**Geospatial modeling of water supply distribution system: A case study of Dehradun city, India**

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**Abstract**

Water utilities form the core part of any urban infrastructure. A spatial database of water distribution system (WDS) for Dehradun city has been created in a geographic information system (GIS) environment, while drawing data inputs from diverse sources and water supply-demand gap analysis has been performed. Environmental Protection Agency Network (EPANET, 2.0) has been used to analyze the WDS to explore its reliability in current and future scenarios. Mapping of the existing 564 km long distribution network revealed that more than three-quarters of the system has outdated water pipelines. An accuracy of 93% for pipe diameter estimation has been obtained upon validation by ground penetrating radar (GPR) survey. Water supply-demand gap analysis confirmed that although Dehradun city has surplus supply, it suffers from scarcity, mainly due to the unsatisfactory condition of the existing WDS. Twenty-seven percent of the existing pipes are smaller than the prescribed standards; there is an undesirable practice of direct pumping of water from tube wells into the network and storage tanks are required for at least 29 locations in the network. A 24-hour extended period EPANET simulation helped to identify the areas where water supply network experienced very low or negative pressure.

**Key words:** EPANET, GPR, GPS, population scenarios, water distribution system

**Highlights**

- Use of Remote Sensing and GIS for creating water distribution system network.
- WDS modelling using EPANET for Dehradun city.
- Evaluation of existing WDS network, including use of GPR.
- Future water demand simulations.
- Supply-Demand analysis for present and future water requirements.

**Introduction**

Water is the most vital natural resource for sustaining life on Earth. It is a basic necessity of mankind. Due to rapid urbanization and population explosion, the whole world is facing a water crisis as one of the biggest challenges today. Especially, in developing countries like India, the safe drinking water crisis is being faced by many cities as the population is rising at an alarming rate and existing infrastructure is not able to cater for the ever-growing needs of the people. One of the biggest challenges currently being faced by Indian civic authorities with aging water, storm water, and wastewater infrastructure is creating a digital database and proper management of valuable assets. More than 90% of India’s urban population receives drinking water, but access to affordable, sustainable, and reliable water supply and sanitation service is by far lagging behind. Only 50% of this population has access to piped water supply. The non-revenue water (NRW) due to leakages, illegal pumping of groundwater, billing and collection inefficiencies (no water metering system), unauthorized connections, theft, etc. is huge, and is estimated as between 40 and 70% of the total water supply. Most urban water supply operations are surviving on capital grants and subsidies provided by the government and other financial institutions, and the operation and maintenance cost recovery through user charges is only 30–40% of the total expenditure. Piped water is never distributed for more than a few hours per day, regardless of the quantity...
available (The World Bank 2011). In developing countries generally, the focus of urban water management is towards building infrastructure in which prime attention is for augmentation, but the distribution network hydraulics are usually ignored and this mismanagement does not lead to sustainable services. Cities have intermittent systems of water supply, in which distribution hours range from only 2–4 hours per day (Ingeduld et al. 2006). The expenditure on the water distribution system (WDS) alone accounts for 80–85% of the total cost of a water supply project. Design and construction of water supply systems is a long-term investment (minimum 30 years) and requires periodical maintenance (CPHEEO 2005). Also, as most of the water utilities are more than 25 years old and are insufficient to cater for the needs of the ever-increasing population. Owing to a non-scientific philosophy, coupled with lack of funds, haphazard laying of pipelines, and inadequate database of these important utilities, the situation has developed that, even though sufficient water is available it does not reach the end consumer due to poor management and lack of information available to these water utilities managers.

Geographic information system (GIS) is a powerful spatial information system that can store, retrieve, analyze, and display geographic data attached to various utilities (Bhave & Dumbre 2012) and, leads to several improvements in their effective management of civic utilities. Main benefits of GIS are: (1) lowering operation and maintenance cost by adopting preventive maintenance practices, (2) increasing the revenue, (3) improving quality of service to customers in terms of appropriate and quick service, (4) achieving public participation and customer satisfaction, and (5) development of hydraulic tools fulfilling the various requirements. GIS provides a platform to integrate spatial data with non-spatial data, which is of utmost importance for mapping of water utilities because no such data are often available for a quick response to any emergency situation for civic authorities. GIS-based data management and hydraulic modelling of water supply utility network helps in improving operational and cost efficiencies as well as data storage and retrieval (Grise et al. 2012). Surani & Dihora (2015) have described major advantages of remote sensing and GIS in water supply management.

Potable water can be drawn from various sources like rivers, lakes, springs, or groundwater. In an urban environment, a piped water supply is desirable, as it is safer and more reliable (World Health Organization & UNICEF 2010). Urban water utilities are nothing but the various components of a water distribution network (WDN), such as reservoirs (surface and sub-surface), storage tanks, pipes, valves, pumps, fire hydrants, etc. (Garg 2010). All the components are very important, because if one malfunctions, the whole system is affected and, as a result, many people and their day-to-day activities are affected. Water pipelines are the backbone of a water utility network. The essential point of a WDS is to convey water from sources to expected end users while meeting the specified necessities such as water quantity, quality, and pressure. Regularly, this is accomplished by means of interconnected components, e.g., tanks, reservoirs, pipes, valves, and pumps. Each component is topologically interrelated with its neighbor. The real-world layout of these elements depends on their topographical interdependencies with urban infrastructure such as roads and buildings along with their land uses, i.e., residential, commercial, industrial, etc. (Todini 2000).

Water utilities are surface as well as sub-surface. Remote sensing technologies for mapping surface utilities like overhead tank (OHT) include data analysis from high-resolution satellite images, differential global positioning system (DGPS), mobile GPS, total station, etc., whereas technologies for mapping sub-surface utilities include magnetic locators, electromagnetic surveys, ground penetrating radar (GPR), acoustic location methods, and non-destructive air-vacuum excavation (Rana 2009). A topologically accurate geodatabase of all the utilities is crucial for further modeling of a WDS. Interaction with these objects in the real world is diverse and we can model them in different ways (Zeiler 1999). A WDS can have looped or branched layout. Looped layout is used for cities that have high demand with many service connections, and it has the advantage of alternative pathways to water flow in case of any breakdown and significantly improves hydraulics of the network. Branched layout, on the other hand, is economical but has many disadvantages. In most WDSs, a combination of both are used (Walski et al. 2003). There can be practical problems during the lifespan of a WDS, such as inaccurate population projections, pipe breakage, failure of pumps, power loss, malfunctioning of storage tanks, water scarcity in reservoir, etc. A good WDS should be such that it can satisfy in terms of both water quality and quantity for basic requirements along with accommodating all such abnormal conditions (Garg 2010).

Planning, designing, operating, maintaining, and optimizing a WDS is a complex task, which is governed by many criteria, simultaneously. Moreover, this problem becomes bigger when there are so many components which drive the network and which are inter-dependent on each other. This has led to several computerized
mathematical models being developed in order to aid engineers and planners to understand the hydraulic behavior of a WDS. There are several commercial as well as public domain software available for hydraulic modeling of WDS. A few of them include AquaNet, Archimed, Branch/Loop, Cross, EPANET 2.0, Eraclito, H2Onet/H2Omap, Helix Delta-Q, Mike Net, Netis, OptiDesigner, Pipe2000, Stanet, Wadiso SA, WaterCAD, etc. (Schmid 2002). In this study, leading industry standard Environmental Protection Agency Network (EPANET, 2.0) is used for WDS analysis.

