Challenges in calibration of water distribution network: a case study of Ramnagar Elevated Service Reservoir command area in Nagpur City, India

Shweta Rathi, Rajesh Gupta, Pawan Labhasetwar and Pranav Nagarnaik

ABSTRACT

Calibration of a hydraulic model is a challenging task as it considers the involvement of a large number of uncertain parameters. There are some parameters like length and diameter of pipes, for which fairly accurate values can be obtained. As with all hydraulic models, water demands are one of the main parameters that cause the most uncertainty in the model outputs. The calibration of the water demands is usually not feasible, which is attributable to the limited quantity of available measurements in most real water networks. However, some parameters like nodal demands and pipe roughness coefficients are estimated close to the actual values. Various types of valves are used for flow control by throttling. Hence, their setting in the field is also an important input to the model. Having more precise data helps in reducing time and results in better calibration as presented in the case study of one hydraulic zone served from Ramnagar Elevated Service Reservoir (ESR) (Zone II) in Nagpur City, Maharashtra State, India. This paper aims at presenting the complexities and challenges involved in calibration of the study area. It further describes the entire process from collection of the required data to the calibration of the network.

Key words | calibration, hydraulic model, network simulation, water distribution network

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LIST OF ACRONYMS

BV	Butterfly valve
CEO	Chief executive officer
CP	Critical point
ESR	Elevated Service Reservoir
FCV	Flow control valve
FM	Flow meter
GA	Genetic algorithm
GIS	Geographical information system
HDPE	High-density polyethylene
HGL	Hydraulic grade line
HSC	House service connection
HW	Hazen–Williams
LSL	Lowest supply level
NEERI	National Environmental Engineering Research Institute
NLP	Nonlinear programming
NMC	Nagpur Municipal Corporation
NRW	Non-revenue water
OCW	Orange City Water Works
PMP	Pressure monitoring point
PRV	Pressure reducing valve
SCADA	Supervisory Control and Data Acquisition
SV	Sluice valve
VNIT	Visvesvaraya National Institute of Technology
WDS	Water distribution system

INTRODUCTION

Hydraulic models are widely used as vital tools to facilitate the design, operation, and management of water distribution systems (WDSs) (Méndez *et al.* 2013). Several methodologies

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have been developed in the past to improve WDS modeling technologies. Without appropriate estimation of parameters, a numerical model would not correctly simulate reality. As a result, the planning or operational decisions based on such simulation analysis may lead to serious errors. Calibration of a water distribution systems model is defined as the process of adjusting network parameters so that the output from the computer model matches the field measurements, which are usually the pressures and flow rates at particular locations in the network (Shamir & Howard 1977). The calibration procedure for a water network model has been well addressed by Ormsbee & Lingireddy (1997). A number of previous studies have demonstrated that many systems and operation factors can affect the calibration accuracy of WDS models, such as nodal demands (Huang *et al.* 2017a), pipe friction/roughness (Duan *et al.* 2010), and pipe defects and devices (Duan 2015; Huang *et al.* 2017b).

Calibration of a water distribution system is a challenging task as there are a large number of input parameters such as nodal elevations and demands, including water losses, pipe length, diameter and roughness coefficients, water level at the source and pump characteristics, valve settings, etc. It is desirable that most of these parameters are measured accurately during field observations so that few uncertain parameters require adjustments during the calibration. Field survey provides reliable data regarding pipe length, ground levels, operating valve settings and status, and water level at the sources. In general, data regarding the nodal consumption and pipe roughness coefficients are less reliable and therefore may need adjustment during the calibration. In actual practice, there is a lot of difference between the model-predicted behavior and actual field results. This network must be calibrated so that it can be reliably used for any practical application (Walski 1986).

Calibration methods are classified into three categories: (1) trial-and-error procedure models, (2) explicit method, and (3) implicit method or optimization methods. In the first type of calibration method, several methods have been suggested to simultaneously adjust pipe roughness coefficient and nodal demands (Walski 1983, 1986; Bhave 1988; Boulos & Wood 1990; Reddy *et al.* 1996; Todini 1999; Wu *et al.* 2002; Walski *et al.* 2003; Bhave & Gupta 2006; Kang & Lansey 2011; Dini & Tabesh 2014; Maier *et al.* 2014, etc.). On the other hand, several methods adjust the pipe roughness coefficient only and it is presumed that nodal demands are fairly accurate and do not need any adjustment (Rahal *et al.* 1980; Kumar *et al.* 2010; Jadhao & Gupta 2018, etc.). Several methods have suggested adjustment of the nodal demand and leakage estimation in WDS models (Di Nardo *et al.* 2015; Kun *et al.* 2015, etc.).

In the second approach, the calibration of the model could be carried out through explicit approaches (e.g. Ormsbee & Wood 1986; Bhave 1988; Boulos & Wood 1990; Todini 1999). It involves solving an extended set of continuity and head-loss equations where the calibration problem is required to be even-determined, i.e. the number of calibrated parameters must be equal to the number of measurements. When the number of unknown parameters is larger than the number of measurements, calibration parameters are often grouped that may result in potentially impractical outputs.

The third method for the calibration of the model is through implicit approaches (e.g. Ormsbee 1989; Lansey & Basnet 1991; Datta & Sridharan 1994; Greco & Giudice 1999; Lansey *et al.* 2001; Lingireddy & Ormsbee 2002; Bascià & Tucciarelli 2003; Kapelan *et al.* 2007; Koppel & Vassiljev 2009) in which field-observed and measured parameters are treated as known parameters and directly used in the model analysis. The implicit approach requires that the number of flow and pressure measurements exceeds the number of unknowns. The implicit problem formulation can be solved using optimization techniques, e.g. nonlinear programming (NLP) or an evolutionary technique like genetic algorithm (GA).

Jadhao & Gupta (2018) carried out the manual calibration of one of the zones of Nagpur City, where the nodal demands are calculated based on the consumers' billing record. The non-revenue water losses were uniformly allocated to all junctions. Valve positions and their opening status were obtained from the field and pipe roughness coefficient values were adjusted for calibration. A similar study is carried out in this paper. However, the very complex zone of Nagpur City, India, is considered for the study purpose and the complexities, challenges and detailed procedure for calibration are discussed herein.

In this paper, a case study of one of the parts of Nagpur City in Maharashtra State in India is considered for calibration of the network of Ramnagar Elevated Service

Reservoir (ESR) in the pilot zone after its conversion to a continuous water supply system. Nagpur Municipal Corporation (NMC) in Nagpur City, India, has implemented a 24 × 7 water supply project on a pilot basis in one of the water supply zones having 7,254 consumer connections with the objective of water and energy loss control to provide better services to consumers. The main aim of the paper is to describe the challenges and complexities involved in the study area for calibration. Further, it describes the detailed steps of calibration of the study area. The procedure of calibration is described in the following different steps: (1) collecting calibration data, (2) hydraulic model preparation and initial results, (3) data validation, (4) hydraulic model improvement, (5) micro-calibration, and (6) results and conclusions.

METHODOLOGY USED

Several methods are available in the literature for calibration of water distribution networks (WDNs) (Bhave & Gupta 2006; Kang & Lansey 2011; Sanz & Pérez 2015; Do *et al.* 2016). One group of methods considers both pipe coefficient and nodal demands as uncertain and adjusts them simultaneously during calibration, while the other group of methods presumes nodal demands are fairly accurate and do not need any adjustment. Only pipe roughness coefficients are adjusted.

A reasonable agreement between the computed and observed values of field pressure should be reached during calibration. Walski (1983) suggested an average difference of ±1.5 m with a maximum value of ±5.0 m in computed and observed field pressures for a good data set and the corresponding values of ±3 and ±10 m for a poor data set. Cesario & Davis (1984) recommended an accuracy of 3.5–7.0 m as a reasonable target.

In this study, pipes are divided into groups based on material, diameter and age, and a common value of pipe roughness coefficient is considered for all pipes in a group. Online monitoring of flow at the source and pressures at two salient points are carried out and hourly flow and pressure data are used for calibration. The sum of squares of the difference between the observed and modeled values is minimized for optimum values of pipe coefficients. Percentage error in calibration is calculated.

