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Modeling of drinking water distribution and its quality for an Indian state municipality

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ABSTRACT

Residents of Dhanbad Municipal Corporation (DMC), Jharkhand, India, are suffering from water scarcity in summer season. At the same time drinking water quality is also questionable because of the damages in the pipeline and old water treatment techniques. In this paper, water demand and distribution are examined for 18 sub-zones of DMC as per guideline of Indian Standard 1772:1993. Among them, one of the most vulnerable areas within the DMC is identified as Steel Gate sub-zone. Further, modeling of drinking water distribution of steel gate sub-zone and its quality analysis is done using HAMMER, ArcGIS software and renewal of pipeline viz., P30, P33, P57, P62, P64, P70, P63, P71, P73 is proposed under continuous water loss condition based on futuristic water demand. Residual chlorine concentrations at various locations of this sub-zone revealed that chlorine concentration is 0.1 mg/L and lasts for approximately 8 h, which is also validated through field survey. This value must be increased in order to maintain permissible range of the chlorine value in the network.

Keywords: Dhanbad Municipal Corporation; Water distribution network; HAMMER; Population; Three-parameter logistic growth model; Residual chlorine modeling

1. Introduction

During last few decades, residents of Dhanbad Municipal Corporation (DMC), Jharkhand, India, have been suffering from drinking water scarcity, especially in summer season. Present status shows that only 48% household of DMC is having authorized drinking water supply connection. The population of the DMC (Division – 1, that is, Dhanbad city) is almost 1.16 million extended over an area of approximately 52 km^2 [1] (Fig. 1). Possible reason behind this scarcity are power scarcity in summer, population growth in recent decade, water loss in terms of mechanical damage, leakage or illegal water connection in the water distribution network (WDN) for running small industry or agriculture. Thus, access to ground water table became very difficult as water table was found very low during summer. During field survey, it is observed that huge amount of accidental and intentional (in form of illegal water connection) water loss is occurring in the raw water supply route originated from Maithon to Bhelatand water treatment plant. As a result, DMC is experiencing significant amount of financial loss also [2]. Therefore, to fulfil water demand of the huge population, necessary steps are required to reduce water loss, locate the position of water loss, renewal of WDN based on future water demand and maintain the water quality of the distributed water.

Literature revealed that Mohan [3] found the trend in institutionalizing people participation and discussed various experiences and coverage for rural water supply sector in India. Agrawal et al. [4] discussed about determination of the accurate peak daily demand in order to design future water supply system in India. Puust et al. [5] worked on optimization of pumping system and leakage management of a network like lost water volume assessment, detecting leakage point, reduction of lost water volume and its control within a WDN. Whereas, Sægrov [6], and Dziedzic and Karney [7] described about the pump or pipe renewal, leakage or pressure management, pipe failure rate within a

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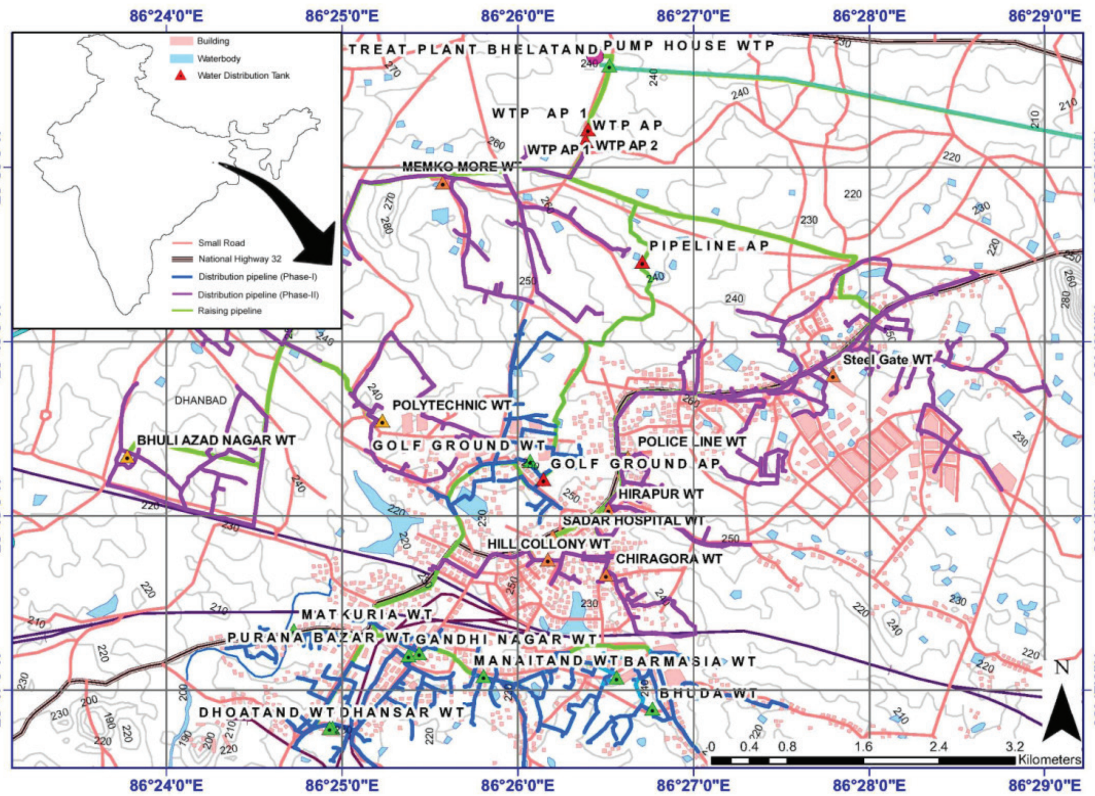

Fig. 1. Water distribution piping network (raising and distribution pipeline) of Dhanbad Sadar Block, DMC.

piping system and its remaining asset life. Based on historical data, a few researches discussed forecasting and designing the cost-effective, sustainable water distribution system for expansion of urban water supply system [8,9]. In view of the literature review, it is observed that the whole WDN is better to be divided into some manageable areas or zones into which the flow can be measured and location of disturbance can be determined.

Not only the sufficient quantity of drinking water that is required in an urban area but also the quality of water that plays an important role. Different researchers explored the challenges associated to provide good quality of water to the consumers. The chlorine is generally considered to be the most primary water treatment disinfectant as it controls the microbial growth, reacts with organic and inorganic matter in water which is directly related to the health risks [10–13]. Excessive presence of chlorine in water also affects human health. Permissible range of chlorine must be 0.2–0.8 mg/L [14]. The minimum value required to be maintained to prevent the growth of pathogenic microbes up to a certain limit, and the maximum limit is required to control taste, odor and the formation of disinfection by-products [15,16]. Any treatment plant flaw, biofilm release, small pipe leaks and other sources of contamination in pipeline may cause chlorine decay and aggravate water quality loss [17]. Therefore, decaying of chlorine is an important factor of water distribution. Presence of organic, inorganic material in water responsible for chlorine decay is called bulk decay and chlorine loss due to reaction of chlorine with biofilm formed in pipe inner wall is called wall decay [18]. Variation of chlorine decay throughout the day is reported by Clark et al. [19] depending on the flow path and residence time of the water reaching a location. Several researchers tried to develop and modify models for wall and bulk reaction [20–22], optimal sampling locations for chlorine decay model calibration [20] and water quality at end node in WDN considering both temporally and spatially varied flow demands [23]. Mckenzie and Ray [24] described the water quality conditions of pipe water supply of different cities in all over India, which reports the lack of quality and quantity in most of the cases.

Therefore, in this paper, considering the severity of drinking water scarcity in DMC, the following objectives were set for the analysis: (i) calculation of spatial water demand at the proximity of different distribution tanks; (ii) exploring water distribution pattern of the tanks having water deficiency; (ii) identification of vulnerable zones in WDN; (iii) modeling of the existing WDN of the study area and steady and transient analysis; (iv) calculation of 30 years' future demand based on population growth; (v) provide solutions by modifying the WDN corresponding to the increasing drinking water demand; (vi) calculation of water quality at different distribution nodes in the WDN, their validation and necessary suggestions.

2. Description of study area

It is found that water demand 90.5% of DMC water is fulfilled by surface and subsurface resources; rest (i.e., 9.5%) from ground water resources. The ground water level varies from 150 m in east to 250 m in the west. The dug well are

10–15 m deep below ground level. Among the total household, only 48% (approximately 34,589 out of 72,593 in ward no. 16–33) household is having authorized access to DMC drinking water supply [2].

In DMC, the first protected water supply system was established for rural areas during 1914–24 mainly for coal mining areas. The second protected WDN, that is, existing WDN in DMC came into existence during 1955–60s with seven numbers of tank, which is presently maintained by Public Health Engineering Department (PHED). Presently, the water supply system of DMC is based on surface water of Maithon Dam, which is situated on Barakar River, and located 44 km from Dhanbad city. The raw water comes from Maithon Dam to Bhelatand water treatment plant (WTP) having a total capacity of 77 MLD through 1,000 mm ductile iron (DI) pipeline by two centrifugal pumps having 1,770 m^3/h capacity; 250 m head; 1,490 rpm; 2,000 kW each with two standby pumps (Fig. 1). This WTP is based on conventional treatment using clariflocculator, rapid sand filtration followed by chlorination. After treatment, this water is supplied to 18 sub-zones consisting of distribution water tank through mainly 500 mm DI pipe by four centrifugal pumps having 775 m^3/h capacity; 100 m head; 1,490 rpm; 315 kW each. Last 5-years' pump operation data show that these pumps are being operated on an average of 20 h per day. In 2004, intake from Maithon Dam to Bhelatand WTP was established and in 2009 remaining 11 water tanks out of a total of 18 were commissioned, and some of the pipelines were renewed in DMC. Generally, these tanks are operated once in a day during summer season due to lack of electricity, and sometimes twice in rest of the year when required using gravity flow.