Conventional WDS designs are a long, tedious, and error-prone process, which have mostly used Hardy-Cross method (Cross 1936) for mathematical calculations in order to solve the network hydraulics (Garg 2010). Three factors, which govern the mathematical model of a WDS are: (1) its topology, (2) two conservation laws, namely, mass balance (flow continuity) at nodes and energy conservation (head loss continuity) around hydraulic loops and paths, and (3) equations of components (Br dys & Ulanicki 1994). As information and communications technology (ICT) has advanced and GIS has emerged as a boon for asset management, the information about topology and topography can be easily included using a GIS system for the modeling of distribution systems (Shamsi 2004). The analysis of a looped WDN, operating under pressure and in steady flow conditions can be accomplished once the topology of the network, the geometry of the pipes, the water demands at the nodes, and the head value of at least one node are known (Giustolisi & Todini 2009; Shrivastava et al. 2018). GIS is not perfect but it is one of the most convenient systems available today to model such networks (Filion & Karney 2003).

EPANET is a public domain software, which provides complete solutions to hydraulic analysis as well as for water quality analysis of a pressurized piped network system. It can perform single as well as extended period simulation of a WDS and gives pressure at each node, flow in each pipe, height of water in tank, etc. as output, which are helpful for water distribution engineers and planners. The capabilities of EPANET include analysis of any size of network, computation of friction head loss using Hazen-Williams, Chezy-Manning or Darcy-Weisbach formulas, variability in shape of tanks, definition of different time patterns, computation of energy and cost required for pumping, computation of minor losses due to bends and fittings, etc. A WDS contains various physical and non-physical components, which include pump curves, time and demand patterns, and controls which describe the behavior and operational aspects of the system (Rossman 2000).

Several studies have demonstrated the use of EPANET as a tool for WDS modeling in India as well as worldwide (Shrivastava et al. 2018). Ingeduld et al. (2006) carried out modeling of WDS on intermittent water supply of Shillong city in India and Dhaka in Bangladesh using EPANET and feeding GIS-based data into the model. Their findings were that solutions obtained by EPANET for a hydraulic network were simple as well robust and they provided a convenient platform to model the WDS. Khadri & Pande (2014) did a case study on Chalisgaon city of Dhule district in Maharashtra, India and concluded that remote sensing, GIS, and GPS techniques are effective tools for mapping, managing, and modeling of a WDS. The WDS network assessment of both continuous and intermittent water supply while integrating GIS and EPANET was carried out by Mohapatra et al. (2014) on Untkhan area in Nagpur district of Maharashtra, India. They concluded that intermittent supply has many disadvantages, including depreciation of both water quantity and quality over time whenever situations like negative pressure exist in a network, which lead to pipe bursts and damage to other water utilities such as valves and poor conditioning of storage tanks. Water supply should be continuous, but in India, no city gets water supply for 24 hours a day (Ingeduld et al. 2006; Surani & Dihora 2015). Evaluation studies over an existing WDS have been done using EPANET and their feasibility for future scenarios have been determined in Chirala municipality of Prakasam district in Andhra Pradesh by Anisha et al. (2016). The locations for new storage tanks were identified and planned augmentation or expansion of the network was proposed to cater for future needs. Venkata Ramana & Sudheer Chekka (2018) suggested that whenever demand for water exceeds the supply by a larger amount, there is no other way but to overhaul the whole network with the replacement of pipes with bigger diameter pipes and providing extra storage tanks for continuous water supply. Abdelbaki et al. (2017) combined GIS and EPANET for effective water supply distribution modeling for Chetouane, Algeria, which is characterized by water scarcity and poor water management practices. They concluded that combining GIS with WDS modeling allows for better analysis, diagnosis of problems, improved management and understanding of a WDS along with prediction of the future situation, which assists greatly in making decisions that are more informed and ensures optimum levels of satisfaction from the consumer side for WDS operation. EPANET’s performance was compared with other WDS modeling software, WaterGEMS in addition to AutoCAD. The calibration and
modeling were carried out by Alves et al. (2014) for data inventory in order to optimize the network for equitable distribution of pressure at nodes. Farina et al. (2014) suggested a suitable pipe roughness correction in order to represent accurate head losses for real-world situations where water demands are distributed irregularly over the network. Menapace et al. (2018) introduced a relaxation factor in the algorithm of EPANET for better pressure distribution in the pipe network.

STUDY AREA AND DATA USED

Dehradun city is located between 77°58'E to 78°07'E longitude and 30°16'N to 30°24'N latitude within the Doon valley, about 230 km to the north of India's capital, New Delhi. The city is located at an elevation of about 635 m above man sea level. The municipal area of the city is 196.48 sq. km (https://nagarnigamdehradun.com/about-us.php). It lies in the foothills of the Himalayas in the north, the Siwalik hills in the south, the Ganga in the east, and Yamuna River in the west. The lowest altitude is 596 m in the southern part, whereas the highest altitude is 1,024 m in the northern part. The topography of the city slopes gently from north to south and south-west and is heavily dissected by the number of seasonal streams. The drainage of the city is borne by two rivers, namely, Bindal and Rispana. The direction of flow of these seasonal streams in the Eastern part, is from North to South, while in the Western part, it is North to South-West.

Dehradun is also the capital of the state of Uttarakhand province and has many administrative and functional attributes attached to it. The city has a growing residential population, a migrant population comprising students, administrative staff, and officers from various central and state government institutions. With the good connectivity and its closeness to various famous tourism spots in the state, the city acts as a connecting link between them and attracts a huge number of tourists, contributing to the floating population of the city. With the increase in the population, the dependency on natural and infrastructure resources also increases.

A piped water supply system has been in existence in Dehradun for more than a century, dating back to 1885 under British rule. Pipelines were laid from a natural spring at Kolukhet situated about 25 km from Dehradun city. This source is no longer in use. Between 1936 and 1937, the water supply system was remodeled and it underwent major augmentation (Anon 2018). It was again redesigned in 1962. A 20-million liter per day (MLD) capacity water treatment plant (WTP) was built at Dilaram Bazaar in 1936, which is still under operation. This plant presently draws water from Bijapur Canal and Bandal River. Earlier, six MLD of water was brought to Dilaram Bazar Water Works from the Bandol source via a 350-mm pipeline that was laid in 1936. It was subsequently augmented to carry 10 MLD water by laying another 250-mm pipeline parallel to the old pipeline in 1962. These two raw water mains are still in use. Later, an additional WTP of 14 MLD capacity was constructed in 1984 near Shahanshahi Ashram at the northern end of Dehradun city. This treatment plant receives raw water from Massi and falls through a 350-mm pipeline. Another source (Kyarkuli River), Galogi Power House, distributes water directly after chlorination to the upper zones of the city by connecting to the main gravity line of Shahanshahi Ashram WTP. The older part of Dehradun consisted of areas close to, and at the foothills of Mussoorie, with drinking water sources located high up in the hills and the habitation was served with water exclusively by gravity, without any need for pumping. The town grew towards the plain areas in the south, and the existing area fed by surface sources was extended, with addition of more surface sources at higher altitudes. However, with limitations in the availability of water in the surface sources, the possibility of groundwater was explored and the explorations were successful. As Dehradun city grew, more zones were created and which were mostly fed by groundwater. Therefore, to cater for the ever-rising water demands of the city, in addition to the above surface water sources, several tube wells have been commissioned since 1962. Presently, water is being supplied from about 96 tube wells and 34 mini-tube wells. The water supply is sufficient to cater for population growth up to 2025 and there is no need to augment capacity of sources; however, some work is needed to repair or rectify leakages. The major part of the city receives its water supply from groundwater sources, i.e., tube wells, and about 33% of the city receives water from surface sources. There are 96 tube wells with pumping machinery installed and they are under operation to produce about 142.81 MLD of water.