STUDY AREA AND NETWORK DETAILS

Nagpur, a second capital of Maharashtra State, is situated in the center of India. The population of the city is 2.53 million (2015) spread over 217 sq. km. The total water supply to the city is over 650 MLD through 54 service reservoirs and a 3,200-km-long distribution network covering 239,000 connections. The study area consists of one hydraulic zone of Ramnagar ESR located at the western part of Nagpur City and composed of a residential area with all types of dwellings including slum areas as well as institutional and commercial areas. During the conversion of mode from intermittent to continuous, all property connections were changed, faulty meters were replaced/repaired, illegal connections were removed/regularized, public stand posts were converted to grouped pipe connections with metering, and old pipelines (about one-third of total pipelines) were replaced by new pipelines.

The water distribution network shown in Figure 1 has one source of supply (R-1), 619 nodes and 733 pipes. The network is organized in 33 subzones consisting of 12 wards. Out of the 33 subzones, 26 are fully served by Ramnagar ESR and seven are partly served. The pressure and flow in these 33 subzones are controlled by 69 valves. Each of the subzones is controlled by one or more valves. The network has two inlets, i.e. water enters into the network from two sources such as from the reservoir as well as a bypass line, which is shown in Figure 2.

CHALLENGES IN STUDY AREA

1. Ramnagar ESR is located at elevated areas as compared with other ESRs on feeder mains named as Gayatri Nagar, Pratap Nagar, Chinchbhuwan and others.
2. Some portions in this study area are at higher elevation and some are at lower elevation. As a result, when the supply is at a lower elevation area, the pressure at the higher elevation areas reduces. Therefore, the main challenge is that it is difficult to manage the pressure in systems overall.

Figure 1 | Water distribution network of Ramnagar ESR, Nagpur, Maharashtra, India.

3. As shown in Figure 2(a), the supply is from ESR and from a bypass line. ESR supplies the water for very little of the period and most of the time water is supplied from the bypass line. Network inlet and outlet pipe arrangements are shown in Figure 2(b).
4. Valves operated in ESR premises result in significant head loss and low-pressure issues in elevated areas.
5. One of the critical points (CP1) or pressure monitoring point (PMP-1) named as Ambazari Hill-Top Slum is at higher elevations and another critical point (CP2) or PMP-2 named as Telankhedi Slum (CP2) is at lower elevation.
6. Only 30% of the pipelines have been replaced by high-density polyethylene pipe (HDPE) while other pipes have remained as they are and therefore they are prone to leakages.
7. In this particular zone, the demand is very high (i.e. 18 MLD), but the capacity of the ESR is deficient, i.e. 2.27 ML (2,270 m^3). Therefore, the system is in imbalance at the storage itself. As a result, the bypass line is provided and hence there is a utilization of the bypass line in the system.

STEPS FOR DATA COLLECTION AND CALIBRATION OF HYDRAULIC MODEL

Data collection

For preparation of the hydraulic model of the existing WDN, the network data, demand data and operational data are required. Data pertaining to water demand, water supply and water billed are collected for analysis from the water works department of Nagpur Municipal Corporation and Orange City Water Works (OCW) in India.

Network data collection

Networks are made up of sources, nodes, links and valves and their data are collected from the water utilities

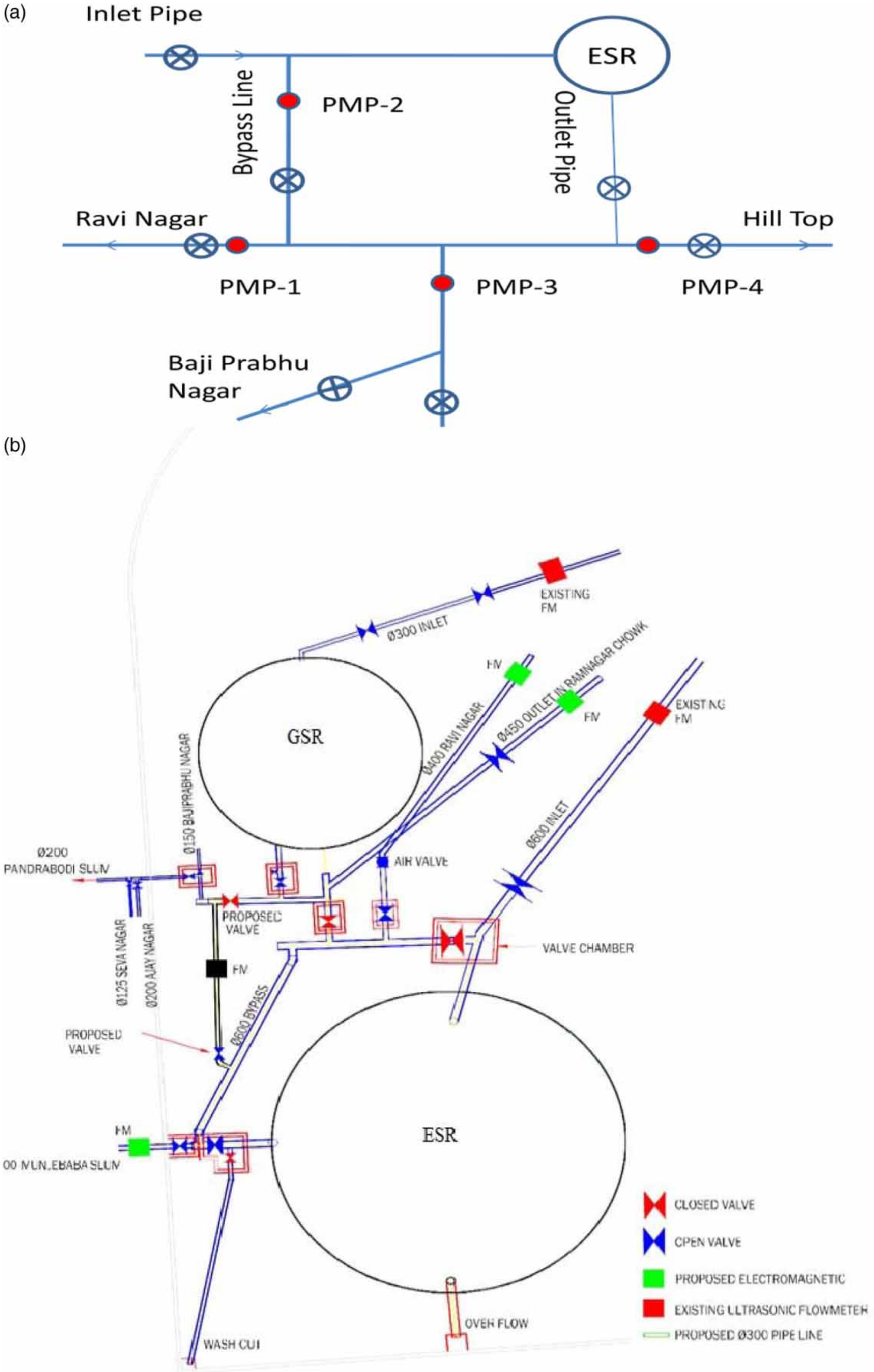

Figure 2 | (a) Networks having multiple sources, bypass line and from ESR; (b) schematic layout of plan of Ramnagar ESR premises. Please refer to the online version of this paper to see this figure in color: http://dx.doi.org/10.2166/ws.2020.047.

(OCW). Data are collected in the geographical information system (GIS) format and are used for preparing the hydraulic model of the WDN. Sources, nodes and valves represent WDN features at specific locations. Network data are mainly composed of pipe and node data.

The base map of the existing WDN gives the details of source, lengths, diameters and material of pipes, and service connection details, and the GIS base contour map for ground elevation is collected from the water utilities. Pipes of different materials such as cast iron, ductile iron and HDPE have been installed at different locations and at different times.

