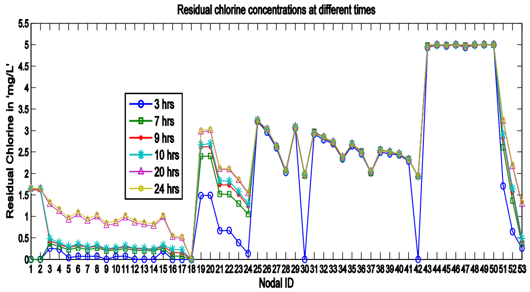

Fig. 4 Residual chlorine concentrations at selected times

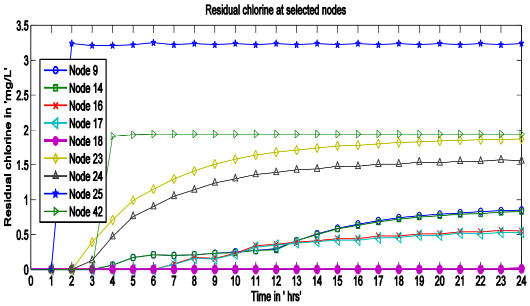

Fig. 5 Residual chlorine concentrations at selected nodes

The total amount of chlorine required for the disinfection purpose per day is about 78 kg with input concentration of chlorine as 5 mg/L. Out of this 78 kg, 34.9 kg is lost due to reaction with bulk flow, pipe wall reaction and tank reaction. The corresponding percentage of reaction is occurred with the system is shown in Fig. 6. The percentage contribution of reactions with bulk flow, wall and tank are 10.74, 81.86 and 7.4 respectively. Total quantity of chlorine consumed for reaction with bulk flow, wall and tank are 3.7, 28.6 and 2.6 kg for 24 hrs simulation period. Out of which wall reactions consume more chlorine; it shows the actual condition of the pipe roughness and pipe materials.

Sharp et al. [23] suggested from their experimental results that the unlined cast iron pipe has higher chlorine consumption than polyvinyl chloride pipe (PVC) and that of the larger diameter cast iron pipe has lower consumption than the smaller diameter pipe.

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Conventionally chlorine dosage is added at the source location only. So chlorine dosage requires large amount at the source location to get the desirable residual concentration for all nodes. Higher dose of chlorine is uneconomical and has adverse health impact due to disinfection by products. The multiple source disinfection location can be identified using direct analysis of water quality models. But it is a tedious trial and error process in which it is difficult to identify the proper location for large networks.

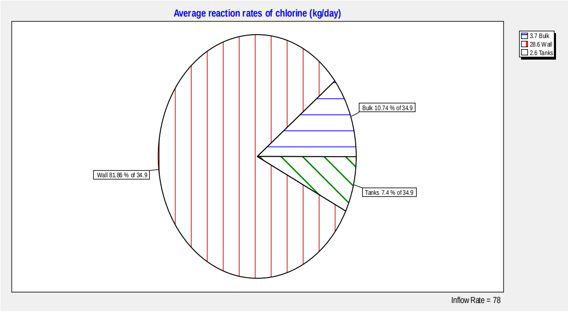

Fig. 6 Average reaction rates of chlorine per day

As mentioned earlier, the source qualities of chlorine at CWRs are concentration type. Their values are adopted as 2 mg/L, 1.5 mg/L with respect to CWR node 49 and 50 respectively using trial and error process. The booster locations are identified to get the minimum residual chlorine to the nearby nodes. The location booster stations are shown in Fig.7.

