

A Review on Population Projection and Demand-Based Design of Urban Water Supply Systems

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Abstract: *The existing water supply infrastructure is under immense stress in Indian towns due to rapid urbanisation and population growth. Water shortages, pressure deficits and inequity in water services are chronic problems that are caused by outdated projections, inadequate per-capita norms, and unscientific network designs. A sustainable water supply plan requires careful population forecasts, demand estimation, and demand-driven hydraulic design for a long term planning horizon. The paper summarizes the existing knowledge on population projection techniques, water demand estimation frameworks, hydraulic design of distribution network and treatment system dimensioning with the help of a detailed case-study of Banda town, Sagar District (M.P.), a medium sized urban local body in India where water supply and sanitation planning are faced with challenges. The Incremental Increase Method is best suited to growth stabilisation trends and gives a 2055 design population of 57,333 with a base population of 39,187 in 2025. The water demand increases from 5.87 MLD to 8.59 MLD. Hydraulic analysis verifies the Hazen-Williams exponent relationship ($H_f \propto Q^{1.85}/D^{4.87}$) is used to optimise pipe diameters. The redesigned system provide 100% coverage, 24 hours/day continuous, and 135 LPCD per capita as compared to the previous 44% coverage, 1.5 hrs/day, and 77 LPCD. Priority future research directions include integration of SCADA, IoT pressure monitoring, climate-adaptive multi-variable demand modelling, solar-powered pumping and AI leakage detection.*

Keywords: Water Demand Projection; Population Forecasting; Hazen-Williams Equation; Hydraulic Network Design; CPHEEO Guidelines; Distribution Network Optimisation; WaterGEMS V8i; Service Level Benchmarks; Urban Water Supply; Sustainable Infrastructure Planning

I. INTRODUCTION

Overview of the Topic

Water is one of the basic elements for human life, public health and socio-economic development. These urban water supply systems, which include the development of water sources, the transportation of raw water, its treatment, storage and distribution, represent the backbone of a modern city. These systems are under great stress in India, where rapid urbanization, population growth, and limited water supplies create a situation of high strain [1]. The National initiatives, such as AMRUT (Atal Mission for Rejuvenation and Urban Transformation) and Jal Jeevan Mission (JJM) along with CPHEEO norms of 135 litres per capita per day (LPCD) for sewered urban towns [35] dictate science-based demand driven planning. Even with these instructions, half of medium-sized towns in India are still using outmoded population figures, poorly designed networks, and sporadic supply schedules, creating structural disparities in access to services.

Importance and Motivation

The importance of demand related water supply planning is double-fold: if the water supply system is undersized, it may cause hydraulic deficiencies and water service failures; if the system is oversized, it may lead to unnecessary capital expenditures and operating costs. This is a challenge that is very prevalent in Banda town (case study of this review) in the Sagar district of Madhya Pradesh. Although its population has increased from 7,630 in 1971 to 30,923 in



2011 [2], the per capita supply is still 77 LPCD, the coverage rate has been 44.01% and the continuity of supply is 1.5 hours per day [35]. The unreliable availability of the existing source – the seasonal Bewas River – in the summer period makes water security further precarious. Medium sized medium-sized urban local bodies in India face such problems, which inspire the extensive review and case analysis provided.

Objectives of the Review

The purpose of this review is to:

- To draw together and collate existing literature on population projection techniques and water demand estimation approaches.
- Discuss hydraulic design principles to transmission mains and distribution networks such as Hazen-Williams and Darcy-Weisbach equations.
- Produce a demand based design case study for Banda town covering projection, treatment, storage and network redesign.
- Enlist existing research problems, gaps and promising technological trends related to sustainable provision of water in urban areas.

II. LITERATURE REVIEW

Existing Studies

There has been a significant increase in the body of literature to support population projection and water supply designs based on demand over the last twenty years. Sharma et al. [2] showed that the water supply planning decision most significantly affecting water supply demand levels is the selection of the projection technique, with markedly different population estimates resulting from different projection techniques. In order to demonstrate the material improvement in long-term system reliability that can be achieved by a design that is properly demand-calibrated, Verma et al. [6] used CPHEEO per capita norms and peak demand factors.