Source head and supply from source

The elevation of the ESR is 340.930 m. The storage facility is modeled as a reservoir having a capacity of 2.27 ML (2,270 m^3). The supply rate of the reservoir is measured by installing a digital water meter at the outflow pipe and also the water level in the reservoir is noted.

Demand data collection

The nodal demands are obtained from consumer usage information, i.e. from billing data. The billing data cover the water usage of a total of 7,254 consumers. Of these, 6,771 are quarterly billed consumers and 483 are monthly billed consumers. The average daily demand is obtained based on the consumer data for three billing cycles for both quarterly and monthly billed consumers. The average daily requirement for the entire water distribution is 16.96 MLD. The consumer data include the consumer index number, meter number, meter installation date, consumer address and meter reading with date. Water demand data are assigned to nodes in the water distribution network model. The water demand is calculated by using the billed consumption plus assessed losses.

Operational data collection

Operational data describe the actual operating system characteristics at a given time and include the water levels in reservoirs, settings at sluice valves and control policy, etc. Herein, operational data are obtained from field surveys and from water utilities' operational staff.

Water depth (level) in the reservoir is collected from Supervisory Control and Data Acquisition (SCADA). In India and most of the developing countries, sluice valves are used to control flow by reducing the pressure through throttling instead of a pressure reducing valve (PRV) or flow control valve (FCV). Source details (as mentioned above) such as elevation, lowest supply level (LSL) and head of the ESR and valve details such as location, type, size, timing, total number of threads and number of threads open are obtained from field survey and operational staff, Table 1. Flow at source node and pressure at pre-determined pressure monitoring points (PMPs) are measured and obtained from the field.

Hydraulic model preparation and initial calibration results

Based on the available data, initially the model is prepared. Each house service connection (HSC) is geographically linked with pipe number using street addresses with plot number in the billing data and location of the consumer meter. Consumer demands are equally distributed to both the junctions and in some situations to the downstream node only. The total system inflow is calculated based on the flow recorded by the flow meter installed on the outlet pipe of the Ramnagar ESR, i.e. at the inlet of the water distribution network. The difference between the average billed water volume per day and daily system inflow is non-revenue water. Non-revenue water is allocated to all junctions considering uniform distribution of losses all along the pipe length. The average nodal demands, including the losses during the period of calibration, are obtained for one cycle, i.e. from the period of May 2017 to July 2017.

The generalized diurnal demand pattern for the entire distribution network is created based on an hourly flow recorded by the flow meter installed on the outlet pipe of the Ramnagar ESR, i.e. at the inlet of the distribution network. The observations of flow from the source and water level in the reservoir on the day of observation (5 January 2018) are given in Table 2. The average flow during the day was 679.74 m^3/hr. The flow multiplier was obtained for extended period simulation as given in Table 2, since

Table 1 | List of the valves with operational status during the studies

Sr no.	Locations	Valve no.	Valve located on	Valve type	Size (mm)	Total threads	Threads open	Percentage closed
1	Sudhamnari Slum	Iso-141	PHT-488	SV	100.00	24.00	22.00	8.33
2	Sudam Nagri valve	Iso-147	PHT-145	SV	150.00	30.00	CLOSED	100.00
3	Mahatma Fule Slum valve	Iso-63	RNE-219	SV	100.00	24.00	22.00	8.33
4	BajiPrabhu Nagar Slum	Iso-166	RNE-302	SV	100.00	24.00	22.00	8.33
5	Ramnagar LIT Road	Iso-216	RNE-384	SV	100.00	24.00	22.00	8.33
6	Nansela Hostel	Iso-206	RNE-397	SV	100.00	24.00	22.00	8.33
7	Telkhedi Gondwana Slum valve	Iso-187	RNE-344	SV	100.00	24.00	22.00	8.33
8	Opp Mangalchal Bagle Home valve	Iso-112	RNE-65	SV	150.00	30.00	28.00	6.67
9	Telankhedi Shiv	Iso-85	RNE-38	SV	150.00	30.00	28.00	6.67
10	PNT Colony	Iso-138	RNE-83	SV	150.00	30.00	22.00	26.70
11	Hill Top valve	Iso-176	RNE-455	SV	100.00	24.00	22.00	8.33
12	Pandrabodi near house	Iso-43	RNE-33	SV	200.00	36.00	34.00	5.56
13	Hill Top MSCP Office	Iso-185	RNE-182	SV	125.00	27.00	CLOSED	100.00
14	DOUBLE (ON Sr no. 17)	Iso-94	RNE-404	SV	100.00	24.00	22.00	8.33
15	Pandhrabodi Slum	Iso-146	RNE-138	SV	125.00	27.00	25.00	7.41
16	Shubhamkar Apartment	Iso-171	RNE-303	SV	100.00	24.00	CLOSED	100.00
17	Ambazari Tekadi	Iso-94	RNE-141	SV	250.00	42.00	40.00	4.76
18	Ambazari Tekadi	Iso-65	RNE-52	SV	150.00	30.00	28.00	6.67
19	Law square valve	Iso-22	RNE-578	SV	250.00	42.00	40.00	4.76
20	Munje baba layout	Iso-66	RNE-289	SV	150.00	30.00	28.00	6.67
21	Hindustan Colony	Iso-136	PHT-208	SV	125.00	27.00	25.00	7.41
22	Futala Square	Iso-10	PHT-24	SV	300.00	48.00	CLOSED	100.00
23	Bharat Nagar Near Sapphire Colony	Iso-83	PHT-229	SV	125.00	27.00	25.00	7.41
24	Amravati Road Bharat Nagar valve	Iso-84	PHT-111	SV	150.00	30.00	28.00	6.67
25	Bharat Nagar	Iso-39	PHT-192	SV	150.00	30.00	28.00	6.67
26	Ganesh Tower	Iso-111	PHT-185	SV	150.00	30.00	28.00	6.67
27	Ramnagar Busstop	Iso-40	RNE-30	SV	200.00	36.00	26.00	27.78
28	Mochiwala valve	Iso-33	RNE-32	SV	200.00	36.00	22.00	38.89
29	Opposite Sony Centre	Iso-114	RNE-163	SV	125.00	27.00	25.00	7.41
30	Dhande Hospital	Iso-58	RNE-237	SV	125.00	27.00	25.00	7.41
31	Opposite Sony Centre	Iso-68	RNE-104	SV	150.00	30.00	2.00	93.33
32	Tilak Nagar valve	Iso-77	RNE-270	SV	125.00	27.00	20.00	25.93
33	Mansi Girls Hostel	Iso-210	RNE-363	SV	100.00	24.00	16.00	33.33
34	Bhole petrol pump	Iso-25	RNE-80	SV	200.00	36.00	10.00	72.22
35	Bhole petrol pump valve	Iso-302	RNE-171	SV	150.00	30.00	CLOSED	100.00
36	Bhole petrol pump valve	Iso-59	RNE-158	SV	150.00	30.00	28.00	6.67
37	Vasantrao Naiyak valve	Iso-292	RNE-1615	SV	150.00	30.00	28.00	6.67
38	Near Gokulpeth Old Office	Iso-174	RNE-116	SV	100.00	24.00	16.00	33.33
39	Ramnagar Square	Iso-38	RNE-26	SV	225.00	39.00	37.00	5.13

(*continued*)