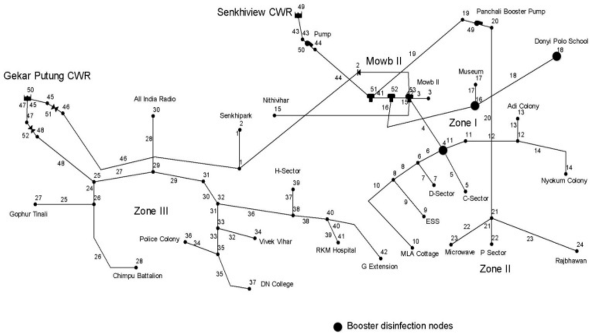

Fig. 7 Pictorial layout showing booster stations at node 4, 16 and 18

Junction nodes of 4 and 16, and distribution node of 18 are added with flow paced booster type with 0.5 mg/L. In Fig. 4, all distribution nodes belong to Zone III has the residual chlorine values more than 2 mg/L because source concentration of CWR node 50 was 5 mg/L. After modification of concentration levels at CWRs and introducing the booster stations at selected nodes, all distribution nodes receives the residual chlorine levels vary from 0.35 mg/L at node 15 to 0.84 mg/L at node 22. All the junction nodes draw water with the residual chlorine levels below the 1 mg/L. The variation of the residual chlorine from 0.00 hrs to 24.00 hrs with corresponding nodes is shown in the Fig 8. Normally the chlorine levels are stabilized at 4 hrs for Zone III and 16 hrs for Zone I and Zone II respectively. But at the nodes 2 and 15 takes 8 hrs and 16 hrs to get 0.48 mg/L and 0.30 mg/L respectively. After 16 hrs from starting of the simulation, all chlorine levels are stabilized. Fig. 9 shows the residual chlorine levels of selected nodes for 24 hrs. In this figure, all are distribution nodes except node 16 which is a junction node. Comparing Fig. 5 with Fig. 9, node 16, 17 and 18 are getting the improved result due to addition of booster station in the node 16 and 18. Likewise, the installation of flow paced booster added at node 4 with the concentration of 0.5 mg/L and even reduction of concentration type of 5 mg/L to 2 mg/L at CWR node 49, the available residual chlorine level at nodes 4 to 14 are within the permissible limits.

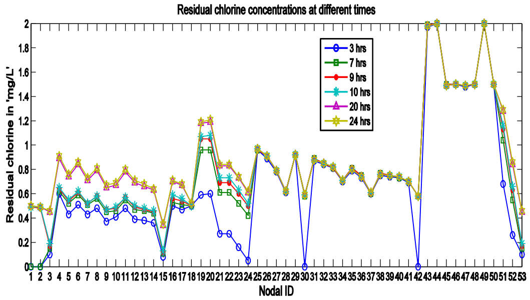

Fig. 8 Residual chlorine concentration after installation of booster stations

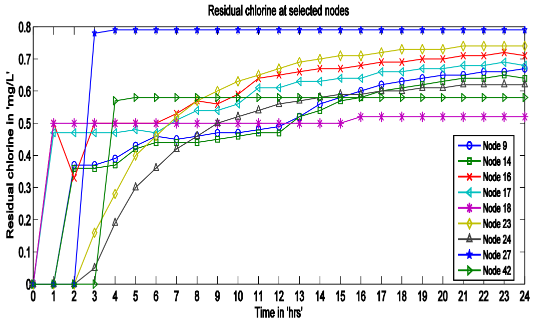

Fig. 9 Residual chlorine concentration at selected nodes after installation of booster stations

The frequency plot of the variations of chlorine levels of all nodes without booster is shown in Fig 10. Zone I, have the residual chlorine of about 1.00 mg /L and Zone II have the residual chlorine of about 2.00 mg/L. But in Zone III all nodes have the variation in the levels of chlorine of about 2 – 3 mg/L. It shows the various levels of chlorine in the whole distribution network before the addition of booster location at selected nodes.