Water distribution pipes are normally made of DI. These pipes are externally coated with black bituminous paint zinc primer with suitable internal cement mortar lining. Tuberculation in pipes are formed from iron-oxidizing bacteria that congregate in water lines. As the bacteria metabolize, a brown slime builds up and coats the interior of the pipe. This sludge left behind by the bacteria is known as tubercles. The tank surface of the concrete support wall is designed by architectural concrete. All tanks are covered and cleaned up regularly twice in a year.

Water is treated by coagulation, flocculation, sedimentation, sand filtration and finally disinfection is done with gaseous chlorine. In the coagulation, three type of processes are involved viz., parshall flume (artificial drainage), stilling chamber (addition of alum), polyelectrolyte for remove turbidity, lime for controlling pH and flash mixture (mixing of all chemicals properly). Clariflocculator has two concentric tanks with inner tank serving as flocculation basin (for settlements of mud, sand) and outer tank serving as clarifier. Sand infiltration is done by rapid gravity filter bed and finally disinfection is done with gaseous chlorine. Average chlorine content is kept approximately 0.5 mg/L at the WTP outlet.

3. Methodology

In this study, ward-wise population data of 2011 (Directorate of Census Operations Jharkhand, 2014) [1], number of household, number of water connection are obtained from DMC database. These data are used to calculate the standard daily water requirement in a particular area based on standard water requirement for per person as per IS 1772:1993 [25]. Details of steps are shown using a flowchart in Fig. 2.

3.1. Selection of zones having water deficit problem

Details of tanks, corresponding zones and their operating time are obtained from DMC for 2 years' (2012–13) tank operation database, which was collected from DMC office. These data were again verified during field survey. Average water supply rates from different distribution tanks were measured by non-destructive type ultrasonic flow meter during field survey. Moreover, discharge rates at different distribution points were also measured in several parts of the WDNs during field survey, which were found exposed and approachable. It is found that ranges of measured distributed water are close to the calculated amount of discharge, which verifies the amount of actual distributed water throughout the WDNs in some points. Daily water demand of the residents living surrounding the tanks are calculated as per guidance of IS 1772:1993, based on 2011 population data, land use (Table 1). Further, dailywater deficit is calculated by subtracting supplied water amount from the demand that gives a clear picture of water scarcity in these areas, which is also observed during field survey. Moreover, it is observed that populated areas of DMC-WDN can be categorized mainly of three types, viz., zones with surplus water supply, zones with minimum water deficit and zones with significant water deficit (Table 1). Last 2 years' field survey also verified the severity of water scarcity in these areas. Study revealed that there are serious water scarcity in some areas of DMC, viz., Tank 4, that is, Gandhi nagar, Tank 6, that is, Dhoatand, Tank 12, that is, Bhuli, Tank 13, that is, Steel Gate and Tank 16, that is, Hill-colony, due to insufficient water supply and may be unexpected population growth occurred in recent past. Calculated results and field survey revealed that among the above-mentioned five water deficit areas, Steel Gate and Bhuli are the severely affected by water scarcity and having significant administrative importance in DMC also (Table 1). Therefore, detailed steady and transient analyses of these two areas have been performed in order to find out weak points of these WDN systems (Fig. 3). Further, the WDNs were explored to find out the possible drawbacks in fulfilling the water demand corresponding to future population and necessary suggestions are prescribed. Furthermore, water quality of one of these zones is assessed and necessary suggestion is prescribed.

3.2. Preparation of WDN map for transient analysis

Study area map has been prepared combining the data obtained from the following sources (i) Survey of India (SOI) 1:50,000 Topomap (73I/5) [26], (ii) WDN plan provided by DMC& PHED, (iii) GPS coordinate of all major node points (junction of two pipelines or end of pipeline etc.) in the WDN during field survey, (iv) Google earth images, (v) Shuttle Radar Topographic Mission (SRTM) data of 90 m resolution [27]. Finally, ArcGIS software is used to compile all the layers into a single map, which is already shown in Fig. 1. In some

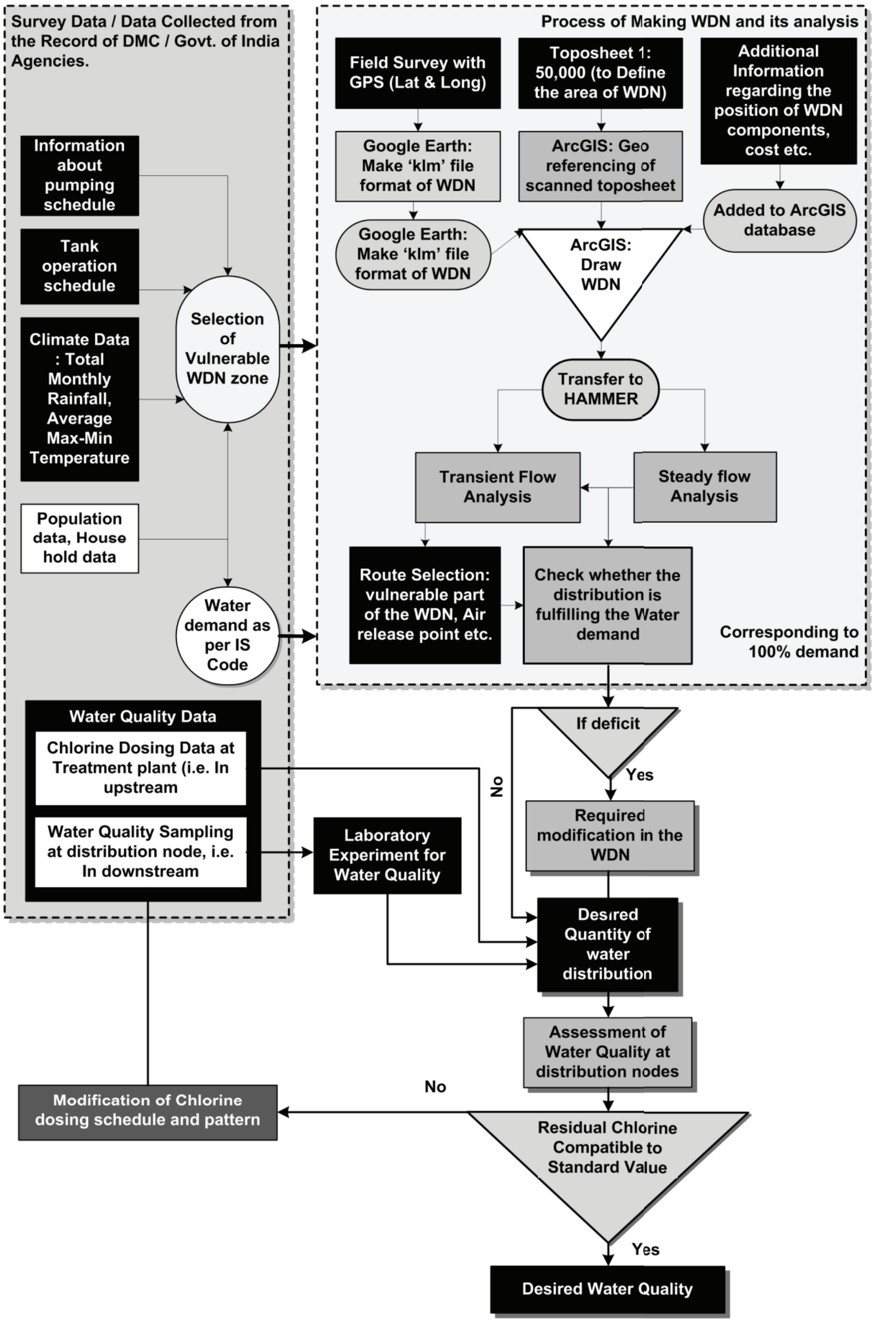

Fig. 2. Flow chart of methodology.

cases, percentage of spatial coverage of different municipal wards surrounding water distributed tanks is calculated from the GIS database and type of urbanization or land use is derived from GIS database. Ultimately, the WDN of ArcGIS is transferred into the HAMMER V8i software to prepare the WDN ready for transient analysis [28,29].

3.3. Steady and transient analysis of the WDN

In the analysis of WDN, generally pipes are considered as link, and joining of two or more pipes is called as node/junction. For modeling of the WDN, the following assumptions are made: (i) demands, that is, water supply occurs at node; (ii) water contribution to the WDN is considered as negative demand; (iii) network analysis proceeds with forward problem considering demands and system characteristics are known. Finally, pressure and flow need to find out along the link or at each node points [30].