Table 1 | continued

Sr no.	Locations	Valve no.	Valve located on	Valve type	Size (mm)	Total threads	Threads open	Percentage closed
40	Ambazari Layout valve	Iso-62	RNE-121	SV	150.00	30.00	28.00	6.67
41	Yeshwant Nagar valve	Iso-199	RNE-450	SV	100.00	24.00	22.00	8.33
42	Yeshwant Nagar valve	Iso-54	RNE-49	SV	150.00	30.00	28.00	6.67
43	Verma Layout Part I	Iso-190	RNE-202	SV	100.00	24.00	22.00	8.33
44	Verma Layout Part I	Iso-189	RNE-259	SV	100.00	24.00	22.00	8.33
45	Vera Layout	Iso-232	RNE-489	SV	80.00	18.00	16.00	11.11
46	Ambazari Garden	Iso-291	RNE-21	SV	250.00	42.00	18.00	57.14
47	Futala Command Area	Iso-93	RNE-203	SV	100.00	24.00	10.00	58.33
48	Pandrabodi Mata Mandir valve	Iso-194	RNE-404	SV	100.00	24.00	16.00	33.33
49	Bajiprabhu Nagar valve	Iso-102	RNE-125	SV	150.00	30.00	CLOSED	100.00
50	Sanjay Nagar Single gali	Iso-298	RNE-1634	SV	150.00	30.00	28.00	6.67
51	Ramnar Square	Iso-97	RNE-86	SV	150.00	30.00	28.00	6.67
52	Ramnagar Square	Iso-207	RNE-354	SV	100.00	24.00	22.00	8.33
53	Ramnagar Prabhat restaurant	Iso-214	RNE-311	SV	100.00	24.00	22.00	8.33
54	Mahatoli opp suryavanshi decoration	Iso-196	RNE-216	SV	100.00	24.00	22.00	8.33
55	Mashid Road	Iso-217	RNE-271	SV	100.00	24.00	22.00	8.33
56	Nayarsan office valve	Iso-113	RNE-183	SV	125.00	27.00	25.00	7.41
57	Nayarsan office valve	Iso-100	RNE-172	SV	100.00	24.00	2.00	91.67
58	Opp Gokulpeth (Khabadi Store)	Iso-221	RNE-360	SV	100.00	24.00	22.00	8.33
59	Kumar Bekri valve	Iso-226	RNE-241	SV	100.00	24.00	22.00	8.33
60	Kumar Bekri valve	Iso-163	RNE-359	SV	100.00	24.00	22.00	8.33
61	Ravi Nagar Cement Road	Iso-121	RNE-113	SV	150.00	30.00	20.00	33.33
62	Valmiki Nagar	Iso-67	RNE-155	SV	150.00	30.00	28.00	6.67
63	Gokul peth Canal Road	Iso-86	RNE-91	SV	150.00	30.00	CLOSED	100.00
64	Tilak Nagar	Iso-164	PHT-537	SV	100.00	24.00	CLOSED	100.00
65	Near Girls Hostel Tilka	Iso-211	PHT-96	SV	150.00	30.00	28.00	6.67
66	Bharat Nagar	Iso-64	PHT-167	SV	150.00	30.00	28.00	6.67
67	Bharat Nagar	Iso-23	PHT-26	SV	300.00	48.00	46.00	4.17
68	Bharat Nagar	Iso-225	PHT-382	SV	100.00	24.00	22.00	8.33
69	Ramnagar ESR outlet	Iso-1	RNE-1	BV	600.00	96.00	94.00	2.08

most of the time, water is supplied by bypass line only and the ESR is used for withdrawing water for far fewer hours. Further water levels in the reservoir were noted to obtain the hydraulic grade line (HGL) at the source. Also, the HGL multiplier of the source was obtained as shown in Table 2. For calibration, it is necessary to assign the Hazen–Williams (HW) coefficient value initially. Therefore, pipes are grouped on the basis of pipe material and age of installation in years, and initial assigned values of the HW coefficients are shown in Table 3.

Measurement of the pipe flow at the source using a flow meter (FM) and pressure measurements at two locations PMP-1, i.e Ambazari Hill-Top Slum (CP1) and PMP-2, i.e. Telankhedi Slum (CP2), were carried out and readings are shown in Table 2 and Figure 1. An FM was installed at the entry point of the water distribution network for measuring

Table 2 | Flow and observation of pressures at salient points on 5 January 2018

							Observed pressure	
Date	**Time**	**Flow**	**Flow multiplier**	**Level in tank (m)**	**HGL (m)**	**HGL multiplier**	**PMP-1 (Ambazari CP)**	**PMP-2 (Telankhedi CP)**
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
05/01/2018	0:00	471.97	0.694	2.05	342.98	1.0060	4.41	7.91
05/01/2018	1:00	474.87	0.699	2.05	342.98	1.0060	5.36	8.72
05/01/2018	2:00	456.25	0.671	2.05	342.98	1.0060	5.23	8.62
05/01/2018	3:00	452.59	0.666	2.03	342.96	1.0060	5.43	8.76
05/01/2018	4:00	479.14	0.705	2.03	342.96	1.0060	6.56	9.81
05/01/2018	5:00	674.31	0.992	2.02	342.95	1.0059	10.62	14.13
05/01/2018	6:00	678.12	0.998	2.03	342.96	1.0060	7.58	11.02
05/01/2018	7:00	923.18	1.358	2.02	342.95	1.0059	7.02	10.00
05/01/2018	8:00	763.57	1.123	2	342.93	1.0059	3.70	5.83
05/01/2018	9:00	782.95	1.152	1.99	342.92	1.0058	2.39	3.55
05/01/2018	10:00	718.56	1.057	1.99	342.92	1.0058	0.67	1.86
05/01/2018	11:00	641.04	0.943	1.97	342.90	1.0058	1.80	1.70
05/01/2018	12:00	686.82	1.010	1.95	342.88	1.0057	0.47	−0.41
05/01/2018	13:00	731.53	1.076	1.94	342.87	1.0057	4.80	2.96
05/01/2018	14:00	740.23	1.089	1.93	342.86	1.0057	4.80	1.59
05/01/2018	15:00	750.3	1.104	1.92	342.85	1.0056	5.41	2.11
05/01/2018	16:00	789.21	1.161	1.91	342.84	1.0056	5.57	5.25
05/01/2018	17:00	751.67	1.106	1.9	342.83	1.0056	5.53	5.37
05/01/2018	18:00	749.38	1.102	1.9	342.83	1.0056	5.72	5.59
05/01/2018	19:00	777.76	1.144	1.91	342.84	1.0056	5.82	5.82
05/01/2018	20:00	742.97	1.093	1.62	342.55	1.0048	8.28	9.57
05/01/2018	21:00	704.67	1.037	1.08	342.01	1.0032	8.23	10.08
05/01/2018	22:00	837.28	1.232	1.01	341.94	1.0030	8.32	10.78
05/01/2018	23:00	743.28	1.093	1.03	341.96	1.0030	8.07	11.01
05/01/2018	0:00	471.97	0.694	2.05	342.98	1.0060	8.91	12.01

Table 3 | Assumed value of Hazen–Williams coefficients

Pipe material	**Assigned group no.**	**No. of pipes in group**	**Age of installation in years**	**Assigned Hazen–Williams c-value**
Cast iron & galvanized iron	1	29	>30	85
Cast iron	2	361	<30	100
Cast iron	3	4	<10	130
Ductile iron	4	24	<10	125
HDPE	5	315	<10	135

inflow, and pressure data loggers were placed to record hourly pressure readings for 24 hours on the same day. Water level variation information of the reservoir is acquired from the SCADA system for the same day. Based on the collected data, the hydraulic pattern of the reservoir or hydraulic grade line (HGL) and demand for the demand junctions were created. Total inflow to the network is worked out as 16.960 MLD. The difference between the inflow and billed water volume of the network is worked out as 6.307 MLD, known as non-revenue water (NRW), which is calculated as 37%. Thus, the NRW of 0.165 lps is uniformly allocated to all non-slum junctions.