There are two major water works, namely, Dilaram Bazar water works (20 MLD) and Shahanshahi Ashram (14 MLD).

Ever since the piped water supply was introduced in Dehradun, the distribution network has been growing, with the addition of new sources such as tube wells and construction of OHTs. Over the years, Dehradun city has expanded in terms of aerial coverage. Older, sparsely populated localities have become transformed into
more densely populated areas. Pressing needs for drinking water have forced water supply designers to lay new distribution pipelines. Over the years, the distribution network of Dehradun has grown from 25 km in 1885 to more than 550 km of pipeline, from one small clear water reservoir (CWR) at Kolukhet to 15 CWRs and 64 OHTs in different parts of the city.

In Dehradun, the Uttarakhand Jal Sansthan (UJS), an institution under the Department of Drinking Water, Government of Uttarakhand (GoU), India is the designated civic body responsible for operation and maintenance of the water supply system. Another body, Uttarakhand Pey Jal Nigam (UPJN), is responsible for overall planning, construction, and large capital works related to water supply and its augmentation. According to UJS officials, at present, there are 46 zones of water supply, with a few zones divided into sub-zones. These zone boundaries are different from municipal ward boundaries and have been essentially based on the topography of the city.

The present study aims at analyzing the WDS of Dehradun city to explore its reliability in current and future scenarios using GIS-based WDN and EPANET software. The study is divided into two parts: first, the water supply system of the whole city has been analyzed at city level and second, a detailed study has been carried out for one zone of water supply consisting of two wards of the study area. Figure 1 represents the study area map showing wards and water supply zones of Dehradun and Table 1 gives an overview of the WDS. Out of these zones, Zone 11 – Rajender Nagar – has been chosen to carry out the study in detail at ward level. This ward was chosen due to the availability of data for validation of the model, as an ongoing project of laying new water supply pipes is going on in this area by GoU.

**Figure 1 | Study area.**

**Table 1 | Water distribution scenario**

| Sl. No. | Parameters                              | Present scenario                      |
|--------|-----------------------------------------|---------------------------------------|
| 1      | Coverage of water supply connections    | 78%                                   |
| 2      | Per capita supply of water              | 135 LPCD                              |
| 3      | Extent of metering of water connections | 8%                                    |
| 4      | Extent of NRW                           | 40%                                   |
| 5      | Cost recovery in water supply services  | 52% (Rs. 175.7 million collection/Rs. 340 million expenditure) |
| 6      | Continuity of water supply              | 4–6 hours                             |
Data used (spatial and non-spatial data)

Water supply distribution network map

The water supply network map of Dehradun is prepared from data sourced from various Government institutions by conducting multiple field visits. The data obtained were in the form of hand-drawn hard copy maps, computer-aided design (CAD) files, and portable document format (PDF) files (see Figures S1 and S2 of the Supplementary data).

Remote sensing data

Remote sensing data of the Indian Remote Sensing Satellite (IRS)-P6 satellite image (02.02.2017) was sourced from the National Remote Sensing Centre (NRSC), Hyderabad, India and a Quickbird imagery (31.03.2017) was sourced from Google Earth (see Figure S3 of the Supplementary data).

Ancillary data

A digital elevation model (DEM) was prepared from spot levels along the roads and junctions obtained from a topographic and levelling survey done using Total Station surveying instrument carried out by Uttarakhand Urban Sector Development Investment Program (UUSDIP) in the year 2013. The non-spatial data used for the present study are, Census (2011) data for Dehradun municipal area and existing water supply network parameters such as details of pumping plants, hours of operation, etc. Capacity of various existing OHTs and CWR, demarcation of various zones of water supply, length, and material of pipelines, etc., were sourced from UJS officials from their hard copy records. Tables S1, S2, S3, and S4 of the Supplementary data provide a detailed summary on GPR based pipe diameter calculations, size of existing storage tanks, list of existing tube wells and their yield, and list of gravity sources of water, respectively. The road layer was obtained from OpenStreetMap (OSM).

METHODOLOGY

In the present study, WDN layers were established in the GIS environment with high resolution images in the background. Field visits were undertaken to collect the ground coordinates of water utilities with handheld GPS, and the diameter and height of OHTs as needed for hydraulic design were collected with a Leica distometer. Various thematic maps were prepared in GIS to assign water demands at every node. A DEM of the entire city was produced using contours at 1-m interval and spot levels obtained by topographic and leveling survey carried out by UPJN. At certain places, the pipe locations, depth and diameter were verified and updated using the GPR and GPS. The water demand at each node was assigned using Thiessen polygon method as the UJS did not have household level maps of water connections, and only distribution mains data were available. Using the population density map, the per capita demand for each node was estimated. The details about elevation, level, diameter, and capacity of all the storage tanks as obtained from water utility survey were fed into the EPANET model and a 24-hour extended period simulation was run over the network and two important parameters, i.e., pressure at all nodes and velocity in all the pipes, were analyzed for a 24-hour period at 1-hour intervals. The methodology adopted is shown in the form of a flowchart in Figure 2 and, the whole process carried out to accomplish the task is described in the following sub-sections.

Working with spatial data – creating a GIS database of water utilities

Geo-referencing and GIS database creation

The high-resolution images from Google Earth extracted using Google Earth Pro as well as the IRS Linear Imaging Self-Scanning System (LISS)-IV image were georeferenced in Universe Transverse Mercator (UTM) projection system with WGS84 datum and UTM Zone 44 N. Later, the water supply network map was created in GIS environment with high-resolution image in the background. The road layer was also overlaid to get a preliminary idea of the correctness of the map, as all water pipelines should coincide with the road network.

After all the data were georeferenced, separate vector layers of tanks, reservoirs, nodes, pumps, and pipes were created, containing point and line data and stored in a file geodatabase. These data were spatially adjusted wherever they did not correctly overlay the roads. Topology is important to carry out any network analysis, therefore the WDN was topologically corrected. It was ensured that not even a single link was left unjointed to another and every node was connected to a link. Therefore, in order to create a WDN, all the topological errors like undershoot, overshoot, overlap, multipart features, duplicate features, etc. were removed using the topology tool in
After the removal of errors, the data were exported as shape files (.shp) format so that they could be taken as input in EPANET.