The transient flow inside the pipeline is described as follows in terms of conservation of mass (continuity equation) and conservation of energy (momentum equations) [31,32].

Table 1
Details of tanks, corresponding zones, their operating time as per 2 years' tank operation database (2012–13) and standard water demand based on Census data of 2011 collected from DMC and IS 1772:1993 [25]

Tank no.	Water distribution zone, WT name	WT capacity (million liter), (pipe diameter at exit from WT [mm])	Location: Municipal ward no.	Percentage of spatial coverage of Municipal Ward	No. of building under zone/WT	Ward wise popula-tion	Ward wise no of water connec-tion	Type of urbanization/ land use	Daily Water demand as per IS 1772:1993 (liter per person per day)	Daily water demand (lit/d)	WT wise daily water demand (m^3/s)	Daily Average operation time of tank min)	Daily water distribution rate from tank (m^3/s) – field survey	WT wise daily water deficit (million liter/d) (m^3/s)
(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	(viii)	(ix)	(x)	(xi)	(xii)	(xiii)	(xiv)	(xv)
1	16,Golf Ground	1.45 [450]	27 - I	30	1,053	5,140	421	Residence and office	70	359,800	0.094	63.7		
			27 - II	50	1,756	8,566	702	Office	45	385,470	0.101			[0.01]
			25	39	1,774	9,169	709	Residence and office	70	641,830	0.168			
			24	10	485	2,524	194	Office	45	113,580	0.030			
	Total				5,068	25,399	2,026			1,500,680	0.393		0.390	0.003
2	02, Matkuria	0.56 [350]	21	17	580	3074	232	Moderate residence with personal land	80	245,920	0.054	75.4		[-0.46]
			18	42	1,658	9,440	663	Office	45	424,800	0.094			
	Total				2,238	12,514	895			670,720	0.148		0.250	-0.102
3	05,Purana Bazar	0.378 [300]	23	23	1,021	5,514	408	Office	45	248,130	0.072	57.6		
			21	30	1,024	5,426	410	Market/factory	30	162,780	0.047			[-0.13]
			20	24	1,164	6,058	466	Market/factory	30	181,740	0.053			
	Total				3,210	16,998	1,284			592,650	0.171		0.210	–0.039
4	06,Gandhi nagar	1.75 [450]	23	72	3,196	17,260	1,278	Dense residence	130	2,243,800	0.694	53.9		
			21	26	888	4,702	355	Dense residence	130	611,260	0.189			[1.59]
	Total				4,084	21,962	1,633			2,855,060	0.883		0.390	0.493
5	04, Dhansar	0.56 [300]	22	38	1,805	9,247	722	Residence and mines	70	647,290	0.217	49.7		[0.02]
	Total				5,888	9,247	722			3,502,350	0.217		0.210	0.007
6	03, Dhoatand	1.45 [450]	22	62	2,944	15,088	1,178	Dense residence	130	1,961,440	0.471	69.4		
			21	27	922	4,883	369	Dense residence	130	634,790	0.152			[0.97]
	Total				3,866	19,971	1,547			2,596,230	0.623		0.390	0.233

(*continued*)

Table 1 (*continued*)

Tank no.	Water distribution zone, WT name	WT capacity (million liter), (pipe diameter at exit from WT [mm])	Location: Municipal ward no.	Percentage of spatial coverage of Municipal Ward	No. of building under zone/WT	Ward wise popula-tion	Ward wise no of water connec-tion	Type of urbanization/ land use	Daily Water demand as per IS 1772:1993 (liter per person per day)	Daily water demand (lit/d)	WT wise daily water demand (m^3/s)	Daily Average operation time of tank min)	Daily water distribution rate from tank (m^3/s) – field survey	WT wise daily water deficit (million liter/d) (m^3/s)
7	07, Manaitand	0.56 [300]	33 - I	23	1,105	5,940	442	Residence with barren land	60	356,400	0.096	62		[0.12]
			33 - II	22	1,057	5,682	423	Office	45	255,690	0.069			
			31	19	616	3,164	246	Residence with barren land	60	189,840	0.051			
			23	5	1,021	1,199	408	Moderate residence with personal land	80	95,920	0.026			
	Total				3,798	15,985	1,519			897,850	0.241		0.210	0.031
8	08,Barmasia	1.45 [500]	32	57	2,407	13,083	963	Moderate residence with personal land	80	1,046,640	0.282	61.8		[0.01]
			33	25	1,201	6,457	480	Moderate residence with personal land	80	516,560	0.139			
	Total				3,608	19,540	1,443			1,563,200	0.422		0.420	0.002
9	09, Bhuda	1.45 [500]	32	22	929	5,049	372	Moderate residence with personal land	80	403,920	0.113	59.8		[–0.48]
			33	30	1,441	7,748	576	Moderate residence with personal land	80	619,840	0.173			
	Total				2,370	12,797	948			1,023,760	0.285		0.420	–0.135

(*continued*)

Table 1 (*continued*)

Tank no.	Water distribution zone, WT name	WT capacity (million liter), (pipe diameter at exit from WT [mm])	Location: Municipal ward no.	Percentage of spatial coverage of Municipal Ward	No. of building under zone/WT	Ward wise population	Ward wise no of water connection	Type of urbanization/ land use	Daily Water demand as per IS 1772:1993 (liter per person per day)	Daily water demand (lit/d)	WT wise daily water demand (m^3/s)	Daily Average operation time of tank min)	Daily water distribution rate from tank (m^3/s) – field survey	WT wise daily water deficit (million liter/d) (m^3/s)
10	15,Memco More	1.45 [450]	25	49	2,229	11,519	891	Residence with barren land	60	691,140	0.198	58.1		[0.02]
			28	19	1,134	5,980	454	Residence with barren land	60	358,800	0.103			
			24	11	534	2,777	213	Residence with barren land	60	166,620	0.048			
			16	15	491	2,726	196	Residence with barren land	60	163,560	0.047			
	Total				4,387	23,002	1,754			1,380,120	0.396		0.390	0.006
11	17, Polytechnic	1.75 [500]	24	68	3,299	17,164	1,320	Residence with barren land	60	1,029,840	0.277	61.9		[0.03]
			19	24	1,147	6,997	459	Moderate residence with personal land	80	559,760	0.151			
	Total				4,446	24,161	1,779			1,589,600	0.428		0.420	0.008
12	18, Bhuli	1.75 [500]	19	76	3,632	22,157	1,453	Residence	130	2,880,410	0.764	62.8		
			16	20	655	3,635	262	Residence	130	472,550	0.125			[1.77]
	Total				4,287	25,792	1,715			3,352,960	0.890		0.420	0.470
13	14, Steel Gate	2.1[500]	29	80	3,528	17,542	1,411	Residence	130	2,280,460	0.422	90.1		
			28	46	2,745	14,477	1,098	Residence	130	1,882,010	0.348			[1.89]
	Total				6,273	32,019	2,509			4,162,470	0.770		0.420	0.350

(*continued*)

Table 1 (*continued*)

Tank no.	Water distribution zone, WT name	WT capacity (million liter), (pipe diameter at exit from WT [mm])	Location: Municipal ward no.	Percentage of spatial coverage of Municipal Ward	No. of building under zone/WT	Ward wise population	Ward wise no of water connection	Type of urbanization/ land use	Daily Water demand as per IS 1772:1993 (liter per person per day)	Daily water demand (lit/d)	WT wise daily water demand (m^3/s)	Daily Average operation time of tank min)	Daily water distribution rate from tank (m^3/s) – field survey	WT wise daily water deficit (million liter/d) (m^3/s)
14	13,Police Line	1.45 [450]	27	5	176	857	70	Moderate Residence with personal land	80	68,560	0.016	72		[−0.06]
			26	69	2,811	13,674	1,124	Moderate Residence with personal land	80	1,093,920	0.253			
			25	12	546	2,821	218	Moderate Residence with personal land	80	225,680	0.052			
			28	15	895	4,721	358	Office	45	236,050	0.055			
	Total				4,428	22,073	1,770			1,624,210	0.376		0.390	−0.014
15	11, Hirapur	0.378 [400]	30	23	1,119	5,740	447	Residence and office	70	401,800	0.118	56.9		[0.01]
			26	31	1,263	6,143	505	Moderate Residence with personal land	80	491,440	0.144			
	Total				2,382	11,883	952			898,240	0.262		0.260	0.002
16	12,Hill Colony	1.45 [450]	31	81	2,624	13,491	1,050	Dense residence	130	1,753,830	0.517	56.5		
			30	32	1,556	7,986	623	Office	45	359,370	0.106			[1.01]
			24	11	534	2,777	213	Moderate Residence with personal land	80	222,160	0.066			
	Total				4,715	24,254	1,886			2,335,360	0.689		0.390	0.299
17	10,Chiragora	0.56 [350]	32	21	887	4,820	355	Residence with barren land	60	289,200	0.093	52		[0.11]
			30 - I	15	730	3,743	292	Residence and office	70	262,010	0.084			
			30 - II	30	1,459	7,487	584	Office	45	336,915	0.108			
	Total				3,075	16,050	1,231			888,125	0.285		0.250	0.035
18	Sadar Hospital	0.094 [80]	27	14	492	2,398	197	Residence and office	70	167,860	0.015	184.2		[0.06]
	Total				492	2,398	197			1,055,985	0.015		0.010	0.005