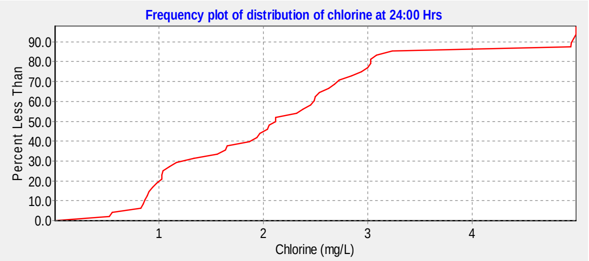

Fig. 10 Frequency plot of distribution of chlorine at 24.00 hrs without booster location

These values considerably changes after the modification of chlorine dose at the corresponding nodes (Fig. 11). It shows the most of the chlorine concentrations lies in the range of 0.6 – 1.0 mg/L at all nodes and all times. The same result is obtained after extending the simulation period to 48 hrs.

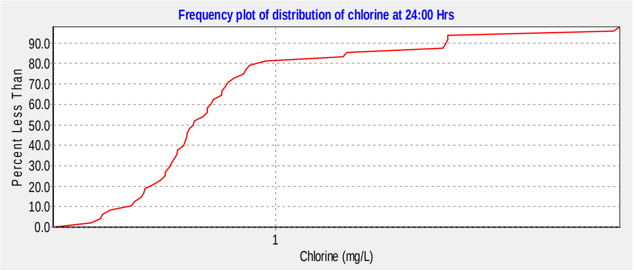

Fig. 11 Frequency plot of distribution of chlorine at 24.00 hrs with booster location

The average reaction rates of chlorine are shown in Fig. 12. The total amount of chlorine requires for the disinfection purpose per day is about 29 kg. It reduces the required quantity of chlorine from 78 kg to 29 kg with reduction of about 63%. In conventional process, addition of chlorine dose at source node i.e. reservoir is uneconomical and could not deliver desired level of chlorine concentration at all nodes and it delivers more concentration level of water to nearby areas and less concentration level of water to far-off nodes from the reservoir. It is difficult to maintain the desirable residual chlorine at all nodes in the conventional disinfection process.

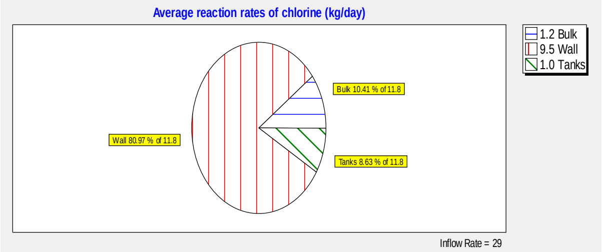

Fig. 12 Average reaction rates of chlorine per day

In the normal simulation works, nodal base demand values are fixed and it does not vary with time for the whole simulation period. By considering the present water shortage problem, the usage of water quantity is optimised to benefit the consumer. Four demand patterns are assumed according to the usage at consumer ends to save the water. The four time periods are grouped from 12 a.m. to 6 a.m., 6 a.m. to 12 p.m., 12 p.m. to 6 p.m. and 6 p.m. to 12 a.m. with demand factors of 0.2, 1.0, 0.6, and 0.8 respectively. The optimal pump speeds adopted for both the pumps (link 49 and link50) are taken as 0.584, 1.0, 0.842 and 0.927 for the four time periods 1 through 4 respectively [24]. To reduce the pumping cost over the different time periods according with pump speed, optimal pump power obtained for the link 50 is 136.50 kW. The pump power for link 49 is considered same as for normal fixed demand condition is 110 kW.

After adopting the variable demand pattern in the simulation, the total mass of chlorine required per day is obtained. The various simulation patterns are adopted to derive the requirement of chlorine such as fixed and variable demand pattern with or without booster disinfection. The detailed data with derived results are given in the Table I. Approximately 63% of amount of chlorine is reduced for the fixed demand pattern without booster station in comparison to booster station. A considerable amount of reduction in chlorine achieved while applying the booster station with variable demand pattern in WDN. Subsequently, 76% chlorine reduction is obtained if network adopt the variable demand pattern with booster station instead of constant demand with no booster stations. Storage facility for chlorine is also another important task. Some of saving in cost for procurement of chlorine, storage facility, and manual handling in disinfection system is reduced by adopting the reasonable method.