The initial comparison of modeled and observed pressures at the two predetermined pressure monitoring points PMP-1 and PMP-2 is shown in Figure 3. The assumed

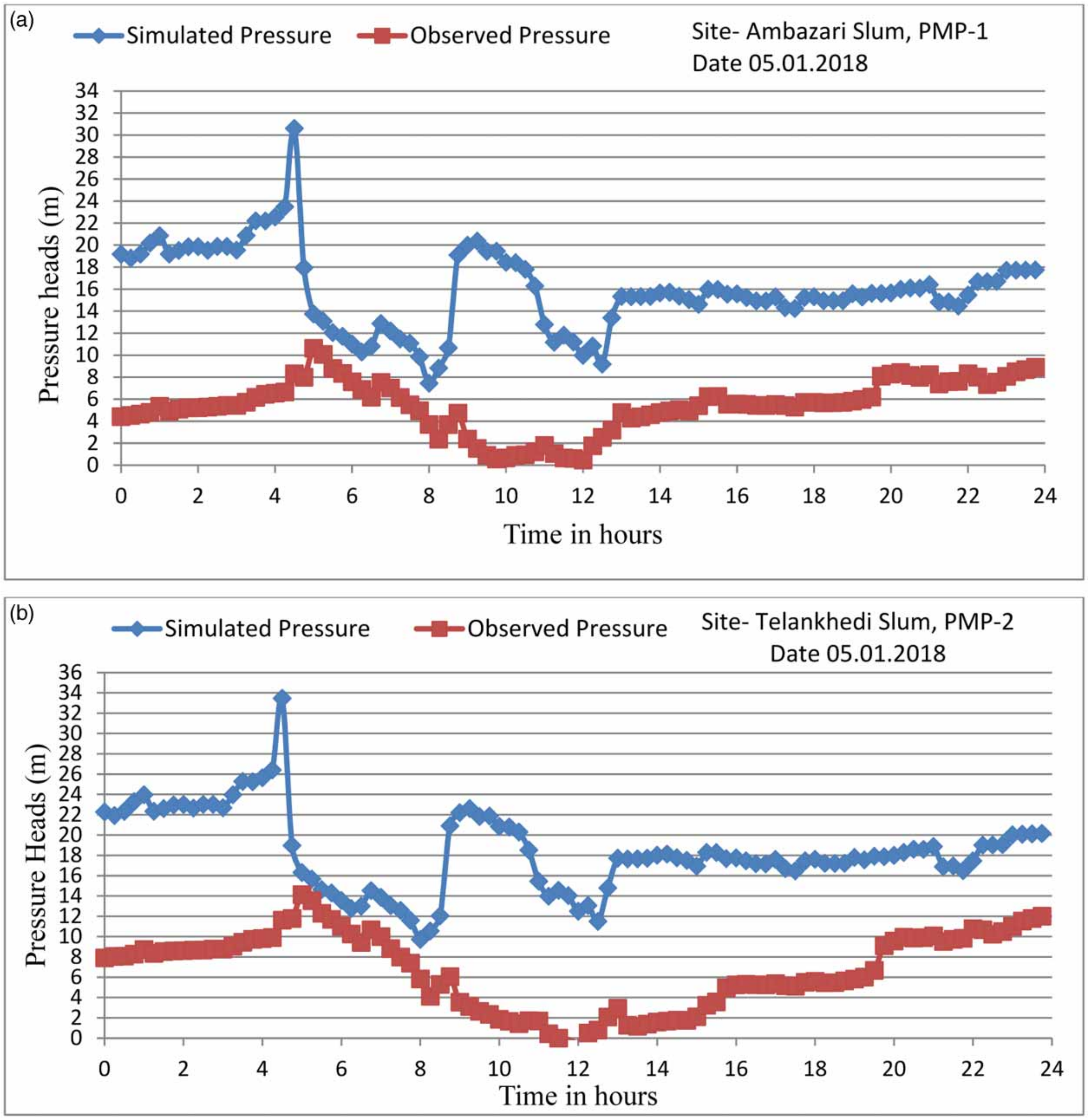

Figure 3 | Comparison of computed (simulated) pressure with observed pressure at both CP: (a) Ambazari Hill-Top Slum (PMP-1/CP1), (b) Telankhedi Slum (PMP-2/CP2).

values of HW-coefficients (C) for the five groups are 85, 100, 130, 125, and 135 as shown in Table 3. It is observed that the measured field pressures at both the PMPs are quite different than the simulated model pressure. These observations are considered without valve inclusions.

Validation, hydraulic model improvements and micro-level calibration

Observed pressure is measured at two predefined PMPs named as Ambazari critical point (CP) and Telankhedi CP in the study area. From the initial calibration results (Figure 3), it is observed that there is a large pressure difference between simulated and observed pressures at both the PMPs. Therefore, the data are validated from field survey and physical verification.

Data collected of existing WDN (pipes, valves, source), demand-node-related data, and consumer data of the identified zone were verified by physical survey for any erroneous pipe lengths, diameters and materials, node elevations, demand and operational zoning. Further, data will be verified again from the field in case of doubts.

After the field survey and data collection from the municipal authority, various errors are observed such as pipe materials, pipe diameters, missing links and nodes, wrongly added pipes and valve operational status of valve settings, nodal elevations and demands. Ramnagar ESR operational water distribution network and its coverage were collected from the site. These errors are now incorporated and the model is accurately corrected with an acceptable accuracy.

Ramnagar ESR operational WDN and its coverage were collected from the water utility. Initially, it was supplying water to the 33 sub-zones as mentioned in the study area and network details section. After surveying and discussion with the authority, it was found that the supply from Ramnagar ESR is in 38 sub-zones as shown in Figure 4.

MICRO-LEVEL OF CALIBRATION OF THE MODEL

Even from the macro-level of calibration, an observed large pressure difference between simulated and observed pressures at both the PMPs is still observed. Therefore, for minimizing the pressure difference at both the PMPs, six pressure loggers are installed, two at PMPs (pre-defined critical monitoring points, i.e already existing) and four in the Ramnagar ESR premises area since there are four main pipelines emerging from Ramnagar ESR, as shown in Figure 2. All pressure loggers are located before valves and are shown by red colors (Figure 2(a)). Further, it is observed that one of the PMPs (Ambazari CP) is on the Ambazari Hill Top line and another CP (Telankhedi CP) is on the Ravi Nagar line. The Ambazari Hill Top line is at a higher elevation and the Ravi Nagar line is at a lower elevation. Two main valves are operated on the ESR premises. One is on the Ravi Nagar line and another is on the Ambazari Hill Top line. According to field observations, the valve settings are provided for both the valves which are on the Ambazari Hill Top line and Ravi Nagar line.

Pressure readings from different pressure loggers installed at different points on the ESR premises and two PMPs (i.e. at six different locations) are taken on a number of days. For two to three months continuously the systems are observed and readings are taken in every three to four days so as to obtain good data sets for calibration. From the huge database, readings are observed on specific days, say on 22 April 2018 to 5 May 2018, and many more days on both pressure loggers installed at the PMPs and it is noted that negative pressures are observed at both PMPs at specific durations on all the days. Negative pressure

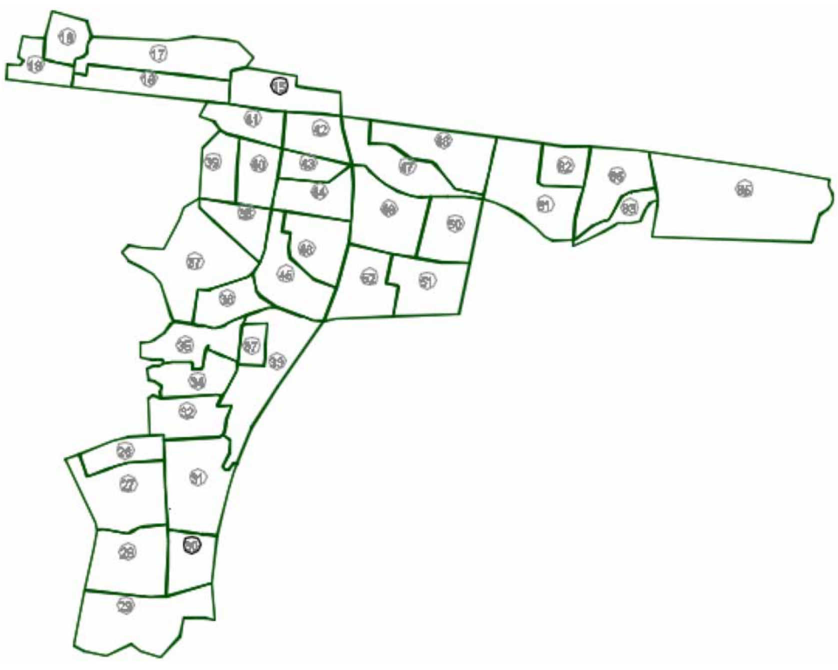

Figure 4 | Ramnagar ESR operational hydraulic zone showing 38 sub-zones.

readings on the particular day of 28 October 2018 at both the PMPs are discussed. It is observed that on 28 May 2018 at Ambazari critical point, at times 0 am to 4.30 am, and 10.15 am to 15.30 pm, and from 22.45 pm to 24 pm and at Telakhedi critical point, at times 1.30 am to 16.15 pm and from 15.30 pm to 23.15 pm negative pressures are observed in the field. The reason identified is that the source itself is deficient and therefore after discussion with water utilities such as NMC and OCW, the inlet flow of the system is increased to 18.5 MLD. With this increased flow, the system is evaluated and now everywhere positive pressures are obtained in the systems. Based on observations taken from the huge data of readings, the best observation day is selected based on no power cut and good observed pressure readings on both PMPs. The day of observation and the best day is selected as 31 October 2018.