Inappropriate population estimation along the design chain is highlighted by Patel et. al. [4] who explained that an under estimated population in a design environment leads to chronic pressure deficiencies, whereas an over estimated population wastes capital resources. Reddy et al. [5] used WaterGEMS-based scenario modelling to confirm that hydraulic inadequacies are not present at any intermediate growth stage when designing for final year. The authors of Kumar et al. [7] have systematically compared Arithmetic, Geometric, and Incremental Increase methods, and found that the growth characteristics of the local context should dictate method choice.

From a system perspective, Mishra et al. [8] validated that the design process with a demand-based approach maintains sufficient residual head and reduces NRW. Singh et al. [14] showed that the accuracy of the forecast impacts the capacity of the treatment plant, the diameters of pipes, and the size of storage reservoirs. Chatterjee et al. [11] proposed to combine demand management and supply planning to incorporate lifestyle driven demand fluctuations. Mehta et al. [21] demonstrated that demand-oriented design helps to achieve the optimal infrastructure sizing, minimize capital investment, and maximize operational efficiency throughout the design process.

Methods and Technologies Used

The reviewed literature ranges from demography, through hydraulics, to the computation. There are five commonly used methods for population forecasting as mentioned in the CPHEEO Manual [35]:

Arithmetic Increase Method: Arithmetic Increase Method: Base population plus a constant average decadal increase; Appropriate for slowly growing towns.

Geometric Increase Method: Assumes the percentage increase is constant; over estimates for towns that have a decreasing percentage increase.

The Incremental Increase Method: Takes into consideration the average increase in size and the growth rate, and is most balanced for stabilising towns.



Decadal Growth Rate Method: This is the method that uses the mean of the historical decadal percentage; falls between Arithmetic and Geometric methods.

Graphical Trend Analysis: Curves a trend to historical values; can serve as a validation check.

In Indian practice, the Hazen-Williams equation is the most commonly used equation for hydraulic analysis [6],[7],[8].

The speed of the flow is given by:

$$V = 0.849 \times C^{HW} \times R^{0.63} \times S^{0.54} \quad \dots \quad (1)$$

where V is flow velocity (m/s), CHW is the Hazen-Williams roughness coefficient (C = 140 for DI; C = 140–150 for HDPE), R is hydraulic radius (m), and S is hydraulic gradient (Hf/L). The head loss per unit length follows:

$$\frac{H_M \propto Q^{1.85}}{D^{4.87}} \quad \dots \quad (2)$$

Equation (2) reveals the extreme sensitivity of friction loss to pipe diameter: a modest increase in D produces a disproportionately large reduction in Hf, which is the mathematical basis for pipe diameter optimisation [5],[8]. The Darcy-Weisbach equation provides the theoretically rigorous counterpart:

$$H_M = f \times \left(\frac{L}{D}\right) \times \left(\frac{V^2}{2g}\right) \quad \dots \quad (3)$$

The Darcy friction factor f, the length of pipe L (m) and the gravitational acceleration g (9.81 m/s²). The CPHEEO formula is used to estimate the water demand, which is given as:

$$Q_{DEMAMD} = [P \times (1 + 0.01) \times 135 / 10^6] \times (1 + 0.10) \text{ MLD} \quad (4)$$

The projected population is represented by P, the floating population is represented by 1%, per capita norm (LPCD) is represented by 135 and system transmission and distribution losses is represented by 10% [35].

Through the use of advanced computational modelling with WaterGEMS V8i, multi-node pressure verification, pipe sizing optimisation and peak demand simulation can be carried out in complex looped or dead-end distribution networks [5],[8],[29]. The Mass Balance Curve Method calculates the balancing volume required by integrating the hourly demand and supply pattern, to determine the storage capacity.