VI. CONCLUSIONS

The conventional disinfection process normally provided with the more doses of chorine at the source node i.e., reservoir. But it would not meet the desirable residual chlorine concentration at all nodes at different times. Hence in this process, addition of chlorine dose at source node is uneconomical because of the higher dose of chlorine. Further in this process it would not to possible to deliver desire level of chlorine concentration at all nodes. It delivers more chlorine concentration to nearby areas and less concentration level to far-off nodes from the reservoir. Also it is difficult to maintain the desirable residual chlorine at all nodes in the conventional disinfection process. In the present WDN the residual chlorine levels are found to be 0.02 mg/L at far-off nodes and more than 3 mg/L at nearer nodes. Zone wise residual chlorine concentrations are found to be approximately 1 mg/L, 2 mg/L, and 2.5 mg/L in Zone I, II and III respectively. Moreover, the total amount of chlorine required per day is 78 kg. After adopting the three booster locations (i.e., at nodes 4, 16 and 18) with the input concentration of 0.5 mg/L and modified dose of chlorine of 2 mg/L at source node 49 and 1.5 mg/L at source node 50, the total amount of chlorine required per day is 29 kg. Hence the total required chlorine is considerably reduced by about 63%. Further, the amount of chlorine required per day reduces to about 76% for the variable demand pattern with booster station in comparison with the conventional disinfection process having constant demand pattern. The adoption of booster station is not only economical it would not pose any adverse health impact

As observed from the results, variable demand patterns have many advantages over the constant demand pattern including water saving and disinfectant consumption for water quality analysis

TABLE I.Requirement of Chlorine from Different Adopted Methods

Without booster station						
	Node type	Node number	Source quality (mg/L)	Source type	Demand pattern	chlorine required (kg/day)
Source	Reservoir	49	5.0	Concentration	Constant demand	78
		50	5.0			
		49	5.0		Variable demand	52
		50	5.0			
With booster station						
Source	Reservoir	49	2.0	Concentration	Constant demand	29
		50	1.5			
Booster station	Junction	4	0.5	Flow Paced booster		
		16	0.5			
	Distribution	18	0.5			

Source	Reservoir	49	2.0	Concentration	Variable demand	19
		50	1.5			
Booster station	Junction	4	0.5	Flow Paced booster		
		16	0.5			
	Distribution	18	0.5			

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REFERENCES

[1] R. M. Clark, and R. M. Males, "Simulating cost and quality in water distribution," *J. Water Resour.Plann.and Manage.*, vol.11, No. 4, pp. 454-466, 1985.

[2] H. Kitazawa, "Keeping residual chlorine and decreasing unpleasant odour caused by disinfection of tap water," *Water Supply*, vol. 6, No. 2, pp.193-199, 2006.

[3] L. Lienyao, L. Chungsyng, and K. Shyang- Lai, "Spatial diversity of chlorine residual in a drinking water distribution system," *J. Envir.Engrg.*, vol. 130, pp. 1263-1268, 2004.

[4] I. Hasmi, S. Farooq, and S. Qaiser, "Chlorination and water quality monitoring within a public drinking water supply in Rawalpindi Cantt. (Westridge and Tench) area, Pakistan," *Environ Monit Assess*, vol. 158, pp. 393-403, 2009.

[5] R. M. Clark, W. M. Grayman, and R. M. Males, and A. F. Hess, "Modeling contaminant propagation in drinking-water distribution systems," *J. Envir. Engrg*., vol. 119, No. 2, pp. 349-364, 1993.

[6] *The EPANET users manual*, Risk Reduction Engrg. Laboratory, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1993.

[7] R. M. Clark, W. M. Grayman, J. A. Goodrich, R. A. Delinger, and K. Skov, "Measuring and modeling chlorine propagation in water distribution systems," *J Water Resour. Plann.and Manage*., vol. 120, No. 6, pp. 871-887, 1994.