RESULTS AND DISCUSSION

Figure 5 shows the readings of four pressure loggers installed at different points on the Ramnagar ESR premises and their nearest points. Graphs in Figure 5 show that the system is calibrated at four points at the ESR premises with observed readings on 31 October 2018.

The generalized diurnal demand pattern is again created based on an hourly flow recorded by the flow meter installed on the outlet pipe of the Ramnagar ESR, i.e. at the inlet of the distribution network. The observations of flow from the source and the water level in the reservoir on the day of observation (31 October 2018) are given in Table 4. The average flow during the day was 734.14 m^3/h. Pressure logger readings are noted at every 15 minutes. Flow multipliers were obtained for extended period simulation as given in Table 4, since most of the time, water is supplied by bypass line only and the ESR is used for withdrawing water for much less of the time. Further water levels in the reservoir were noted to obtain the hydraulic grade line (HGL) at the source. In addition, the HGL multiplier of the source was obtained as shown in Table 4.

Water level variation information of the reservoir is acquired from SCADA system for the same day, i.e. 31 October 2018. Based on the collected data, the hydraulic pattern of reservoir HGL and demand for the demand junctions were created. Total inflow to the network is increased and considered as 18.5 MLD. The difference between inflow and billed water volume of the network is worked out as 6.552 MLD, known as non-revenue water, which is calculated as 37%. Thus, non-revenue water (NRW) of 0.123 lps is uniformly allocated to all non-slum junctions.

After model simulation and micro-calibration, again the comparison of modeled and observed pressures at the two predetermined pressure monitoring points PMP-1 and PMP-2 is done and the results are shown in Figure 6.

From Figure 6(a), it is observed that the difference between observed and simulated pressure is small for Ambazari Hill-Top Slum (PMP-1/CP1) and the maximum difference observed is 4.137 m and 4.034 m at times 20.15 pm and 20.30 pm, respectively, and at the rest of the times the pressure difference is much less, about 1 to 2 metres. Figure 6(b) shows the results for Telankhedi Slum (PMP-2/CP2). It shows that at times 0 am to 6.15 am, minimum and maximum pressure difference between observed and simulated pressure ranges from 1.836 m to 4.386 m, at times 6.30 am to 7.45 am, pressure values range from 4.738 m to 6.177 m, and pressure values are less for times 8 am to 21 pm and range from 0.812 m to 2.762 m. At times 21.15 pm to 22 pm, values lie between 2.082 m and 3.464 m, however, this difference is high during the period from 22.15 pm to 23.15 pm and the values range between 6.085 m and 8.337 m. A little lower difference is observed at times 23.30 pm to 23.45 pm, the pressure values ranging between 4.384 m and 5.616 m.

Looking at this and from Figure 6, it is observed that little effort again is required for best matching the graph at PMP-2. However, one can use the model for various purposes for design, analysis, and operation of water distribution systems.

SUMMARY AND CONCLUSIONS

Calibration of water distribution is a challenging task for large real water distribution systems. In this paper, a case study of the water distribution network of Ramnagar Elevated Service Reservoir (ESR) which is a part of Demo Zone of Nagpur City located in Maharashtra State of India is considered for calibration. This paper describes

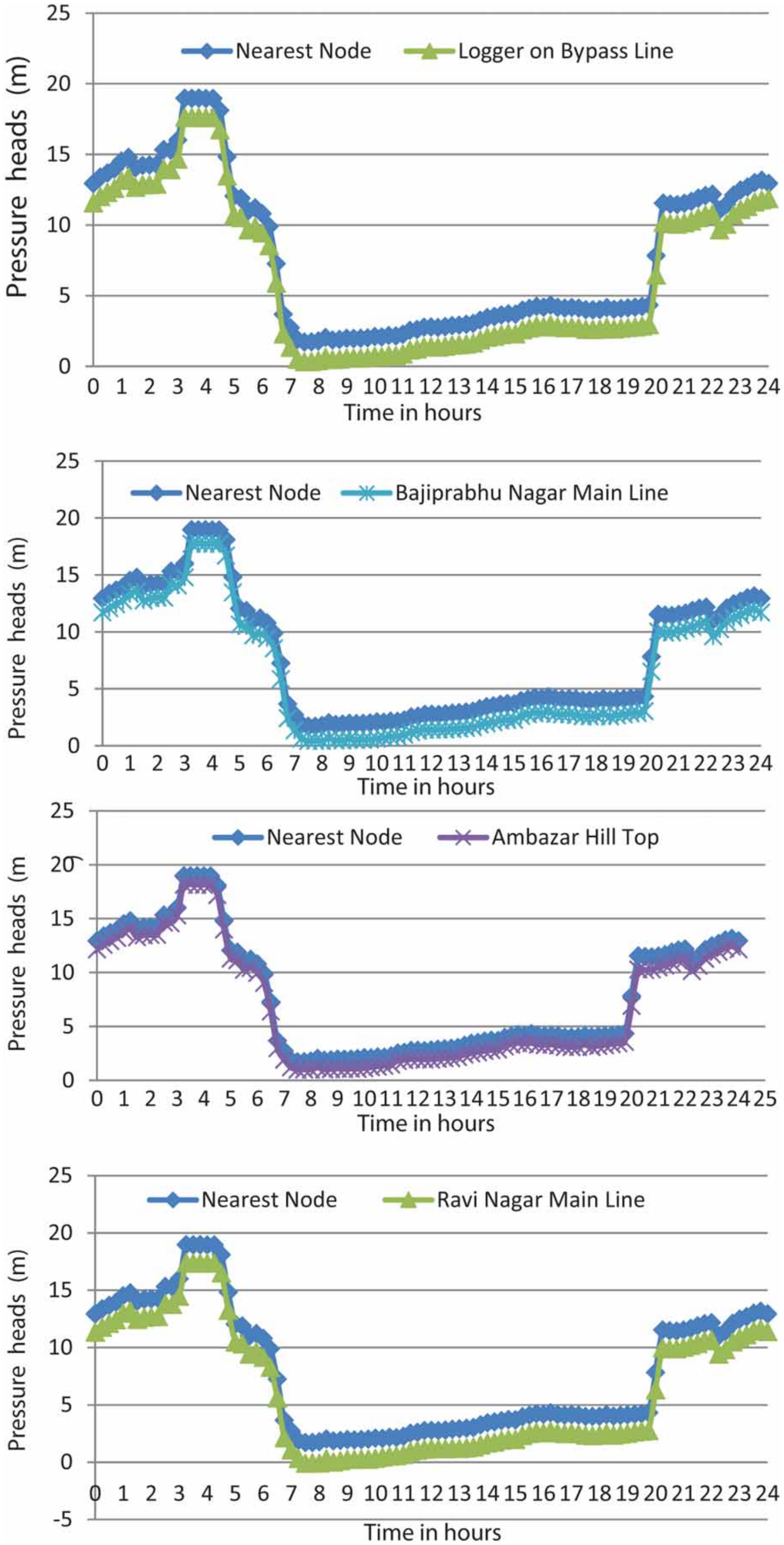

Figure 5 | Comparison of readings of pressure loggers at four main lines emerging from Ramnagar ESR and nearest points.