Water utility and GPS survey
Field visits were carried out to determine the ground coordinates of water utilities such as OHTs, pumping plants, and tube wells with handheld GPS. All essential parameters, such as diameter and height of OHTs, as required for hydraulic design, were collected with the help of a Leica distometer. The pipe distribution network was digitized and all the attributes such as pipe diameters and material were manually entered in consultation with the supervisors and junior engineers of UJS. UJS did not have household-level maps of water connections, and only distribution mains data were available. All this information was reproduced in GIS by creating a spatial geodatabase and then attaching their non-spatial attributes to them.

Thematic layers’ creation
Thematic maps like LULC, zonal plan, population and population density, slope, etc. were generated in ArcMap 10.1 to assign water demands at every node. LULC was prepared based on supervised classification of IRS LISS-IV data. The zonal development plan for the year 2025, as obtained from Mussoorie Dehradun Development Authority (MDDA), was geo-referenced and digitized. Accordingly, the maps of all planning zones of Dehradun city, which were in pdf format, were digitized. Road and road buffer maps were generated using OSM data and then edited by overlaying on IRS LISS-IV image of Dehradun city. Slope map was generated from DEM created from total station surveying data. Population and population density maps were produced from Census (2011) data by linking non-spatial population data with the spatial ward map of Dehradun.

Digital elevation model (DEM) generation
The study of a water supply system requires the detailed topography of the town, i.e., reduced level (RL) of roads and road crossings. The available topographical map of Dehradun city from Survey of India was last prepared in 1971. Since then, the urbanization pattern has changed significantly and many new layouts have arisen in different parts of the city. Some freely available DEM data such as CartoDEM have 30 m and Advanced Land Observing Satellite Phased Array-type L-band Synthetic Aperture Radar (ALOS-PALSAR) has 12.5 m spatial resolution. In a water supply network having 20-m high overhead tanks, this accuracy is far too insufficient for what is required. Therefore, DEM of the whole city was generated using contour lines of 1-m interval sourced from UUSDIP and spot levels obtained by topographic and leveling survey carried out by UPJN. Later, a triangular irregular network (TIN) was generated while making use of the Delaunay triangulation, in which three points are joined to form a unique triangle; thereafter, making use of linear interpolation method, the raster grid of cell size of 1 m was generated.
Updating the WDS using GPR

GPR (otherwise called ground probing radar/georadar) is a non-invasive geophysical procedure for subsurface investigation. GPR sends electromagnetic (EM) energy into the ground through a transmitter antenna, and the transmitted energy gets reflected wherever there is a ‘dielectric contrast’ between the subsurface layers (Martinez & Byrnes 2001). The transmitter sends EM waves underneath the surface that bounce back if they encounter any material, which has a dielectric contrast from the other material (see main Figure 3 for overall GPR data processing and see Figure S4 of the Supplementary data for GPR functionality). These reflected signals are received by the receiver present in the antenna. The GPR data-logger simultaneously plots these signals received on the screen and creates an image called a radargram, which provides the presence of any object beneath the surface (Annan 2009; Cassidy 2009). As EM waves from antenna travel sub-surface and are reflected back from the cylindrical surface of the pipe, the radargram shows a shape of hyperbola (Figure 4) exactly where the pipe lies beneath the surface (Yelf 2007).

Extraction of pipe diameter using GPR data can be done by making use of the Pythagoras theorem and canonical hyperbola equations curve fitting methods (see Figures S5 and S6 of the Supplementary data for illustration). These methods are derived based on the relationship between pipe radius and wave propagation velocity of the EM waves by using the equation below (Shihab & Al-Nuaimy 2005; Ristic et al. 2009):

$$R = \frac{\left(\frac{v_{t_1}}{2}\right)^2 - \left(\frac{v_{t_2}}{2}\right)^2 + (x_t - x_o)^2}{v(t_1 - t_0)}$$ (1)

where, $R =$ radius of pipe; $x_t =$ starting position of the GPR when the sensor started detecting the pipe; $x_o =$ point at which GPR is perpendicularly above the pipe; $t_1 =$ two-way time of the wave at the tail of the hyperbola; $t_o =$ two-way time of the wave at the mid-point of the hyperbola; $v =$ wave propagation velocity; $t_i$ and $r_o =$ distance travelled by the waves from the transmitter to the pipe.

Cylindrical objects appear as a hyperbola in a radargram when scanning is done across the plane. Shihab & Al-Nuaimy (2005) developed a model for estimation of pipe diameter, depth of the pipe and surrounding medium’s relative permittivity. They applied various image processing techniques to the radargram in order to obtain the hyperbola and used curve-fitting methods on these hyperbolae to estimate the depth and diameter of underground cylindrical pipes and successfully estimated the depth and radius to within 10% accuracy. Ristic et al. (2009) proposed a method, which utilizes a non-linear least square fit to estimate the diameter. Their final processing results optimally estimated values of both propagation velocity and radius of pipe with an estimation error of up to 10%. Pipe diameter estimation using along the plane scanning can also be done (Jaw & Hashim 2013). A very high precision of less than $+0.10$ m was obtained conforming to Quality Level

![Figure 3](http://iwaponline.com/h2open/article-pdf/doi/10.2166/h2oj.2021.118/978836/h2oj2021118.pdf)
A utility data in their experiment. Advanced techniques like full waveform inversion have also been used in recent studies for material characterization and utility mapping using GPR (Jazayeri et al. 2018). The GPR data analysis of underground water utilities offers a twin advantage as it constitutes a non-destructive method to understand pipe characteristics and also to quantify its diameter and depth below the surface at higher confidence level (less than \( \sim 8\% \) misfit). Once the scans are done on the field, the processing of the data can be carried out in IDS GRED HD software. The broad methodology for GPR data processing is shown in Figure 3 (Szymczyk & Szymczyk 2013).

Sub-surface water supply pipes have an average depth of 1 m below the ground surface and are distinguishable from other objects like sewer and other utility pipes such as communication or electric cables by this prior knowledge. In this study, visual interpretation technique is used to identify the hyperbola and then fitting the best-fit curve to obtain the various parameters required for diameter calculation of the pipe. Figure 4 shows a GPR scan performed on street no. 8 of Rajender Nagar, Dehradun, India. Various hyperbolae can be seen and each represents a pipe beneath the road. The figure also highlights a pipe and hyperbola fitted on it. Readers can refer to Table S1 of the Supplementary data for details on GPR calculations and derived pipe diameters.

Population projections and water demand

The first step in design or evaluation of any water supply network is population projection (CPHEEO 1999). This is done to ascertain that a water supply network is not only capable of meeting existing water demands but also capable enough to meet future demands. The growth and development of a city is a function of its population size and economic profile (MoUD 2015). Therefore, the study of changes in population over a period of time and thereby forecasting the future population enables one to foresee the future requirements of the city in all aspects like water supply, road, sewerage, drainage, and other infrastructure facilities (Garg 2010). CPHEEO (2005) guidelines enumerate the use of arithmetic increase, incremental increase, geometric increase, logistic curve, decreased rate of growth, simple graphical and comparative methods for population projections for Indian cities (Garg 2010; Gawatre et al. 2016). For more details on population projections, readers may refer to the text and Figures S7, S8, S9, S10, and S11 of the Supplementary data.