Comparative Summary of Reviewed Literature

Table I: Comparative Summary of Key Studies on Urban Water Supply Planning

Author(s)	Year	Study Focus	Methodology	Key Finding
Sharma et al. [2]	2024	Population projection + demand assessment	Arithmetic, Geometric, Incremental	Projection method choice is critical for long-term adequacy
Verma et al. [6]	2023	CPHEEO guideline demand-based design	Per capita norms + peak factors	Demand-based design enhances reliability
Patel et al. [4]	2023	Population growth & demand in medium towns	Demographic trend analysis	Poor estimation leads to inefficient infrastructure
Reddy et al. [5]	2023	Hydraulic performance under projected demand	WaterGEMS scenario modelling	Residual pressure compliance validated
Kumar et al. [7]	2022	Urban WSS planning & forecasting	Arithmetic, Geometric, Incremental	Demographic + local data improves accuracy
Mishra et al. [8]	2022	WSS design & performance analysis	Network performance evaluation	Demand-based design preserves pressures
Singh et al. [14]	2021	Population projection for infrastructure	Multi-method comparison	Accurate forecasting governs all sizing
Chatterjee et al. [11]	2021	Urban water demand	Demand dynamics	Integrate demand



		management	analysis	management with supply
Yadav et al. [18]	2020	Urban water demand forecasting	Long-term demand planning	Demand planning prevents future shortages
Mehta et al. [21]	2019	Demand-oriented WSS infrastructure	Demand-driven design methodology	Optimal sizing, lower capital expenditure
Joshi et al. [19]	2019	Evaluation of forecasting methods	Historical + socio-economic analysis	Method selection governs design accuracy
Rao et al. [26]	2018	Population growth vs WSS adequacy	Growth impact assessment	Population density governs infrastructure sizing
Deshmukh et al. [27]	2017	WSS design based on demand analysis	Case study approach	Demand-based design matches actual needs
Gokila Vani et al. [29]	2016	System dynamics for demand forecasting	System dynamics modelling	Feedback mechanisms improve forecast accuracy
Banerjee et al. [31]	2015	WSS planning under population uncertainty	Flexible design approaches	Need for adaptive infrastructure strategies

Water Supply System (WSS), Electro-Mechanical (E/M), Bentley WaterGEMS (WaterGEMS) V8i.

Case Study: Banda Town — Demand-Based Water Supply System Design

Study Area and Existing Conditions

Banda Nagar Parishad, Sagar district, Madhya Pradesh, has an area of 10.5 km² and a population density of 3534 persons/km² (2021 estimate). The town is divided into 15 administrative wards, and Ward No. 4 (Indira Gandhi Ward) is the most populated ward with 4485 persons while Ward No. 14 (Netaji Subhash Chandra Bose Ward) is the least populated ward with 1034 persons as per Census 2011 [2]. The current water supply system is sourced from the Bewas River (a seasonal source) with a capacity of 2MLD which is much less than the demand of 8.59MLD by 2055. The supply of the per person water (77 LPCD) and the coverage of the water (44.01%) are also very low compared to the CPHEEO benchmarks [35] as is the continuity (1.5 hrs/day).

Historical Population Growth of Banda Town

Table II: Historical Census Population Data for Banda Town

Census Year	Population	Decadal Increase	% Increase
1971	7,630	–	–
1981	12,569	4,939	64.7%
1991	19,830	7,261	57.8%
2001	26,183	6,353	32.0%
2011	30,923	4,740	18.1%

The population figures are taken from Census of India records, and the decadal growth rates were decreasing, suggesting stabilization in the growth process.



Population Projection

Five projection methods were applied following CPHEEO Manual guidelines [35], with 2025 as the base year and 2040 and 2055 as the intermediate and ultimate design years respectively. The Arithmetic Increase Method applies:

$$P_n = P_0 + n \times \Delta \bar{p} \dots \quad (5)$$

where P_0 is the initial (base) population, n is the number of decades, and $\Delta \bar{p}$ is the arithmetic average of the increments over each decade. The Geometric Method uses compound growth with an average rate of $r\%$. The Incremental Increase Method further corrects for the deceleration of the increment itself, and is thus more balanced for towns that show a deceleration in their growth, as seen in the history of Banda (64.7% decadal growth between 1971 and 1981, followed by 18.1% growth between 2001 and 2011).

Table III: Population Projections by Method for Banda Town (Persons)

Projection Method	2025	2040	2055
Arithmetic Increase	39,075	47,810	56,545
Geometric Increase	51,101	87,532	1,49,934
Incremental Increase *	39,187	48,186	57,333
Decadal Growth Rate	40,076	52,099	67,729

The design basis (used Incremental Increase Method) has been adopted but the Geometric Method has been excluded, because it is unrealistic to overestimate [2].