Table 4 | Flow and observation of pressures at critical points on 31 October 2018

						Observed pressure	
Date	**Time**	**Flow**	**Flow multiplier**	**HGL (m)**	**HGL multiplier**	**PMP-1 (Ambazari CP)**	**PMP-2 (Telankhedi CP)**
31-10-2018	00:00	606.098	0.826	340.99	1.0351	14.13	16.57
31-10-2018	00:15	623.951	0.850	341.44	1.0365	14.64	17.07
31-10-2018	00:30	601.367	0.819	341.73	1.0373	15.06	17.4
31-10-2018	00:45	636.769	0.867	342.02	1.0382	15.34	17.81
31-10-2018	01:00	655.538	0.893	342.58	1.0399	15.95	18.36
31-10-2018	01:15	594.348	0.810	342.84	1.0407	16.18	18.55
31-10-2018	01:30	592.517	0.807	342.1	1.0385	15.43	17.96
31-10-2018	01:45	614.643	0.837	342.27	1.0390	15.59	18.16
31-10-2018	02:00	601.215	0.819	342.3	1.0391	15.58	18.2
31-10-2018	02:15	605.182	0.824	342.32	1.0391	15.55	18.24
31-10-2018	02:30	748.924	1.020	343.4	1.0424	16.6	19.25
31-10-2018	02:45	708.029	0.964	343.35	1.0423	16.51	19.16
31-10-2018	03:00	995.972	1.357	344.1	1.0445	17.14	19.8
31-10-2018	03:15	780.926	1.064	347.05	1.0535	19.94	22.46
31-10-2018	03:30	780.926	1.064	347.04	1.0535	20.01	22.47
31-10-2018	03:45	780.926	1.064	347.06	1.0535	20.07	22.5
31-10-2018	04:00	780.926	1.064	347.03	1.0534	20.12	22.49
31-10-2018	04:15	891.293	1.214	347.04	1.0535	20.09	22.31
31-10-2018	04:30	701.773	0.956	346.17	1.0508	19.32	21.24
31-10-2018	04:45	811.640	1.106	342.9	1.0409	16.35	18.2
31-10-2018	05:00	821.558	1.119	340.12	1.0324	13.69	15.49
31-10-2018	05:15	822.779	1.121	339.95	1.0319	13.45	15.33
31-10-2018	05:30	877.712	1.196	339.08	1.0293	12.61	14.19
31-10-2018	05:45	885.037	1.206	339.29	1.0299	12.53	14
31-10-2018	06:00	907.315	1.236	338.87	1.0287	11.96	13.38
31-10-2018	06:15	946.226	1.289	337.97	1.0259	10.77	12.22
31-10-2018	06:30	770.135	1.049	335.31	1.0178	8.19	9.24
31-10-2018	06:45	810.419	1.104	331.72	1.0070	4.99	5.82
31-10-2018	07:00	795.618	1.084	330.77	1.0041	4.03	4.59
31-10-2018	07:15	800.500	1.090	329.93	1.0015	3.35	4.08
31-10-2018	07:30	762.352	1.038	329.76	1.0010	3.17	3.49
31-10-2018	07:45	767.083	1.045	329.77	1.0010	3.18	2.7
31-10-2018	08:00	762.505	1.039	329.83	1.0012	3.17	1.82
31-10-2018	08:15	742.820	1.012	330.07	1.0019	3.28	1.58
31-10-2018	08:30	749.687	1.021	329.9	1.0014	3.15	0.62
31-10-2018	08:45	760.674	1.036	329.94	1.0015	3.11	0.31
31-10-2018	09:00	778.680	1.061	330.02	1.0018	3.22	0.2
31-10-2018	09:15	767.693	1.046	330	1.0017	3.21	0.16

(*continued*)

Table 4 | continued

Date	Time	Flow	Flow multiplier	HGL (m)	HGL multiplier	Observed pressure PMP-1 (Ambazari CP)	Observed pressure PMP-2 (Telankhedi CP)
31-10-2018	09:30	776.086	1.057	330.02	1.0018	3.16	0.23
31-10-2018	09:45	766.015	1.043	330.06	1.0019	3.2	0.37
31-10-2018	10:00	777.764	1.059	330.15	1.0022	3.26	0.51
31-10-2018	10:15	788.446	1.074	330.12	1.0021	3.33	0.66
31-10-2018	10:30	782.189	1.065	330.22	1.0024	3.45	0.77
31-10-2018	10:45	780.663	1.063	330.19	1.0023	3.45	0.89
31-10-2018	11:00	758.690	1.033	330.3	1.0026	3.63	1.02
31-10-2018	11:15	752.739	1.025	330.58	1.0035	3.97	1.39
31-10-2018	11:30	771.508	1.051	330.65	1.0037	4.03	1.63
31-10-2018	11:45	758.232	1.033	330.81	1.0042	4.15	1.73
31-10-2018	12:00	758.843	1.034	330.82	1.0042	4.13	1.86
31-10-2018	12:15	764.031	1.041	330.79	1.0041	4.14	1.91
31-10-2018	12:30	740.684	1.009	330.85	1.0043	4.2	2.08
31-10-2018	12:45	750.298	1.022	330.92	1.0045	4.25	2.08
31-10-2018	13:00	755.943	1.030	330.96	1.0046	4.28	2.14
31-10-2018	13:15	741.752	1.010	331.01	1.0048	4.36	2.13
31-10-2018	13:30	752.892	1.026	331.08	1.0050	4.44	2.26
31-10-2018	13:45	740.837	1.009	331.3	1.0057	4.72	2.55
31-10-2018	14:00	757.012	1.031	331.49	1.0063	4.88	2.79
31-10-2018	14:15	754.112	1.027	331.56	1.0065	4.95	2.96
31-10-2018	14:30	745.567	1.016	331.68	1.0068	5.1	3.16
31-10-2018	14:45	748.619	1.020	331.76	1.0071	5.19	3.39
31-10-2018	15:00	722.373	0.984	331.73	1.0070	5.22	3.42
31-10-2018	15:15	747.703	1.018	332.02	1.0079	5.53	3.89
31-10-2018	15:30	744.041	1.013	332.14	1.0082	5.64	4.16
31-10-2018	15:45	742.058	1.011	332.29	1.0087	5.69	4.43
31-10-2018	16:00	730.155	0.995	332.22	1.0085	5.61	4.45
31-10-2018	16:15	751.823	1.024	332.37	1.0089	5.7	4.25
31-10-2018	16:30	739.006	1.007	332.21	1.0084	5.57	3.9
31-10-2018	16:45	743.736	1.013	332.16	1.0083	5.48	3.95
31-10-2018	17:00	765.557	1.043	332.2	1.0084	5.49	4.07
31-10-2018	17:15	746.788	1.017	332.16	1.0083	5.4	3.87
31-10-2018	17:30	743.431	1.013	332.05	1.0080	5.29	3.81
31-10-2018	17:45	760.063	1.035	332.04	1.0079	5.26	3.85
31-10-2018	18:00	766.778	1.044	332.06	1.0080	5.28	3.85
31-10-2018	18:15	746.635	1.017	332.19	1.0084	5.44	4.1
31-10-2018	18:30	738.243	1.006	332.07	1.0080	5.3	3.97
31-10-2018	18:45	730.613	0.995	332.13	1.0082	5.38	4.17

(*continued*)