Additionally, the current (2016) and future population (2041) scenarios were created using the base population for the census year 2011 (see Figures S10 and S11 of the Supplementary data) to estimate the water supply–
The demand scenario for the whole of Dehradun city. The total absolute water supply after consideration for losses is 188 MLD and demand is 117 MLD and 224 MLD in 2016 and 2041, respectively. This analysis clearly shows that the water supply–demand gap, which is surplus in 2016 (71 MLD) is going to be deficient (136 MLD) for the year 2041, encompassing 65% of wards within Dehradun city (see Figures S10 and S11 of the Supplementary data).

In the present study, the water demand at each node was assigned using Thiessen polygon method. The population density map was converted into raster format. Using ‘extract values to points’ function in ArcMap, these population density (see Figures S8 and S9 of the Supplementary data) values were extracted to each node. The area was calculated for every Thiessen polygon using the calculate geometry tool; thereafter, these areas were attached to their respective nodes using spatial join tool. Once area and population density attributes were obtained in a single shapefile, these two were multiplied together to get the population for every node. Later, this population was multiplied by 155 [135+15% unaccounted for water (UAW)] liter per capita per day (LPDC) of water to get per capita demand for each node, which was converted to liters per minute (LPM) units for the sake of ease while feeding it into the model.

Hydraulic parameters

It is essential to link spatial database to their attributes or, in other words, create a non-spatial database and give specifications of various hydraulic parameters. Figure 5 shows all the physical and non-physical components involved in a WDS and the attributes attached to them to be fed into the EPANET model. The digital elevation model of Dehradun city is shown in Figure 6(a).

Hydraulic simulations

The present study has used EPANET hydraulic model for simulating the piped potable WDN of Dehradun city. The basic principle on which the model’s algorithm runs is ‘hydraulic balancing’ of network using ‘hybrid node-loop’ approach so that flow continuity and head loss continuity conditions are satisfied at every iteration. The algorithm is termed ‘gradient algorithm’ and its calculations are based on the Newton-Raphson method (Todini & Pilati 1987). The following system of equations is solved by the computer program to arrive at the final results after each iteration in the model (Rossman 2000; Garg 2010):

- Hazen–Williams equation (Hazen & Williams 1933) for calculating head loss in pipes:

\[ S = \frac{h_f}{L} = \frac{10.67Q^{1.852}}{C^{1.852}d^{4.8704}} \]  (2)

Figure 5 | Components of a WDS.
where, $S = \text{hydraulic slope}$; $h_f = \text{head loss in meters over the length of pipe}$; $L = \text{length of pipe (m)}$; $Q = \text{volumetric flow rate (m}^3/\text{s})$; $C = \text{pipe roughness coefficient}$; and $d = \text{inside pipe diameter (m)}$.

- The law of conservation of energy or the head loss and law of continuity states that the difference of energy between two points in a network is equal to the major friction loss due to pipe material plus the minor losses due to sudden expansion or contraction, bends, fittings, etc. and the energy added (imparted typically by pumps) to the flow between these points (Mays 2000). Flow–head loss relationship in a pipe between nodes $i$ and $j$ is given below:

$$H_i - H_j = h_{ij} = rQ_{ij}^n + mQ_{ij}^2$$

where, $H = \text{nodal head}$; $r = \text{resistance coefficient}$; $n = \text{flow exponent}$; and $m = \text{minor loss coefficient}$.

Figure 6 | WDS of Dehradun city: (a) DEM of study area; (b) map showing material of existing pipelines; (c) map showing diameter of existing pipelines; and (d) full WDS of Dehradun city.
The second set of equations that must be satisfied is the law of conservation of mass or flow continuity around all nodes, which states that water sum of outflows and inflows at a given node at a given time, must be equal to zero (Mays 2000):

$$\sum_j Q_{ij} - D_i = 0$$  \hspace{1cm} (4)

where, $D_i$ = flow demand at node $i$.

In a WDS, the pipes or links are the elements where the law of conservation of energy holds good, and nodes or junctions are the elements where the law of conservation of mass holds good (Berardi et al. 2010).

The gradient solution method begins with an initial estimate of flows in each pipe that may not necessarily satisfy flow continuity. At each iteration of the method, new nodal heads are found by solving the matrix equation:

$$AG = F$$  \hspace{1cm} (5)

where, $A$ = an $(N \times N)$ Jacobian matrix; $G$ = an $(N \times 1)$ vector of unknown nodal heads; and $F$ = an $(N \times 1)$ vector of right hand-side terms.

After new heads are computed by solving the above equation, new flows are found from:

$$Q_{ij} = Q_{ij} - (y_{ij} - p_{ij}(H_i - H_j))$$  \hspace{1cm} (6)

where, $y_{ij}$ = flow correction factor; $p_{ij}$ = inverse derivative of the head loss in the link between nodes $i$ and $j$ with respect to flow.

This algorithm is implemented by a simulation routine containing two main loops. Solution of the set of non-linear equations is contained in one loop, while simulation of the water network model over a desired period is taken care of in the other loop.

**RESULTS AND DISCUSSION**

**Mapping and updating existing WDS**

All the data pertaining to pipelines were brought into GIS from CAD files, PDF files, and hand-drawn maps. Table 2 shows a summary of the diameter wise-lengths of all the pipelines currently supplying water to the city. It can be seen that the total length of the existing distribution system is nearly 564 km; of this, the lengths of polyvinyl chloride (PVC) and asbestos cement (AC) pipes are more than 75%. The variable diameter pipes of other materials such as galvanized iron (GI), cast iron (CI), and electric resistance welded (ERW) constitute the remaining 25% of the WDS network (Table 2 and Figure 6(b) and 6(c)). Therefore, after assignment of all the spatial and non-spatial parameters of all the elements involved like pipes, tanks, and reservoirs, the final GIS-based WDS of Dehradun city was drawn. Figure 6(d) shows the complete potable WDS of Dehradun city, along with various input data layers such as DEM, pipe material, pipe diameter, and full WDS system of the city. Pipe's locations were verified and hence updated at certain points using GPR. This helped in verifying the location, depth, and diameter of the pipelines. Based on GPR data analysis and Equation (1), an overall accuracy of 93% is obtained when compared with actual diameter of the pipes with open sections within the study area. It was also observed that PVC and smaller diameter pipes are better detected in 200 MHz frequency and CI and GI pipes of bigger diameter are better detected in 600 MHz frequency of GPR (refer to Table S1 of the Supplementary data for details on GPR calculations and derived pipe diameters). The percentage extent of various pipe material (GI, CI, ERW, PVC, and AC) is 15.53%, 8.46%, 0.80%, 51.37%, and 23.83%, respectively. The report on ‘Rehabilitation and Augmentation of Water Supply in Dehradun’ (https://www.adb.org/sites/default/files/project-document/74120/38272-033-ind-dpp-01.pdf) prepared for Government of Uttarakhand, India states that the condition of the pipe's section with CI and other materials is not satisfactory. Hence, during interaction with UJS it is learnt that such sections are gradually being replaced with PVC pipes under facilities' augmentation. Also, within the study area, nearly 50% of the pipes have diameter sizes of 75 mm, 80 mm, and 90 mm (Table 2 and Figure 6(c)).
WDS analysis in EPANET

In EPANET, a 24-hour extended period simulation was run over the network. A total of 3,718 junctions, 4,295 pipes, 127 reservoirs, 79 storage tanks, and 50 pumps were included in the model (see Figure 6(d)). Two important parameters, i.e., pressure at all nodes and velocity in all the pipes were analyzed over a 24-hour period at 1-hour interval each. It was observed that the existing WDS is plagued with several shortcomings, most striking of which is the diameter of distribution mains all over the city. CPHEEO (2005) guidelines recommend a minimum diameter of 80 mm to be used for the purpose. However, some parts of the system are old, as the piped water supply system to Dehradun city was introduced in 1885 when the water was diverted from a natural spring at Kolukhet situated almost 25 km from the city (Anon 2018), and the pipe diameter is as low as 25 mm, which results in building of negative pressure and insufficient hydraulic head conditions in the network.