By 2055, the Geometric Method projects a population of 1,49,934 persons (almost 2.6 times the Incremental Increase estimate) which is not consistent with the observed stabilising growth trend and local infrastructure constraints [7]. The recommendations by Joshi et al. [19] and Malhotra et al. [33] that the method selection should be based on historical trends along with the local socio-economic analysis was followed where all the design computations were based on Incremental Increase Method projection of 57,333.

Water Demand Estimation

The water demand was estimated based on the Equation (4) with the assumption of 135 LPCD for sewered cities, according to norms of CPHEEO. A 10% loss in the transmission and distribution system and a 1% floating population allowance were added [35]. The resulting demand projections are:

Table IV: Water Demand Projections for Banda Urban Local Body

S.No.	Parameter	2025	2040	2055
1	Projected Population	39,187	48,186	57,333
2	Floating Population (1%)	391	481	573
3	Domestic Demand @ 135 LPCD (MLD)	5.34	6.57	7.82
4	System Loss (10%) (MLD)	0.534	0.657	0.782
5	Total Water Demand (MLD)	5.87	7.22	8.59

LPCD = Litres Per Capita per Day; MLD = Million Litres per Day; Source: Case Study Data [2]

Total demand escalates by 46.4% over the 30-year design horizon (5.87 MLD in 2025 to 8.59 MLD in 2055). Peak demand for a population below 50,000 applies a peak factor of 3.0 as per CPHEEO Table 3.8, yielding:

$$Q_{ea}^k = Q_{av}^c \times PF = 8.59 \times 3.0 = 25.77 \text{ MLD} \quad (\text{Ultimate Year}) \quad \dots (6)$$

The use of pipe diameters in the distribution network, and the selection of pumps for clear water rising mains are determined by this peak demand [6],[8].

Source and Treatment Design

The seasonal source of the raw water was replaced by the perennial source of the Pagra Reservoir (24.040602N, 78.978443E) thus ensuring year round assured raw water supply. The proposed new Water Treatment Plant (WTP) of



5.22 MLD capacity at Ward No. 5 also adds to the existing 2 MLD WTP giving the capacity of 7.22 MLD which is adequate for the intermediate design year of 2040. The treatment train consists of Inlet Chamber, cascade aeration, Parshall Flume, Alum Dosing, Flash Mixer, Clariflocculator, Rapid Sand Filters and Chlorination [2]. Water quality standards for treated water are : Turbidity (NTU) ≤ 5 , pH(PH) 6.5–8.5, TDS (mg/L) ≤ 500 . Sludge management involves gravity thickeners and solid bowl centrifuge dewatering, and sludge cake is sent to engineered landfill as per Solid Waste Management Rules, 2016.

Hydraulic Network Design and Analysis

Effect of Pipe Diameter on Head Loss

From equation (2) it is seen that head loss is proportional to the power of the diameter of the pipe. The head loss decreases by 97% or 24.87 times when the pipe diameter D is doubled, for a given discharge Q. This is the economic compromising factor involved in choosing pipe diameters: the smaller the diameter the less the capital cost, but the more the pumping energy cost [8].

The Present Worth Cost (PWC) method [29] assesses the total cost of the design life of the pipes including the net present value of energy costs over the design life of 30 years, based on the compound interest formula:

$$P = P^0 \times (1 + r)^n \quad \dots \quad (7)$$

In which P0 is the cost in the first year, r = 10% (assumed interest rate), and n is the year. The optimum diameter will balance minimum total PWC with velocity constraints.

The following raw water rising main specifications are chosen:

Pagra Reservoir to New WTP Junction: L = 7.7 km, D = 350 mm DI K-7

Junction to Old WTP: L = 2.5 km, D = 200 mm DI K-7

Clear Water Transmission Main: L = 2,587 m, D = 150 mm DI K-7

Velocity Constraints

According to the continuity equation ($Q/A = V/4 = V/\pi D^2$), for a given Q, as the diameter increases, the velocity decreases monotonically up to a maximum of 3.00 m/s, which is the requirement of CPHEEO. Lower velocities (than sub-minimum, <0.60 m/s) lead to sedimentation and biological growth, and higher velocities (than maximum, >3.0 m/s) result in pipe erosion, pressure surge and water hammer. For clear water rising mains, CPHEEO recommends: V is between 0.75 m/s and 1.8 m/s. These constraints were checked for all of the pipe segments designed.