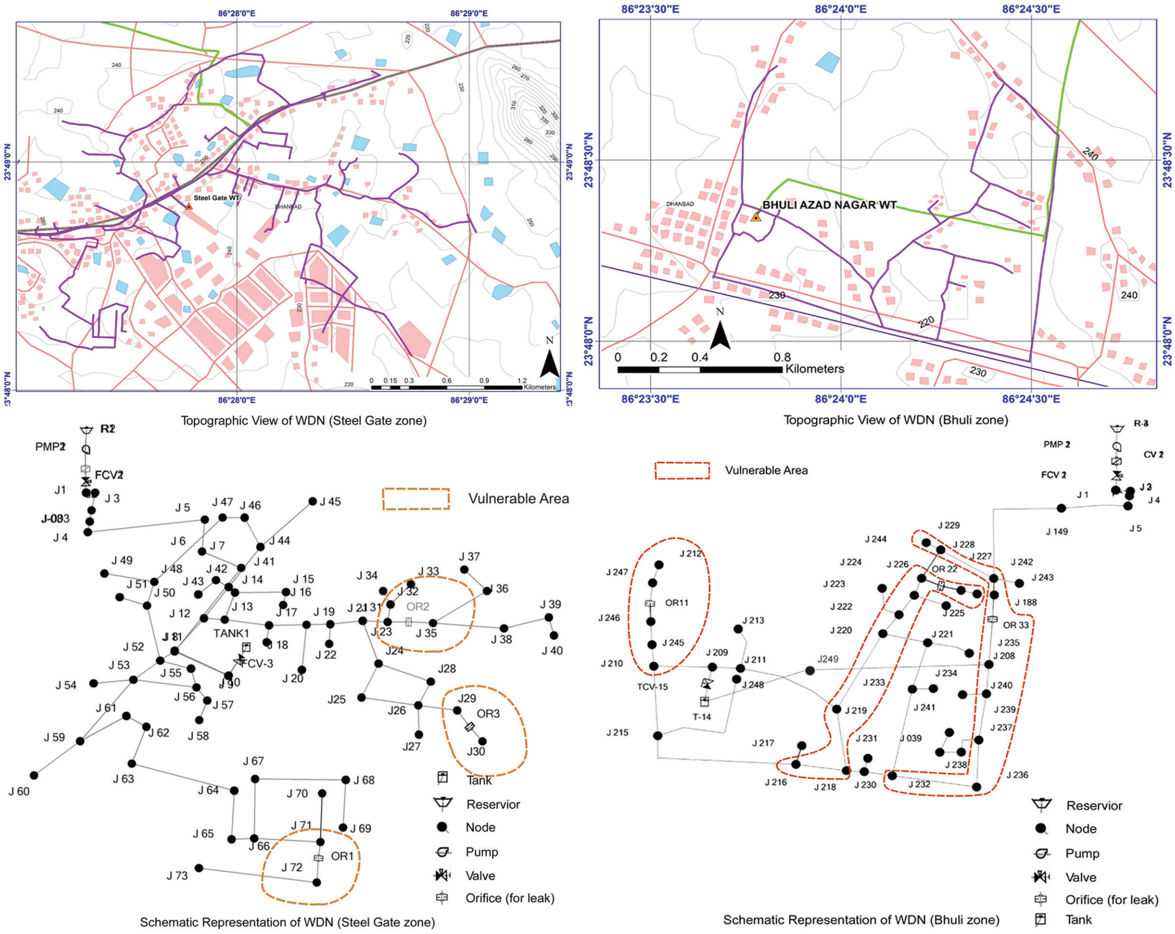

Fig. 3. Schematic and topographics view of Steel Gate and Bhuli sub-zone WDN with different nodes and junctions showing vulnerable parts of WDN (surrounding OR1, OR2 and OR3 for Steel Gate and surrounding OR11, OR22 and OR33 for Bhuli sub-zone).

$$\frac{\partial H}{\partial t} + \frac{a^2}{g\text{A}}\frac{\partial Q}{\partial x} = 0 \tag{1}$$

$$\frac{\partial Q}{\partial t} + g\text{A}\frac{\partial H}{\partial x} + f\frac{Q|Q|}{2D\text{A}} = 0 \tag{2}$$

where x is the distance along pipe, t is time, g is the acceleration due to gravity, A is the cross-sectional area of pipe, D is the pipe diameter, a is the wave speed and f is Darcy–Weisbach friction factor, Q is discharge and H is piezometric head.

3.4. Logistic growth model

The logistic law of growth states that system always grows exponentially until carrying capacity characteristic in the system is approximated. Then the rate of growth slows down and finally saturates, and generates the characteristic curve of S-shape having following equation structure [33].

$$P(t) = \frac{\kappa}{1 + e^{-\alpha t - \beta}} \tag{3}$$

where $P(t)$ is the population, t is year of interest, α is the rate parameter, β is the location parameter and κ is the asymptotic value that limits the function value and provides the specific level of the growth process. When the population of $P(t)$ reaches κ, this leads to sluggish growth rate up to zero after being saturated.

In Eq. (1), β may be considered as $-t_o\alpha$, in order to replace location parameter β by t_o. In population growth, it is important to define a parameter Δt as the length between 10% to 90% of the saturation level κ of growth process. From (1), when $P(t)$ is equal to 0.1 κ and 0.9 κ, $\Delta t = (\ln 81)/\alpha$ is obtained. With the background of time-series data, the three-parameter logistic model can then be defined as follows [34]:

$$P(t) = \frac{\kappa}{1 + e^{\{r(t_o - t)\}}} \tag{4}$$

where $r = \ln(81)/\Delta t$.

3.5. Water quality sampling and experiment

Different sets of water samples were collected from streetside or household taps within Steel Gate sub-zone.

Water sampling is done in different nodes of two paths, Path-I and Path-II in different time of the day (Fig. 4). As, chlorine is not stable in aqueous solution and its exposure to sunlight or other light, and agitation may accelerate the reduction of chlorine, therefore amber bottle was used to collect the sample. At the same time, samples were filled up to the top of the bottle and those were kept in very good cushioned container as per IS code 3025 (Part 1) - 1987 guideline [35]. Later, water samples were tested in Department of Natural Resources and Environment Management, Central Institute of Mining and Fuel Research (CIMFR) laboratory.

Different water quality parameters of the untreated and treated water at different nodes in the WDN are depicted in Table 2. The water quality parameter includes pH, alkalinity, conductivity, hardness, total organic carbon (TOC) and dissolved organic carbon. In general, pH is the concentration of acid protons. If alkalinity increases, pH of the water also increases. Usually pH of drinking water range is kept within 7.5–8.5. In general, dissolved salts and other inorganic chemicals conduct electrical current. Conductivity increases when the salinity in water and temperature increases. A sudden increase or decrease in conductivity in water indicates contamination from agricultural runoff or sewage leak which add phosphate, chloride and nitrate ions to it. Hardness of the water indicates existence of dissolved minerals, specifically calcium and magnesium. Hard water is not always a health risk, but creates mineral build up on fixtures and cause poor soap performance. The value in Table 2 indicates the water is moderately hard after treatment. TOC is the measure of the level of organic molecules or contaminants in purified water.

3.5.1. Sampling procedure

In this analysis, water samples collection were started in the next hour after chlorine dosing initiation at reservoir and completed simultaneously for Path-I and Path-II (Fig. 4). The locations of sample points are depicted in Table 3.

3.5.2. Experimental methods

Residual chlorine measurement is done as per standard analytical procedures prescribed by American Public Health Association for water and wastewater analysis. The free chlorine concentrations were analyzed on 10 mL samples via the N,N-diethyl-p-phenylenediamine colorimetric method [36].

3.5.3. Governing equations of chlorine decay

During chlorinated water movement into the distribution system, the residual chlorine gradually disappears.