A second shortcoming is the direct pumping of water by tube wells into the network. This practice is undesirable as sudden pumping of water in an empty pipe results in development of a huge amount of pressure, which is harmful to the pipelines and leads to frequent leakages and damage to pipelines. A shortage of storage tanks is the third problem. Water is available in plenty but due to lack of storage capacity most of it is not being utilized in the distribution system. As observed over a 24-hour period, there exists situations of negative pressure and very

| Table 2 | Summary of existing pipelines |
|---------|-------------------------------|
| S.No.   | Diameter (mm) and (% of pipes with a given diameter) | GI | CI | ERW | PVC | AC | Total |
| 1       | 25 (2.58) | 14.540 | 0 | 0 | 0 | 0 | 14.540 |
| 2       | 32 (0.11) | 0.599 | 0 | 0 | 0 | 0 | 0.599 |
| 3       | 40 (1.42) | 7.377 | 0 | 0 | 0.617 | 0 | 7.994 |
| 4       | 50 (6.94) | 32.053 | 2.128 | 0 | 4.019 | 3.113 | 41.313 |
| 5       | 63 (4.86) | 0 | 0 | 0 | 25.230 | 25.230 |
| 6       | 65 (0.71) | 0.731 | 2.851 | 0 | 0 | 0.442 | 4.024 |
| 7       | 75 (10.89) | 0 | 0 | 58.728 | 1.408 | 60.136 |
| 8       | 80 (10.53) | 19.144 | 5.869 | 0 | 12.129 | 24.639 | 61.781 |
| 9       | 85 (0.20) | 0 | 0 | 0 | 0 | 0 |
| 10      | 90 (28.77) | 0 | 0 | 162.258 | 0 | 162.258 |
| 11      | 100 (4.91) | 10.130 | 2.187 | 0 | 10.142 | 5.225 | 27.684 |
| 12      | 110 (2.98) | 0 | 0 | 0 | 16.829 | 0 | 16.829 |
| 13      | 125 (5.09) | 1.342 | 12.279 | 3.147 | 0.693 | 4.539 | 22.000 |
| 14      | 140 (0.56) | 0 | 0.539 | 0 | 2.483 | 0.139 | 3.161 |
| 15      | 150 (3.68) | 0.693 | 2.730 | 0 | 13.267 | 4.089 | 20.779 |
| 16      | 160 (0.81) | 0.333 | 0 | 0 | 1.752 | 2.531 | 4.596 |
| 17      | 175 (0.10) | 0 | 0.559 | 0 | 0 | 0.559 |
| 18      | 190 (0.04) | 0 | 0 | 0.198 | 0 | 0.198 |
| 19      | 200 (8.22) | 0.639 | 6.621 | 1.392 | 6.265 | 31.463 | 46.380 |
| 20      | 230 (0.02) | 0 | 0 | 0 | 0 | 0 |
| 21      | 250 (4.05) | 0 | 2.871 | 0 | 0.198 | 19.850 | 22.919 |
| 22      | 300 (1.40) | 0 | 0 | 0 | 0 | 7.882 | 7.882 |
| 23      | 350 (0.40) | 0 | 1.302 | 0 | 0 | 0.959 | 2.241 |
| 24      | 400 (0.11) | 0 | 0 | 0.146 | 0.487 | 0.633 |
| 25      | 450 (1.47) | 0 | 5.846 | 0 | 0 | 2.432 | 8.278 |
| 26      | 600 (0.35) | 0 | 1.949 | 0 | 0 | 1.949 |
| Total   | 87.581 | 47.731 | 4.539 | 289.704 | 134.408 | 563.963 |
| % of total pipe length | 15.53 | 8.46 | 0.80 | 51.37 | 23.83 | 100 |

GI, galvanized iron; CI, cast iron; ERW, electric resistance welded; PVC, polyvinyl chloride; AC, asbestos cement.

WDS analysis in EPANET

In EPANET, a 24-hour extended period simulation was run over the network. A total of 3,718 junctions, 4,295 pipes, 127 reservoirs, 79 storage tanks, and 50 pumps were included in the model (see Figure 6(d)). Two important parameters, i.e., pressure at all nodes and velocity in all the pipes were analyzed over a 24-hour period at 1-hour interval each. It was observed that the existing WDS is plagued with several shortcomings, most striking of which is the diameter of distribution mains all over the city. CPHEEO (2005) guidelines recommend a minimum diameter of 80 mm to be used for the purpose. However, some parts of the system are old, as the piped water supply system to Dehradun city was introduced in 1885 when the water was diverted from a natural spring at Kolukhet situated almost 25 km from the city (Anon 2018), and the pipe diameter is as low as 25 mm, which results in building of negative pressure and insufficient hydraulic head conditions in the network. A second shortcoming is the direct pumping of water by tube wells into the network. This practice is undesirable as sudden pumping of water in an empty pipe results in development of a huge amount of pressure, which is harmful to the pipelines and leads to frequent leakages and damage to pipelines. A shortage of storage tanks is the third problem. Water is available in plenty but due to lack of storage capacity most of it is not being utilized in the distribution system. As observed over a 24-hour period, there exists situations of negative pressure and very
low pressure in almost 50% of the wards (Figure 7(a) and 7(b)). The greatest problem persists between 7 a.m. and 8 a.m. when the water demand is at its peak. These negative pressures gradually reduce as peak demand hours pass and the system becomes stable. In Figure 7, the pipes are shown as lines and nodes as point data.