Table 4 | continued

						Observed pressure	
Date	**Time**	**Flow**	**Flow multiplier**	**HGL (m)**	**HGL multiplier**	**PMP-1 (Ambazari CP)**	**PMP-2 (Telankhedi CP)**
31-10-2018	19:00	743.583	1.013	332.17	1.0083	5.48	4.31
31-10-2018	19:15	720.237	0.981	332.22	1.0085	5.63	4.56
31-10-2018	19:30	723.136	0.985	332.27	1.0086	5.72	4.79
31-10-2018	19:45	736.259	1.003	332.38	1.0090	5.87	4.99
31-10-2018	20:00	671.865	0.915	335.88	1.0196	8.2	4.89
31-10-2018	20:15	684.683	0.933	339.6	1.0309	10.93	3.46
31-10-2018	20:30	667.745	0.910	339.53	1.0307	11.08	3.23
31-10-2018	20:45	646.840	0.881	339.49	1.0305	11.36	3.19
31-10-2018	21:00	662.557	0.902	339.59	1.0308	11.66	3.24
31-10-2018	21:15	635.395	0.865	339.72	1.0312	11.86	3.24
31-10-2018	21:30	663.778	0.904	339.95	1.0319	12.2	3.33
31-10-2018	21:45	670.949	0.914	340.14	1.0325	12.63	3.39
31-10-2018	22:00	660.573	0.900	340.23	1.0328	12.89	3.62
31-10-2018	22:15	695.975	0.948	339.09	1.0293	12.19	5.97
31-10-2018	22:30	627.613	0.855	339.49	1.0305	12.79	12
31-10-2018	22:45	623.646	0.849	340.16	1.0326	13.49	13.11
31-10-2018	23:00	610.828	0.832	340.53	1.0337	14.06	13.95
31-10-2018	23:15	590.838	0.805	340.74	1.0343	14.31	14.69
31-10-2018	23:30	577.868	0.787	341.05	1.0353	14.74	15.53
31-10-2018	23:45	579.699	0.790	341.21	1.0358	14.92	15.88

the complexities and challenges involved in the study area for calibration. Further, it describes the detailed steps in different stages carried out for manual calibration of the study area where the difference between the field observation data and model simulated result is significant.

Initially, data are collected from water supply utilities and from the field. Estimation of nodal demand requires a lot of effort and a huge amount of time. Nodal demand is estimated based on consumer usage information, i.e. from water billing data. The accuracy of static information e.g. node elevation, topological structure, pipe material, length, and diameter, and dynamic information, e.g. operational data of valves, is verified in the process of manual calibration. Data are verified from the field, and based on the operation of the WDN and its coverage, the model is corrected. Based on the readings of the flow meter at the ESR and pressure loggers at two pre-defined PMPs in the field, the initial comparison of modeled and observed pressures at the two predetermined pressure monitoring points PMP-1 and PMP-2 are carried out and it shows that there is a lot of difference between observed and simulated readings at both the PMPs. Therefore, the model requires a micro-level of calibration.

Micro-calibration is performed, where four pressure loggers are additionally installed at the ESR premises. Readings are observed at ESR premises and shown in Figure 5. After observation of readings, it is observed that at both PMPs negative pressure arises at some particular time. Therefore, inlet flow is increased and readings are observed on both PMPs. Throttled valves are modeled based on percentage opening and verified from the field. It is observed that the difference between the observed and simulated pressures for PMP-1 is high, i.e. 4.137 m and 4.034 m at times 20.15 pm and 20.30 pm, respectively, and the rest of day the pressure difference is small (1 to 2 metres). However, this difference is high for PMP-2 during the period from

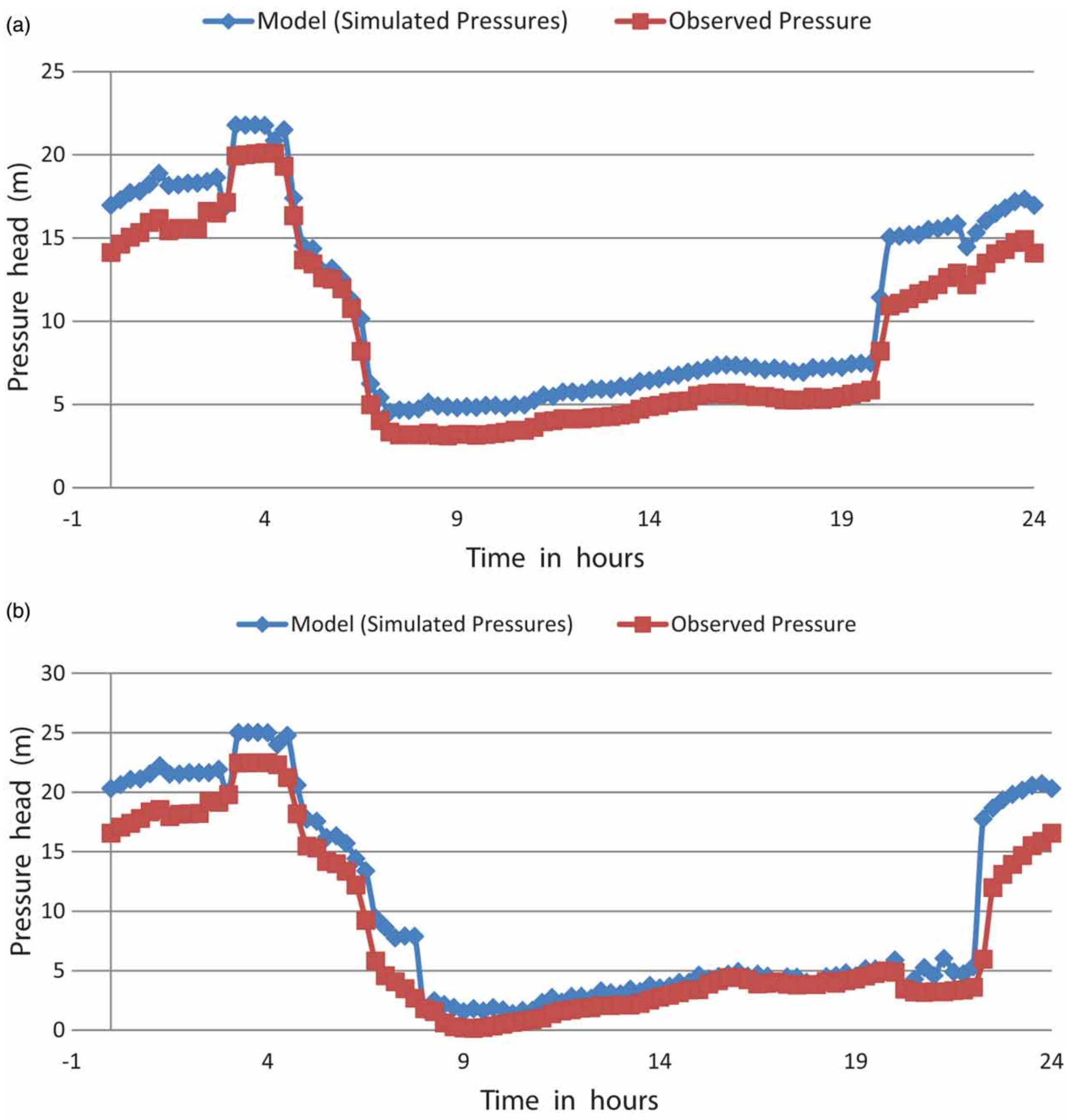

Figure 6 | Comparison of computed/simulated pressure (top lines) with observed pressure (bottom lines) at both CP: (a) Ambazari Hill-Top Slum (PMP-1/CP1), (b) Telankhedi Slum (PMP-2/CP2).

22.25 pm to 23.25 pm and the values range between 6.085 m and 8.337 m, and the rest of the times the pressure is less than 5.6 m since it is difficult to obtain the percentage of valve openings, closings and the timings for the two valves. Little effort is again required for best matching the graph at PMP-2. However, one can use the model for various purposes for design, analysis, and operation of water distribution systems. This method worked well and could be used for any large water distribution system such as in different zones of Nagpur City or any other city in India or another country. The problem identified in the case study is that for the second pressure monitoring point (PMP-2), the pressure difference is quite high because of not obtaining the details of two valves. Therefore, there is a need to calibrate this model using optimization. The process of calibration of the case study using genetic algorithm goes on for minimizing the pressure difference between observed and simulated pressures at both the PMPs. In the optimization process, valve throttling would be the decision variables and work goes on on for exact matching of the graphs of observed and simulated pressure readings.

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