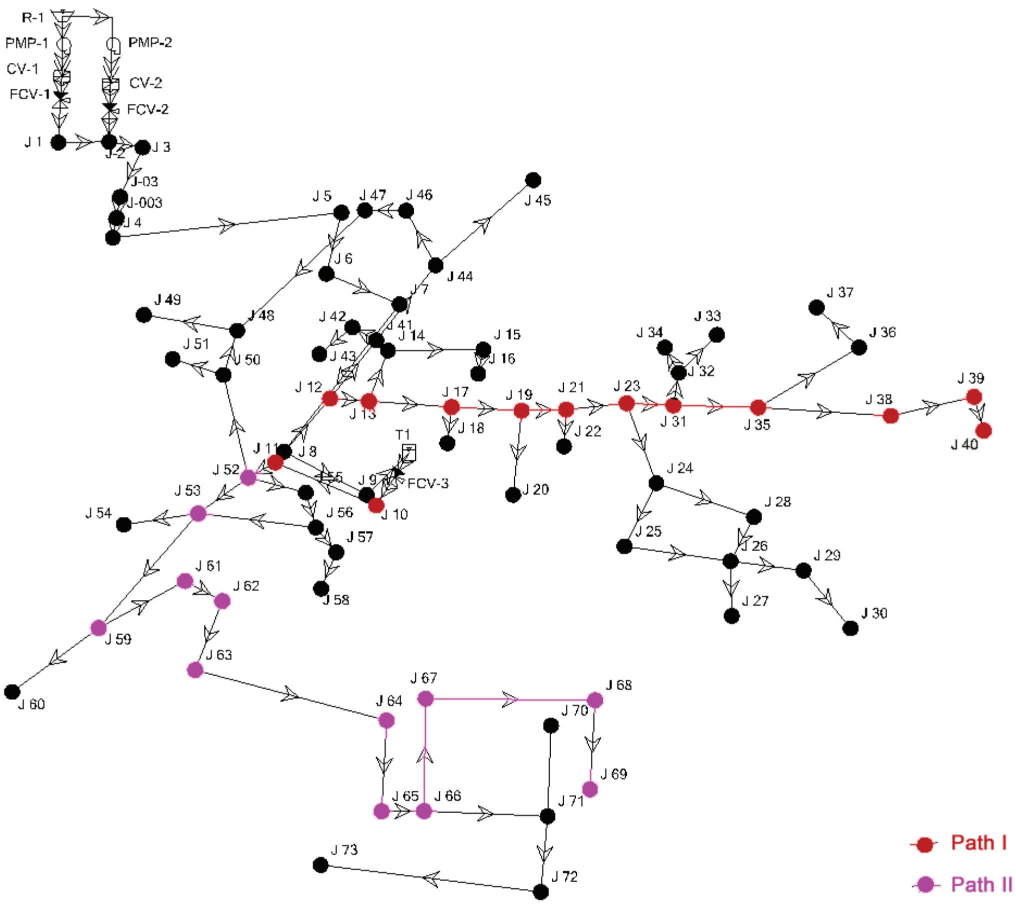

Fig. 4. Schematic view of Steel Gate WDN with Different Nodes and Junctions showing different paths for calculating water quantity and quality (surrounding OR1, OR2 and OR3).

Table 2
Water quality parameters for raw and treated water sample in the distribution system

S. no.	Node	Raw water, upstream of treatment plant	Node points in the rising pipeline			Node points in the Path-I	
	Parameter		J 1	J 003	J 6	J 12	J 35
01	pH	8.7	7.8	8.1	8.1	8.2	8.2
02	Conductivity (μS/cm)	169	167	157	166	164	166
03	Alkalinity (mg/L)	101	74	80	78	78	79
04	Hardness (mg/L)	92	80	71	76	68	64
05	Total organic carbon (mg/L)	3.588	2.178	3.01	3.003	2.991	2.967
06	Dissolved organic carbon (mg/L)	3.012	1.897	2.836	2.782	2.413	2.226

Table 3
Locations of water sampling points in WDN

S. no.	Path in WDN network	Node ID	Location of water sample	
			Latitude	Longitude
1	Path I	J 003	23°50′8.32″N	86°26′23.72″E
2		J 6	23°49′17.61″N	86°27′35.25″E
3		J 10	23°48′47.80″N	86°27′48.39″E
4		J 31	23°48′58.00″N	86°27′54.20″E
5		J 35	23°48′53.23″N	86°28′14.29″E
6		J 40	23°48′42.33″N	86°28′52.32″E
7	Path II	J 59	23°48′40.54″N	86°27′12.04″E
8		J 62	23°48′37.70″N	86°27′21.18″E
9		J 64	23°48′22.09″N	86°27′14.86″E
10		J 65	23°48′17.25″N	86°27′22.45″E
11		J 68	23°48′21.84″N	86°27′31.55″E
12		J 69	23°48′15.24″N	86°27′31.14″E

Following factors usually influence chlorine consumption: (i) reaction with organic and inorganic chemicals in the bulk aqueous phase; (2) reactions with biofilm at the pipe wall; (3) consumption by the corrosion process; (4) mass transport of chlorine and other reactants between bulk flow and pipe wall [15,37].

One dimensional advection-dispersion mass transport equation along with reaction for dissolved substances in water can be stated as follows:

$$\frac{\partial C_i}{\partial t} = D\frac{\partial^2 C}{\partial x^2} - u_i\frac{\partial C_i}{\partial x} - r\left(C_i\right) \quad (5)$$

where C_i is the concentration of dissolved matter (mass/volume) in pipe i (here it is free residual chlorine); t is the time; D is the dispersion coefficient (length²/time); u_i is the mean velocity (length/time) in pipe i; x is the distance (length); $r(C_i)$ is the reaction rate in pipe i (time^{-1}) as a function of concentration C_i.

It assumes that any dissolved substance will travel along the length of pipes of networks with the same average velocity of bulk fluid flow with some given reaction rate. When transport due to the longitudinal dispersion is neglected, Eq. (5) can be simplified as follows [38,39]:

$$\frac{\partial C_i}{\partial t} = -u_i\frac{\partial C_i}{\partial x} - r\left(C_i\right) \quad (6)$$

However, an exception would be an instantaneous release of a substance moving at a very low velocity in a relatively long pipe. The chlorine decay mechanism can be categorized as follows: (i) reaction of chlorine with substances present in water, which is known as bulk rate of reaction or bulk decay (K_b); (ii) the reaction of chlorine with substance present on pipe wall, which is known as wall rate of reaction or wall decay (K_w) [40,18,10,41].

The reaction rate term for K_b can be expressed in the following form:

$$\frac{dC}{dt} = -K_b C \quad (7)$$

Here the term $r(C_i)$ is replaced by K_bC, where C is the chlorine concentration in bulk fluid (mg/L) for the first order reaction rate; K_b is the bulk rate of reaction.

The reaction rate term for K_w can be expressed in the following form.

$$\frac{dC}{dt} = -\frac{K_w}{r_h C_w} \quad (8)$$

Here the term $r(C_i)$ is replaced by K_w/r_hC_w for the first order reaction rate, where K_w is the wall decay coefficient (m/d), r_h is the hydraulic radius (meter) and C_w is the concentration of chlorine at wall (mg/L), which is a function of the bulk chlorine concentration [41]. The literature cites K_w to range in between 0 to 1.52 m/d, depending upon the condition and age of the pipe.

Under the assumption that the material entering a junction node mixes completely and instantaneously, an additional set of conservation equations for junctions can be written as:

$$C_i\Big|_{x=0} = \frac{\sum_{j\in I_k} Q_j C_j\Big|_{x=L_j} + Q_s C_s}{\sum_{j\in I_k} Q_j + Q_s} \quad (9)$$

where i is the link with flow leaving node k; I_k is the set of links with flow into k; L_j is the length of link j; Q_j is the flow in link j; C_s is the external source concentration entering node k and Q_s is the external source flow entering node k.

3.6. Hydraulic and water quality modeling in hammer

The HAMMER V8i has used for hydraulic and water quality analysis in the water distribution system. This software performs extended period hydraulic simulation and dynamic water quality modeling of pressurized pipe of WDNs. The HAMMER V8i uses first order kinetics for bulk reactions and first order mass transfer kinetics for wall reaction.

4. Result and discussion

In this section, detailed steady and transient flow analysis is performed on Steel Gate and Bhuli sub-zones for present scenario, that is, considering the distributed water as current demand. These demands are distributed proportionately to the population clustering around different water tanks, which are given in the following section.

4.1. Analysis of vulnerable most sub-WDNs for present scenario

Before starting the transient analysis, several field surveys were conducted in search of any physical damage of WDN, which is visible from outside, as most part of the WDN is buried. Based upon the field survey, some affected parts were identified in both WDNs and accordingly path for transient analysis is decided for each sub-WDN. During field survey, main three affected parts (mainly leakage) areas were identified in each of the sub-WDN, which are vulnerable. In Fig. 3, affected parts of the sub-WDNs are shown. The affected parts, that is, leakages, are considered as orifice while transient analysis is performed.

Some of the discharge data were validated during field survey. During field survey in Steel Gate sub-zone, discharged of J16, J37, J45, J49 and J64 (Fig. 3) measured are as 11.7–14.3, 15.3–16.8, 10.8–13.2, 6.8–8.2 and 84.8–103.4 m^3/h, respectively, which are validating the calculated discharge in HAMMER. Whereas, during field survey in Bhuli sub-zone, discharged of J225, J228, J234 and J244 (Fig. 3) measured are as 16.4–17.8, 8.1–9.1, 14.4–17.6 and 7.2–8.8 m^3/h, respectively, which are validating the calculated discharge in HAMMER.

4.1.1. Steel gate sub-zone

Paths for transient analysis are selected including three leak, that is, orifice points (OR1, OR2 and OR3) having small opening area and having flow approximately 2 m^3/h as measured in the field (Fig. 3). Route J59-J61-J62-J63-J64-J65-J66-J71-OR1-J72-J73 is named as Path-11, Route J23-J31-OR2-J219-J38-J39-J40 is named as Path 12 and Route J12-J13-J17-J19-J23-J24-J25-J26-J29-OR3-J30 is named as Path 13. Pressure distribution in different nodes along Path 11, Path 12 and Path 13 before and after consideration of leakage incidents show that, there is a sudden pressure increase of 4.9% just before the leakage, that is, orifice for Path 12 (Fig. 3). This happened because there was natural tendency of increasing pressure due to reduction of pipe diameter. Simultaneously, there are 19.2%, 66.2% and 34.8% pressure fall just after the orifice in Path 11 Path 12 and Path 13, respectively.