[8] L. Rossman, R. M. Clark, and R. M. Grayman, "Modelingchlorinre residuals in drinking-water distribution systems," *J. Envir. Engrg.*, vol. 120, No. 4, pp. 803-820, 1994.

[9] R. M. Clark, L. A. Rossman, and L. J. Wymer, "Modeling distribution system water quality: Regulatory implications," *J. Water Resour. Plann.and Manage*., vol. 121, No.6, pp. 423-428, 1995.

[10] V. G. Tzatchkov, A. A. Aldama, and F. I. Arreguin, "Advection-dispersion-reaction modeling in water distribution networks," *J. Water Resour. Plann.and Manage*., vol.128, No. 5, pp. 334-342, 2002.

[11] M. R. Islam, and M. H. Chaudhry, "Inverse modeling of chlorine concentration in pipe networks under dynamic conditions," *J. Envir.Engrg*., vol. 123, No. 10, pp. 1033-1040, 1997.

[12] R. M. Clark, M. Sivaganesan, "Predicting chlorine residuals and formation of TTHMs in drinking water," *J. Envir. Engrg*., vol. 124, No. 12, pp. 1203-1210, 1998.

[13] D. L. Boccelli, M. E. Tryby, J. G. Uber, L. A. Rossman, M. L. Zierolf, and M. M. Polycarpou, "Optimal scheduling of booster disinfection in water distribution systems," *J. Water Resour. Plann.and Manage*., vol. 124, No. 2, pp. 99-111, 1998.

[14] M. E. Tryby, D. L. Boccelli, J. G. Uber, L. A. Rossman, "Facility location model for booster disinfection of water supply networks," *J. Water Resour. Plann.and Manage*., vol. 128, No. 5, pp. 322-333, 2002.

[15] G. R. Munavalli, and M.S. Mohan kumar, "Water quality parameter estimation in steady-state distribution system," *J. Water Resour. Plann.and Manage*., vol.129, No.2, pp.124-134, 2003a.

[16] G. R. Munavalli and M.S. Mohan kumar, "Optimal scheduling of multiple chlorine sources in water distribution system," *J. Water Resour. Plann.and Manage*., vol. 129, No. 6, pp. 493-504, 2003b.

[17] T. D. Prasad, G. A. Walters, and D. A. Savic, "Booster disinfection of water supply networks: Multiobjective Approach," *J. Water Resour. Plann.and Manage*., vol. 130, No. 5, pp. 367-376, 2004.

[18] M. S. Gibbs, G. C. Dandy, and H. R. Maier, "Calibration and optimization of the pumping and disinfection of a real water supply system," *J. Water Resour. Plann.and Manage*., vol.136, No. 4, pp. 493-501, 2010.

[19] S. Liberatore, and G. M. Sechi, "Location and calibration of valves in water distribution networks using a scatter-search meta-heuristic approach," *Water Resour. Manage*., vol. 23, No. 8, pp. 1479-1495, 2009.

[20] *EPANET 2 users manual*, Water Supply and Water Resources Division, National Risk Management Research Laboratory, U.S. Environmental Protection Agency, Cincinnati, Ohio, 2000.

[21] J. C. Powell, J. R. West, N. B. Hallam, C. F. Forster, and J. Simms, "Performance of various kinetic models for chlorine decay," *J. Water Resour. Plann.and Manage*., vol.126, No. 1, pp. 13-20, 2000.

[22] *Bureau of Indian Standards (BIS)*, BIS:10500, Drinking Water Quality Standards, BIS, Thane. 1991.

[23] W. W. Sharp, J. Pfeffer, and M. Morgan, "In situ chlorine decay rate testing," *Water quality modelling in distribution systems*, AWWA Res. Found., pp. 311-321, 1991.

[24] K.S.J. Babu, and S. Mohan, "Extended period simulation for pressure-deficient water distribution network," *J. Comput. Civ. Eng.*, vol. 26, No. 4, pp. 498-505, 2012.