Initially, the negative pressures were observed at J1037 and J1038 nodes. These locations exist in Dobhalwala ward and negative pressures occur due to the uneven topography of the area and sudden change in elevation by 20 m. This was rectified in the model by hypothetically increasing the elevation of J1037 by 20 m. Next, the most critical area identified was in the Turner Road ward. All the nodes were in negative pressure due to lack of OHTs in this area, even though the diameter of pipelines was sufficient. Other locations which were identified included Van Vihar colony in Ballupur ward, which suffers from very small diameter pipes (25 mm) used for water supply, and even though an OHT is present here, it is being used to supply water to another ward. Kaulagarh ward faces another problem altogether, as here water supply and storage are not an issue, but lack of pipelines in part of this area forces people to fetch water from distant sources and water supply is often provided by tankers. Negative pressure also exists in Majra lower ward (Figure 7(a)), which can be solved by increasing the diameter from the current 75 to 110 mm, and also a tube well is required to fill the OHT which has been constructed already but not connected to any source of water. Negative pressure exists in Kargi, as here the diameter of pipes had to be increased to 110 mm because the elevation difference is large between OHT and places of supply and the flow is going against gravity. Areas in outer wards of the city like Majra, lower Majra, Niranjapur, Brahmputri, Indirapuram, Kargi, and Rajeev Nagar face a water crisis due to the fact that these areas until 2007 were rural, where water supply was designed for 70 LPCD, but due to their inclusion in the municipal limits and also due to sudden increase in population and other infrastructure facilities, this supply today is not sufficient to meet the demands. Here, lack of OHTs is a major problem and water is currently being supplied by tube wells pumping directly into empty or half-filled pipes.

Next, areas in the core part of the city which face water crisis included Khurbura, Chukkuwala, Indresh Nagar, Gandhigram, and Dronpuri wards. These areas consist of very old and very dense establishments where pipeline age is more than 50 years old and there is no space for augmentation or modification in the existing pipes. Moreover, OHT (T33) has outlived its design life and needs replacement. Here, simulation of the EPANET model resulted in negative pressure as demands are not met by supply due to the small diameter of pipes and most of the water is lost as frictional and other losses. As the simulation was run, link P1462, which lies in Rajpur, became disconnected, and this problem persisted due to the very small diameter of pipes (32 mm); the problem was resolved as soon as the diameter was increased to 80 mm. Similar problems existed in other localities like Bhagat Singh colony. The situation in upper parts of the city like Rajpur, Jakhan, and

![Figure 7](https://example.com/figure7.png)

**Figure 7** | Sample WDS simulation results showing pressure and velocity at morning (07:00 hr) and day (13:00 hr) time for the entire network. In both the panels, links are represented for velocity in pipes and nodes represent the pressure points. Red color of nodes shows very low or negative pressure and red color for links show high velocity.
Sahastradhara was more related to the gradient available between source and supply. Here, the terrain is undulating, and water head becomes low as elevation jumps suddenly by 20–50 m at some places between two nodes. At these places, water pumping with higher head is required, and these were managed in EPANET by increasing the head in pumping curves of tube wells located at these locations. Pump curve 1, 52, and 84 were increased from the existing 110 m head to supply 140 m head of water at reservoir 1d (a), 15(f), and 31(a), respectively.

Velocities in pipes were other major criteria considered to evaluate the network. According to the CPHEEO (2005) guidelines, the velocity in pipes should be between 0.6 and 2.0 m/s subject to minimum pipe diameter of 80 mm. At several places, this criterion has been exceeded wherever the pumping is direct in the network. There are 29 locations where this phenomenon is happening. Other places where velocity was too low included the pipes which have to carry water from lower to higher elevations.

**Validation of EPANET simulation results**

A household random sample survey of 300 houses was conducted to understand the actual ground scenario and validate the results of the EPANET simulation of water supply (see Figure S12 of the Supplementary data). These survey locations included places where EPANET gave negative pressure as well as locations where pressure was adequate. General observations were that although 88% of the households have piped water supply, still there is no water metering system in Dehradun city; some of the houses have water meters installed but they are not in working condition. The water bill comes in a lump sum amount of Indian Rs. 300–400 per month. Supply is not continuous anywhere in the city and only 15% of the areas receive water in excess of 6 hours daily. The average rate of water supply is 2 hours in the morning and 2 hours in the evening. To overcome this situation, people have devised techniques to tap water, and more than 69% of households have constructed their own underground water tanks which get filled whenever there is water supply and they pump water into their tanks using low-grade low HP pumps locally called ‘tullu pumps’. This practice is not legal and leads to a large chunk of revenue loss to the UJS. During the household survey, it was recorded that only 22% of the households get water which is sufficient to fill the tanks located at the rooftop of a two-storeyed or a three-storeyed building, and the remaining 78% of people were dissatisfied. These locations included Majra, Rajeev Nagar, Niranjanpur, parts of Sahastradhara and Jakhan, Kaulagarh, Khurbura, and Chukkhwuala. Eighty-seven percent of people were satisfied with the quality of water they are receiving, but at some locations, like Gandhigram and Kargi, people complained of the poor quality of water.

Also, officials at UJS were consulted and asked about the state of water supply. It was noted from their side that it is not possible to supply water on a continuous basis due to lack of infrastructure, funds, and manpower available to them and the general perception is that people will waste more water if supplied continuously. However, pumping is done for 16 hours daily and monitored through Supervisory Control and Data Acquisition (SCADA) system and groundwater is treated with chlorination before supply to households. The crisis locations according to official records as per number of complaints registered in their complaint register include Majra, Niranjanpur, Kargi, Turner Road, Khurbura, Badrish colony (Rajeev Nagar), Sahastradhara, Jhanda Bazar, Gandhigram, Kaulagarh, DL Road, Dalanwala, Subhash Road, Kalika Mandir, Dhamawala, Karanpur, Laxman Chowk, and Reetha Mandi.

**WDS modeling in EPANET: future scenario**

A detailed study on Zone 11 (Rajender Nagar) of water supply in Dehradun city has been done to model an ideal WDS for future needs. This zone was chosen because an ongoing project by UUSDIP, GoU has been completed here on this zone recently. New water pipelines have been laid in this area to overcome the shortfalls of the existing pipelines, which are more than 30 years old. This ward was also used for GPR survey and estimation of WDS pipe diameter (see Figure S13 of the Supplementary data for location map of GPR points). The other basic inputs layers, such as, DEM and LULC to calculate the node demands, and other basic EPANET simulation parameters are given in the Supplementary data (see Figures S14 and S15 of the Supplementary data). Therefore, the EPANET model has been run with an aim to evaluate this new pipeline network. This zone of water supply consists of two municipal wards of Dehradun, namely, Ward No. 8 – Krishan Nagar and Ward No. 59 – Ballupur, with a total population of 9,136 and 8,650, respectively in 2011, which corresponds to a total water demand of 3.1 MLD. The projected population in 2041 in these two wards is 25,135 and 21,449, respectively, which leads to a total demand of 8.12 MLD. The total water supply in these two wards is 8.52 MLD considering
three OHTs and 16-hour pumping from a total of ten tube wells supplying water to this area. Figure 8 shows the new WDS network of this area.

In order to simulate the future demands for the above two wards, a similar methodology was followed as described earlier. First mapping of the network into GIS was done by georeferencing the CAD file of the network and then spatially adjusting the data onto GIS domain. All parameters such as elevation of nodes and other non-spatial parameters for tanks, reservoirs, and pipes were entered in GIS to make it compatible for EPANET modeling (Figure 8).