Variations of pipe diameter at different nodes of these paths in steel gate sub-zone show that with the change in diameter of the pipeline the pressure is related inversely, that is, if diameter is decreasing the pressure is increasing until there is an existence of demand at that particular node or another pipeline branch is attached with certain demand. It is found that in case of demand at any node, pressure drop is occurring in the pipeline. For example, at node J62, there is pressure drop due to some water loss or demand.

4.1.2. Bhuli sub-zone

Paths for transient analysis are selected including three leak, that is, orifice points (OR11, OR22 and OR33) having small opening area and having flow approximately 1.8 m^3/h as measured in the field (Fig. 1). Route J210-J245-J246-OR11-J247-J212 is named as Path 21, Route J216-J218-J219-J220-J222-J224-J226-OR22-J227-J228 is named as Path 22 and Route J232-J236-J237-J240-OR33-J242-J244 is named as Path 23. Pressure distribution in different nodes along Path 21 Path 22 and Path 23 of Bhuli sub-zone before and after consideration of leakage incidents show that, there is a pressure fall of 4.4%, 28.4% and 56.8% just after the orifice in Path 21 Path 22 and Path 23, respectively (Fig. 3). Therefore, in order to maintain necessary pressure at the end node and distribute water with its full capacity, immediate renewals of these pipelines become necessary. Moreover, considering future demand and age of these pipelines also renewals of the pipelines are necessary.

4.2. Analysis for 30 years' future demand

The steady and transient flow analysis of steel gate and Bhuli WDNs are further repeated for actual 100% and more demand to account increasing demand in near future. Details of population growth is calculated based on data of last five censuses of India, that is, based on last 40 years' data (1971–2011) [1,42,43]. These population data have been used to estimate 30 years' future demand based on logistic growth model.

In logistic law of growth, rate of growth slows down and finally saturates, and generates the characteristic curve of S-shape having following equation structure [34]. In this paper, curve fitting toolbox of MATLAB is used to find out the three-parameter values based on population data available. Further, using those parameter values, prediction of population growth in DHN territory is made (Fig. 5; Table 4).

As water demand increases with population proportionately, demand can be calculated by multiplying water requirement per capita per day as per IS code 1172:1993 guideline. It is observed from past 40 years' population data that population may be increased by18.7% in next 30 years in Dhanbad Sadar block, DMC. Therefore, in view of this value, considering more safety, water demand value at each concern node is increased up to 125% (approximately) at an increment of 5% to perform steady and transient flow analysis. Details of steel gate sub-zone WDN with different node, junctions, pipe and modification proposed to fulfil water demand of 100% to 125% at an increment of 5% for 30 years' future demand, which is described as follows.

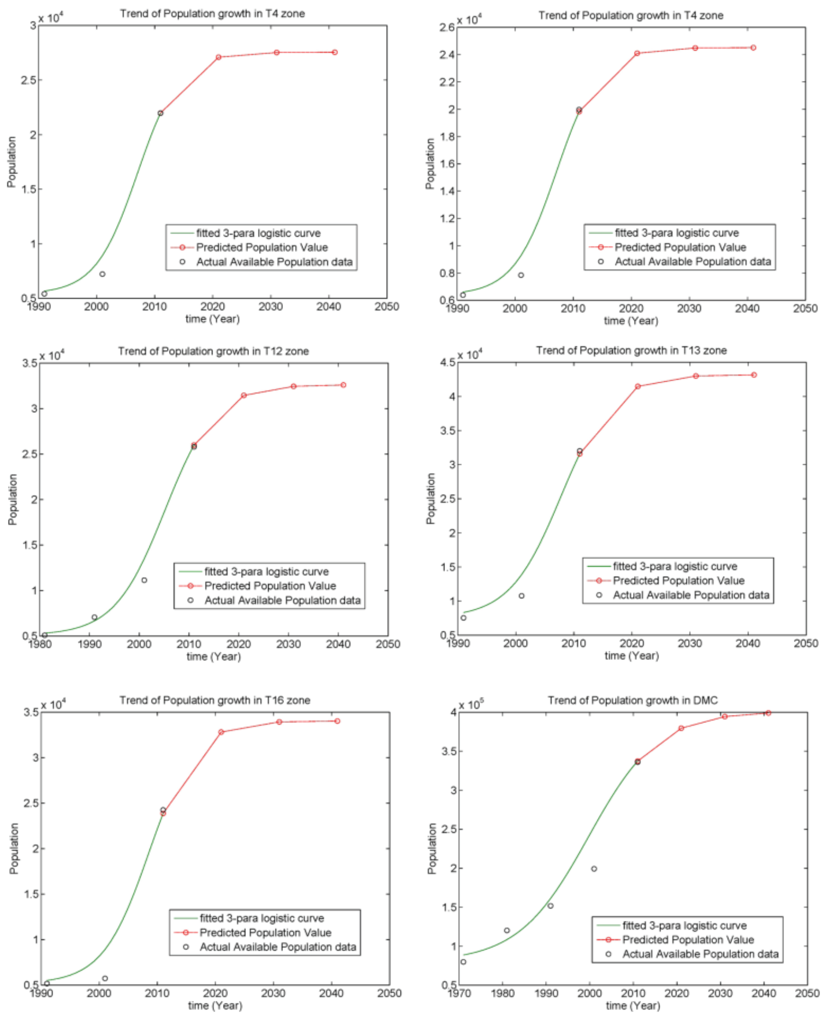

Fig. 5. Population graph in the sub-zones surrounding Tank 4 (Gandhi nagar), Tank 6 (Duatand), Tank 12 (Bhuli), Tank 13 (Steel Gate), Tank 16 (Hill-colony), whole DMC during 1971–2011 and population growth for next 30 years based on three-parameter logistic growth model.

Table 4
Details of actual population of draught prone sub-zones in DMC, their predicted population of year 2041 using three parameter logistic model and model parameter values

Year	T4 (Gandhi nagar)	T6 (Dhoatand)	T12 (Bhuli)	T13 (Steel Gate)	T16 (Hill-Colony)	All tanks in DSB
1971	—	—	—	—	—	79,838
1981	—	—	5,080	—	—	120,221
1991	5,415	6,379	7,063	7,541	5,165	151,789
2001	7,230	7,844	11,138	10,776	5,736	199,258
2011	21,962	19,971	25,792	32,019	24,254	336,045
(Predicted) 2041	27,550	24,514	32,593	43,160	34,027	399,048
% Growth	25.4	22.7	26.4	34.8	40.3	18.7
Parameter values of three parameter logistic growth model						
K	22,136.5	18,136.5	27,536.5	35,637.8	28,871.3	321,116.5
r	0.276	0.271	0.197	0.226	0.251	0.124
t_0	16.05	16.12	24.17	16.77	17.57	28.71

4.2.1. Pipeline renewal in Steel Gate WDN for future demand

At 100% demand, another Tank T20 of 2,100 m^3 volumes is required to be installed to fulfil the demand. Valve of 500 mm diameter is required to be added from raising line at node J5. Finally, it will supply water to distribution pipeline at node J12 via pipe P401 of 350 mm diameter having 230 m length. Moreover, pipelines to be added as P402 of 500 mm diameter and 55 m long, P403 of 500 mm diameter and 320 m long, P404 of 500 mm diameter and 614 m long to complete the route. At 105% demand, renewal of P22 is required to 400 mm diameter. At 110% demand, renewal of P57 is required to 200 mm. At 120% demand, renewal of P33 is required to 250 mm. At 125% demand, renewal of P30 is required to 350 mm and addition of new pipe is required as P406 having 350 mm diameter and 390 m length to join J12 and J52 in order to stable pressure transience in the network.

4.2.2. Pipeline renewal in Bhuli WDN for future demand

At 100% demand, renewal of P248 is required to 350 mm, whereas at 120% demand, renewal of P246 is required to 450 mm. At 125% demand, another Tank T21 of 1,750 m^3 volumes is required to be installed to fulfil the demand. Valve of 500 mm diameter is required to be added from raising line at node J249. Finally, it will supply water to distribution pipeline at Node J215 via pipe P411 of 300 mm diameter having 807 m length. Moreover, renewal of P252, P250, P260 and P258 is required to 300, 350, 450 and 450 mm, respectively.

4.3. Water quality test results

Water quality test (basically residual chlorine concentration) is performed in the Path-I. The analysis is done through HAMMER Software as well as water sample is collected from the field and experiment is done to find out the residual chlorine value.

4.3.1. Residual chlorine concentration in Path-I

Simulated residual chlorine concentration values of different nodes in path-1 (from nearest to farthest) in different interval of time of a day (i.e., 24 h) are shown in Fig. 6. Sequence of the nodes is as follows: J003-J6-J10-J12-J21-J31-J35-J40. Distances of the nodes from chlorine dosing point at reservoir R-1 is as follows 1080-4816-6120-6417-5945-6078-6603-7554 m.

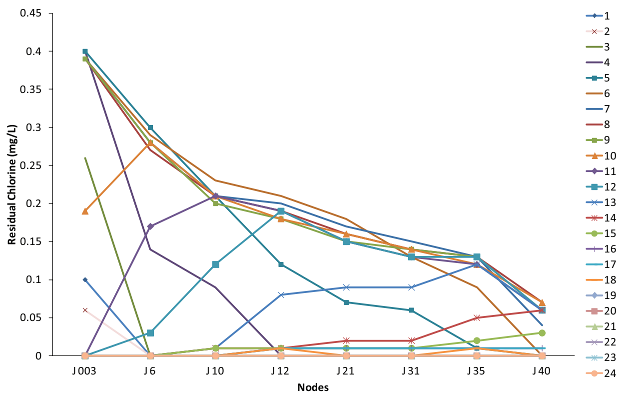

Fig. 6. Simulated residual chlorine concentration values of different nodes of path-1 (from nearest to farthest) in different interval of time.

Following observations are made for Path-I:

- In general, chlorine dosing is done on for 8 h every day at a rate of 0.5 mg/L. At initial condition (i.e., 1st h, i.e., at morning, at 4.00 h during WTP operation time), the chlorine dosing amount is zero, and residual chlorine concentration obtained at the nearest node of the WDN (i.e., J003) is also zero.
- As time progresses, presence of the residual chlorine concentration is observed in each node (Fig. 6). For example, at the 2nd h residual chlorine concentration of the node J003 shows the value 0.06 mg/L. The value increases with time for a particular node. For example, at the 3rd h residual chlorine concentration at node J003 is 0.26 mg/L. In general, residual chlorine concentration reaches its highest value (approximately 0.42 mg/L) at the nearest node from the dosing point (i.e., J003) at the 4th h.
- If space domain is considered, it is observed that in general, in a certain computational time, residual chlorine concentration reaches its highest value at the nearest node from the dosing point (i.e., J003) and the value reduces as water travel through the Path-I, that is, residual chlorine concentration decreases with distance.
- In some of the graphs (say for 11th h, 12th h, etc.), it is observed that the initial value of residual chlorine concentration starts with zero, then the value reaches the peak value and then it reduces to the lower value. This happens as the chlorine dosing is stopped after 8 h of operation, therefore the value observed after 8 h are nothing but the cumulative effect of residual chlorine present in the network.
- It is observed that average value of residual chlorine concentration is 0.2 mg/L. However, the nominal effect of chlorine (0.1 mg/L) remains present after 14 h of initiation of chlorine dosing. The value is at lower side of permissible range of the chlorine value (0.2–0.8 mg/L). Therefore, the time of chlorine dosing may be increase for 4–6 h more in order to meet the permissible chlorine concentration value.

Further, water samples (three sets) are collected from different nodes of the Path-I (Fig. 7). Water sample collection were started 1 h after chlorine dosing initiation at reservoir and completed within approximately 2.5 h for each set of Path-I. Then the samples were sent to CIMFR Laboratory to find out residual chlorine concentration. The sample is tested in Spectrophotometer (Genesys 20) at 515 nm wavelength. Results of the three sets of sample for path-I (i.e., set 11, set 12 and set 13) are shown in Table 5.

Laboratory test results and simulated residual chlorine concentration of each node of path-I in different interval of time are plotted in Fig. 8 in validation purpose.

Following observations are made:

- Line graphs (with markers of different colors) represent the simulated results obtained from HAMMER software V8i. Whereas, point graph (with different

Fig. 7. (a) Water sample collection at Node J6 (23°49′17.61″N, 86°27′35.25″E) is shown. (b) Laboratory test of the water samples collected in Path-I for finding out residual chlorine concentration.

markers) represents the laboratory test value of residual chlorine concentrations. During laboratory test no residual chlorine is found for the first 3.5 h (i.e., in set 11). Further in set 12, residual chlorine value is obtained.

- Laboratory test results validate the simulated results of Nodes J003, J6 better compared with the other nodes, that is, J10, J12, J35 and J40. Nodes J003 and J6 are situated before the Tank T-215, water is stored for a while. Water sample could not be collected for Node J21 and J31, as those points were out of reach. It is observed that after retaining water in T-215, actual residual chlorine value deteriorates than expected, that is, simulated value of J10, J12, J35 and J40, probably because of interaction and reaction chlorine with of more biofilm present in the surface area of tank wall.
- However, test results of J35 and J40 are slightly varying with the simulated results. Probable reason may be as follows: (a) the nodes are situated far from dosing point (more than 6.5 km) and have more interaction with

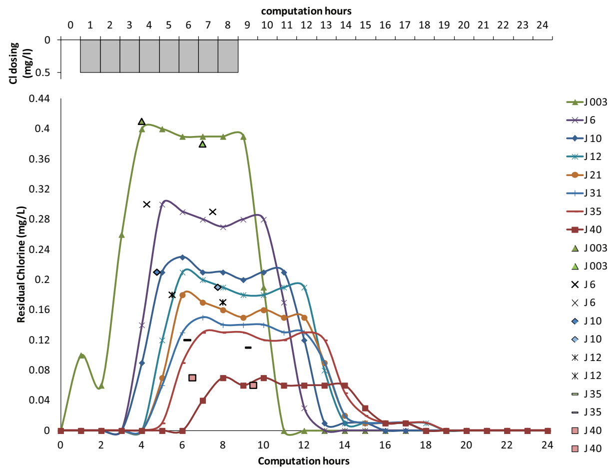

Fig. 8. Simulated residual chlorine concentration of each node of Path-1 in different interval of time and validation with experimental data.

Table 5
Residual chlorine concentration of water sample collected at different nodes at path-I in different time interval after chlorine dosing at R-1

Sample collection at different nodes	Residual chlorine concentration (mg/L)																	
	Set-11						Set-12						Set-13					
	Hour after chlorine dosing at R-1						Hour after chlorine dosing at R-1						Hour after chlorine dosing at R-1					
	1.0	1.25	1.75	2.5	3.25	3.5	4.0	4.25	4.75	5.5	6.25	6.5	7.0	7.5	7.75	8	9.25	9.5
J 003	0.0	—	—	—	—	—	0.41	—	—	—	—	—	0.38	—	—	—	—	—
J 6	—	0.0	—	—	—	—	—	0.30	—	—	—	—	—	0.29	—	—	—	—
J 10	—	—	0.0	—	—	—	—	—	0.21	—	—	—	—	—	0.19	—	—	—
J 12	—	—	—	0.0	—	—	—	—	—	0.18	—	—	—	—	—	0.17	—	—
J 21	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
J 31	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
J 35	—	—	—	—	0.0	—	—	—	—	—	0.12	—	—	—	—	—	0.11	—
J 40	—	—	—	—	—	0.0	—	—	—	—	—	0.07	—	—	—	—	—	0.06

corrosion process with the elongated surface area of long length pipeline, (b) the residual chlorine value deteriorates heavily due to reaction with organic chemicals or biofilm formed in the pipe wall due to age of pipeline (approximately 10 years).

4.3.2. Residual chlorine concentration in Path-II

Simulated residual chlorine concentration values of different nodes in path-II (from nearest to farthest) in different interval of time of a day (i.e., 24 h) are shown in Fig. 9. Sequence of the nodes is as follows: J59-J62-J64-J65-J68-J69. Distances of the nodes from chlorine dosing point at reservoir R-1 is as follows 7068-7481-8134-8417-9090-9300 m.

Following observations are made for Path-II:

- As, chlorine dosing point of Path-II is same as Path-I, at initial condition (i.e., 1st h, i.e., at morning, at 4.00 h during WTP operation time), the chlorine dosing amount is zero, and residual chlorine concentration obtained at the nearest node of the WDN (i.e., J59) is also zero.
- As time progresses presence of the residual chlorine concentration is observed in each node (Fig. 10). For example, at the 5th h residual chlorine concentration of the node J59 shows the value 0.09 mg/L. The value increases with time for a particular node. In general, residual chlorine concentration reaches its highest value (approximately 0.2 mg/L) at the nearest node from the dosing point (i.e., J59) at the 6th h. Average value of residual chlorine concentration is about 0.15 mg/L. Later on, the value reduces with time due to reaction with organic chemicals or biofilm formed in the pipe wall.
- If space domain is considered, it is observed that in general, in a certain computational time, residual chlorine concentration reaches its highest value at the nearest node from the dosing point (i.e., J59) and the value reduces as water travel through the Path-II, that is, residual chlorine concentration decreases with distance.
- It is also observed that the effect of chlorine (0.1 mg/L) remains present after 13 h of initiation of chlorine dosing. The value is at lower side of permissible range of the chlorine value (0.2–0.8 mg/L). Therefore, the time of chlorine dosing may be increase for 4–6 h more in order to meet the permissible chlorine concentration value.