Water demand in this case was considered according to CPHEEO (2005) standards for urban area as 135 LPCD and 15% allowances were considered for losses and added to this daily demand. This demand was distributed over all the nodes using Thiessen polygon method and made to vary over 24 hours by assigning it a demand pattern. The EPANET 24-hour extended period simulation was run over this network with future demands. It was observed that maximum water is consumed between 7 a.m. and 8 a.m. in the morning and then water demand decreases in the daytime and rises in the evening hours (Figure 9(a)). The net flow balance for the system is positive, so there is no problem of negative pressure in this scenario. Simulation was successful without any warning received for negative pressure anywhere in the network. Lowest pressure observed anywhere in the network at any point of time was 13.85 m at node J100 between 7 and 8 a.m., which was well above the 7 m required as per standards. Maximum pressure observed was 70.34 m at node J224 between 4 and 5 a.m. and minimum pressure observed was 16.23 m between 7 and 8 a.m. Figure 9(a) and 9(b) show the contour plots of pressure representing the variation over the whole area spatially at two selected times, i.e., 7 a.m. in the morning and 6 p.m. in the evening, respectively. It is observed that pressure is in acceptable limits at all times. Thus, it is concluded that with the existing WDN, and present and projected water demand, the area is likely to face water shortage in the future.

However, the simulation carried out with the augmented network (Figure 8) highlights that the negative pressure is not seen anywhere in the network for the present and projected water demand until the year 2041. Further details of the EPANET simulations and achieved results are given in the text and Figures S16–S23 of the Supplementary data.

**Figure 8 |** New WDS of Rajender Nagar ward or zone of Dehradun city.
Limitations

One major assumption, which EPANET makes, is that water demand is assigned to nodes in a WDN (Rossman 2000). However, this approximation may introduce errors in hydraulic head distribution because, in reality, this demand is a function of pipes converging at respective nodes rather than the nodes themselves (Giustolisi & Todini 2009). This was further evidenced by studies carried out by Berardi et al. (2010) and Menapace et al. (2018), who modified the original global gradient algorithm (GGA) to remove this anomaly and developed algorithms which were able to simultaneously model both nodal and edges’ demands in a WDN. These algorithms are more complex and beyond the scope of the current study, but can be applied and integrated into EPANET to calibrate the model with higher accuracy and to yield results which better represent the ground conditions.

In addition, intermittent supply was not modeled in the present study, and it can be achieved only by modifying the source code of EPANET (Ingeduld et al. 2006). However, implementing the constraints like operation timings of all the valves are difficult to gather in the field for a large area like the whole of Dehradun city; therefore, those are not considered in this study. Additionally, there is some institutional, housing colony and individual storage and WDNs within Dehradun city (Shrivastava et al. 2018), which are not operated by UJS and, they need to be added in a combined WDN in future studies. Lastly, leakages form an important part in the evaluation of a WDS, but are not modelled in this study, as it was not possible to incorporate them in the study in the absence of node-wise leakage data. The water loss due to leakages has been incorporated in the calculation of water demand and an extra 15% allowance has been added to base water demand. EPANET can be used to model water quality also, but this is not considered due to the unavailability of water quality data. This can be taken up in the future studies, if all data related to water treatment and water quality is available.

CONCLUSIONS

Dehradun being the capital city of the state of Uttarakhand serves as its administrative centre. It has many institutions of national importance and is blessed with scenic beauty, and a pleasant climate along with numerous tourist attractions. Owing to the aforementioned attributes there is tremendous growth potential for the city, because of which, population and hence water demand is rising at a very high rate. The water demand was 117 MLD in 2016 and is expected to reach 224 MLD in 2041. The city relies on surface as well as groundwater sources to meet its demands of water supply. The WDS is old and the piped water supply in the city dates back to 1885 under British rule in India, with newer pipelines laid thereafter, as and when they were required. The current study focused on evaluation of WDS of Dehradun using GIS-based hydraulic modeling and to check its feasibility for current and future scenarios.

It can be concluded that the geospatial techniques like remote sensing, GIS, GPS, GPR, etc. can be used to precisely locate and map various assets, thereby replacing the conventional system of hand-drawn maps or CAD files used for managing urban water utilities. GPR survey showed that many pipelines are running in parallel where one can serve the purpose. For instance, at survey location no. 14 (canal road) near Synergy Hospital, three different water supply pipes of 150 mm, 150 mm, and 50 mm diameter at depths of 0.53 m, 0.52, and 0.43 m are present. The GPR survey has proven that such non-destructive techniques are beneficial for mapping,
validation, and updating of water utilities as depth and diameter of the pipes can be found precisely using GPR. Water supply–demand gap analysis results concluded that, currently, Dehradun is a water surplus city with net surplus of 71 MLD; however, this situation is going to change in 2041 as there is a projected deficit of 36 MLD due to the rise in population and hence water demand.

Geospatial techniques coupled with WDS modeling software like EPANET can help in better evaluation, planning, and design of WDSs. It is concluded that existing water supply infrastructure of the city is inadequate to meet current water demand. The water from the sources is plentiful, but deficiencies in the distribution system, like shortage of storage tanks, small diameter of pipes, large system losses, and direct pumping of water in the network is leading to insufficiency of the whole WDS. At times, more than half of the city face the situation of negative pressure or very low pressure in the wake of peak hour demand in the morning as well as evening time. The water distribution is not equal in all parts of the city, and some areas are in crisis and others are suffering from frequent damage due to high velocities in pipes and high pressures at nodes.

There is an urgent need to implement a more robust, planned, and hydraulically accurate WDS throughout the city to cater for future needs, as piecemeal augmentation of current water pipelines and short-term strategy will be destructive for a flourishing city like Dehradun. This point is validated by a case study for future needs (year 2041) over Rajender Nagar area, whose modified WDS network was modeled in EPANET and a 24-hour simulation was run while feeding the projected water demand of future times. The results showed that a hydraulically efficient distribution network is capable of supplying 24/7 water continuously to all service points. Pressure within the acceptable limits of 7 m to 80 m was obtained at all nodes and velocity in pipes never exceeded 0.6 m/s to 2 m/s range as prescribed by CPHEEO (2005) standards at all times of the day. This is desirable for a city like Dehradun, which has ample availability of water but is suffering from mismanagement of existing resources and an inadequate monitoring infrastructure for water supply.

Similarly, as per our analysis, Dehradun city is going to have a deficient water supply during the decade of 2030–2040 as per projected population scenarios. The projected water deficit of 36–100 MLD by 2041–2050 decade can be met by the proposed drinking water project of the GoU on Song River, where a maximum storage capacity to supply 256 MLD of water is planned. This planned dam and associated pipe WDN can be incorporated into our present WDS to have an impact on water supply–demand scenarios in coming decades.

Government civic authorities like UJS can adopt geospatial techniques to map and manage their assets. GPS coordinates of all the utilities must be stored in a digital GIS database for efficient management of resources. This will lead to faster redressing of complaints and efficient management of resources and, most importantly, will help save water for humanity. Use of GPR for non-destructive mapping or even leak detection surveys can be done. Further, the utilization of GIS-enabled WDS would, as demonstrated for Dehradun city, can be implemented by operational agencies such as, UJS and other civic bodies of India under national programs such as Atal Mission for Rejuvenation and Urban Transformation (AMRUT) and Smart City Mission of Government of India. The same approach can be extended for other flagship programs of Government of India, such as Jal Jeevan Mission, where it is envisioned to provide safe and adequate drinking water through individual household tap connections by 2024 to all households in rural India.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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