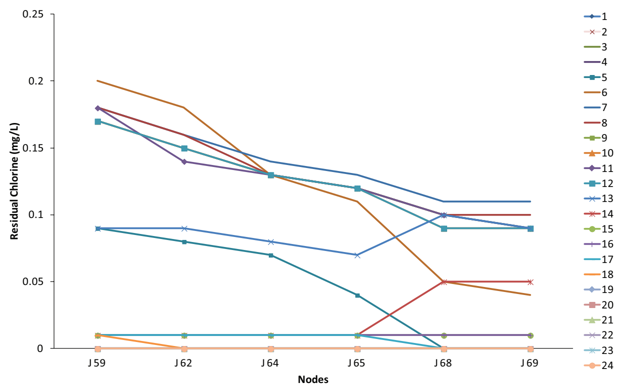

Fig. 9. Simulated residual chlorine concentration values of different nodes of Path-II (from nearest to farthest) in different interval of time.

Further, similar to the Path-I, water samples are collected from different nodes of the Path-II also. After water sample collection at J6 in path-I, water sample collection of Path-II was started, approximately 2.5 h after chlorine dosing initiation in R-1. After water sample collection at J6, one team continued to collect the water sample in Path-I and another team begun water sample collection in Path-II. Water sample collection in Path-II was completed within another 2.5 h for Path-II. Like path-I, the collected samples were sent to CIMFR Laboratory to find out residual chlorine concentration. Results of the same tested in Spectrophotometer (Genesys 20) are shown in Table 6.

Laboratory test results and simulated residual chlorine concentration of each node of Path-II in different interval of time are plotted in Fig. 10 in validation purpose. Following observations are made:

- Line graphs (with markers of different colors) represent the simulated results obtained from HAMMER software. Whereas, point graph (with different markers) represents the laboratory test value of residual chlorine concentrations.
- Laboratory test results validate the simulated results of Nodes J59, J62, J64, J65, J68 and J69.
- At initial phases (during 1st h to 4th h of computation time), the residual chlorine concentration is found to be zero, as the location of the node is far from the chlorine dosing point (i.e., R-1). Therefore, existence of residual chlorine concentration is found with more time lag, compared with Path-I.
- However, test results of J35 and J40 are slightly varying with the simulated results. Probable reason may be as follows: (a) the nodes are situated far from dosing point (more than 9 km) and have more interaction with corrosion process with the elongated surface area of long length pipeline; (b) the residual chlorine value deteriorates heavily due to reaction with organic chemicals or biofilm formed in the pipe wall due to age of pipeline (approximately 10 years).

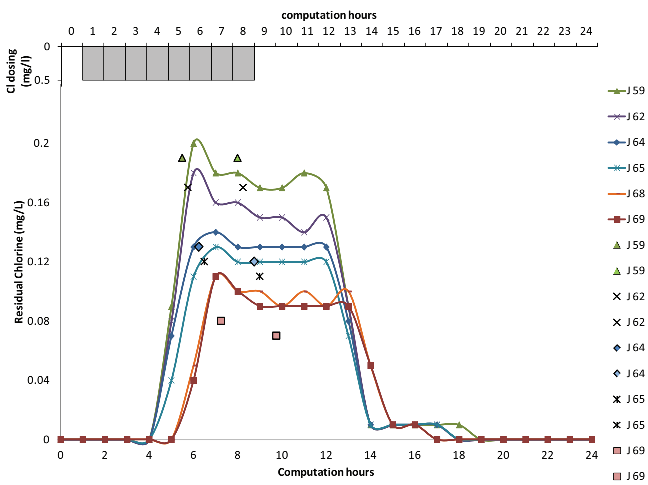

Fig. 10. Simulated residual chlorine concentration of each node of Path-II in different interval of time and validation with experimental data.

Table 6
Residual chlorine concentration of water sample collected at different nodes at Path-II in different time interval after chlorine dosing at R-1

Sample collection at different nodes	Residual chlorine concentration (mg/L)														
	Set-21					Set-22					Set-23				
	Hour after chlorine dosing at R-1					Hour after chlorine dosing at R-1					Hour after chlorine dosing at R-1				
	2.5	2.75	3.25	3.5	4. 25	5.5	5.75	6.25	6.5	7.25	8	8.25	8.75	9	9.75
J 59	0.0	—	—	—	—	0.19	—	—	—	—	0.19	—	—	—	—
J 62	—	0.0	—	—	—	—	0.17	—	—	—	—	0.17	—	—	—
J 64	—	—	0.0	—	—	—	—	0.13	—	—	—	—	0.12	—	—
J 65	—	—	—	0.0	—	—	—	—	0.12	—	—	—	—	0.11	—
J 68	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
J 69	—	—	—	—	0.0	—	—	—	—	0.08	—	—	—	—	0.07

- Amount of chlorine dosing must be increased in order to maintain permissible range of the chlorine value (0.2–0.8 mg/L), whereas, dosing duration must be increased 4–6 h more in order to last the effect of the chlorine in the WDN for more time of use.

5. Conclusion

In this study, WDN of DMC is reassessed in view of the increasing population of the area. Water demand of these areas have been calculated as per IS 1172:1993, land use and corresponding to the population. Field survey revealed that Steel Gate and Bhuli sub-zones are the most vulnerable to water deficit and hence considered as the study area for water quantity (i.e., demand) as well as water quality analysis. WDN maps of these study areas have been prepared combining the field survey GPS data, SOI Topomap, Google Earth and ArcGIS Software. Finally, WDN maps have been transferred to HAMMER Software for flow, pressure analysis (i.e., steady and transient analysis) and water quality analysis. During field survey, some vulnerable parts (leakage) were identified within each WDN, which are considered as path for transient analysis in HAMMER software. It is observed that due to leakage, pressure drop is occurring along the path. Due to this fact, end nodes of these paths are not having sufficient pressure. As a result, users of these paths are not getting sufficient supply water pressure at the present scenario, and water quality is getting deteriorated, which were validated in field survey also. Water demand is calculated as per IS 1172:1993.

5.1. Water demand analysis

To account next 30 years' future demand, an exercise is conducted to find out population growth rate of this region based on past 40 years' population data. MATLAB curve fitting toolbox is used to fit three-parameter logistic growth model with existing population data and thereafter parameter values are used to predict future population growth. It is found that population may be increasing by 18.7% after 30 years. Therefore, in view of this data, considering more safety, flow and pressure analysis is performed for up to 125% water demand in HAMMER to explore the capability of WDNs to supply water to these water deficit areas.

Following observations are made in these exercises:

- For higher demand up to 125% demand, some of the pipeline viz., P30, P33, P57, P62, P64, P70, P63, P71, P73 for Steel Gate sub-zone and P244, P246, P248, P252, P250, P260, P258 in the Bhuli sub-zone were experiencing negative pressure at corresponding nodes. It is suggested that diameter of the pipeline was needed to be renewed to sustain future demand.
- Interestingly, there were other pipelines (between node J29-J30, J31-J35, J71-J72 for Steel Gate and J226-J227, J240-J242, J246-J247 for Bhuli) also in the WDN, where damages have occurred in recent past occurred due to any mechanical fault due to external load or may be due to some illegal activity such as tapping of water. It is suggested that these parts of the WDNS are needed to be renewed in order to prevent water loss and pressure drop in the pipeline.
- To fulfil 30 years' future demand capacity of water supply needed to be increase by installing new tanks viz., T20 and T21of capacity of 2,100 m^3 and 1,750 m^3, respectively, for these sub-zones.
- Additionally, some pipelines are needed to be add in the network afresh viz., P401, P402, P403, P404, P405, P406 for Steel Gate WDN and P411, P412, P413, P414 for Bhuli WDN to make the network functional for fulfilling the higher demand.

5.2. Water quality analysis

In this paper, residual chlorine concentration is calculated for water quality analysis. Modeling is done for drinking water distribution at Steel Gate area of different nodes along the Path-I J003-J6-J10-J12-J21-J31-J35-J40 and Path-II J59-J62-J64-J65-J68-J69. Necessary field survey is done to collect water samples for validation of the simulated results. Following major observations are made in this analysis.

- In general, chlorine dosing is done on for 8 h every day at a rate of 0.5 mg/L at reservoir R-1. In general, through Path-I, residual chlorine concentration reaches its highest value (approximately 0.42 mg/L) at the nearest node from the dosing point (i.e., J003) at the 4th h (Fig. 6). It is observed that average value of residual chlorine concentration is 0.2 mg/L. However, the nominal effect of chlorine (0.1 mg/L) remains present after 14 h of initiation of chlorine dosing.

- In Path-II, residual chlorine concentration reaches its highest value (approximately 0.2 mg/L) at the nearest node from the dosing point (i.e., J59) at the 6th h (Fig. 9). It is observed that average value of residual chlorine concentration is 0.15 mg/L. However, the nominal effect of chlorine (0.1 mg/L) remains present after 13 h of initiation of chlorine dosing.
- These residual chlorine concentration values are at lower side of permissible range of the chlorine value (0.2–0.8 mg/L). Therefore, the time of chlorine dosing may be increase for 4–6 h more in order to meet the permissible chlorine concentration value.
- Laboratory test results validate the simulated results accurately in most of the cases and the discrepancies are probably because of (i) interaction and reaction chlorine with of more biofilm present in the surface area of tank and pipe wall due to age of pipeline (approximately 10 years); (ii) the nodes are situated far from dosing point and have more interaction with corrosion process with the elongated surface area of long length pipeline.

This analysis may be helpful to engineers to understand the necessity and exact location of pipe renewal of WDNs of Dhanbad Sadar Block, DMC.

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