Storage Capacity Design

The Mass Balance Curve Method, which was created by integrating the hourly demand and supply curve over a 24 hour period, was used to determine the required balancing storage for the 2055 ultimate demand, which was 4.29 ML. The existing storage of 1.9 ML (ESR-1: 0.7 ML, ESR-2: 1.2 ML) is insufficient by 2.39 ML [2]. The proposed additional storage of 2.4 ML is achieved by: (i) ESR Proposed (0.3 ML); (ii) ESR Ward No. 11 Proposed (0.5 ML); and (iii) UGSR at New WTP (1.6 ML). A 126% larger balancing storage capacity.

Design Year Allocation

A phased design approach is a method that assigns components to base (2025), intermediate (2040), or ultimate (2055) design years to optimize the use of capital resources and maintain hydraulic adequacy for the long term [6, 35]:

Table V: Design Year Allocation for Water Supply System Components

S.No.	System Component	Design Year
1	Raw Water Intake Well – Civil Structure	2055 (Ultimate)
2	Raw Water Intake Well – E/M Components	2040 (Intermediate)
3	Raw Water Conveying Mains	2055 (Ultimate)
4	Water Treatment Plant	2040 (Intermediate)



5	Elevated Service Reservoir (ESR)	2040 (Intermediate)
6	Clear Water Conveying Mains	2055 (Ultimate)
7	Water Distribution Network	2055 (Ultimate)

Source: CPHEEO Manual [35]; E/M = Electro-Mechanical Components

Current Trends and Developments

Recent Advancements

The modern planning of water supplies has come a long way from empirical projection to data-driven, integrated approaches. Agarwal et al. [1] showed that the accuracy of the demand forecasting of hybrid statistical models, which combine regression, time-series decomposition and machine learning, is much higher than the accuracy of the models based on a single method. Thomas et al. [10] demonstrated that the integration of socio-economic indicators (household income, employment, service sector share) can greatly enhance forecasting of per capita consumption beyond fixed-norm scenarios.

The professional standard has been the computational hydraulic modelling. Multi-scenario steady-state and extended period simulation, real-time pressure zone optimisation and automated leakage localisation can be achieved using platforms like WaterGEMS V8i (Bentley), EPANET 2.2 (US EPA), and InfoWorks WS Pro [5],[8]. A major improvement over the conventional PWC method is the use of network optimisation algorithms in Jain et al. [29] which optimise the lifecycle cost for the pipe diameters, pump scheduling, and storage capacity all in one.

Comparative demand forecasting analyses by Sahu et al. [9] revealed that integrated methods proved better than single method forecasting, especially for the cities with non-linear growth paths in Tier-II cities of India. The scenario-based planning with Monte Carlo simulation was introduced by Nair et al. [13] which allowed planners to consider a variety of growth scenarios and not just single-point estimates.

Emerging Technologies

Smart water management is the new frontier of urban water infrastructure development. When SCADA (Supervisory Control and Data Acquisition) systems are connected to the IoT sensors, flow rates, pressures, turbidity, residual chlorine and energy usage can be monitored as they occur in the distribution network [20]. Automated pressure management in District Metered Areas (DMAs) has shown non-revenue water savings of 15-25%, and energy savings of 20-30% in the pilot sites.

Historical consumption, weather and network topology data can be used to develop AI-powered demand prediction and leakage detection algorithms that are becoming increasingly effective in managing water infrastructure proactively. Das et al. [15] reported measurable NRW results for cities implementing NRW demand management systems through IoT. Membrane bioreactors (MBRs), nanofiltration, and systems that use UV for disinfection are increasingly being added to conventional treatment trains in water treatment, providing better effluent quality and smaller footprints [31].

For towns in the 30,000-70,000 population size range (directly comparable to Banda), there is growing interest in renewable energy integration, particularly in the use of solar powered pumping systems with battery storage and variable frequency drives (VFDs). For the case of solar-diesel hybrid systems, life-cycle cost analysis shows that energy costs can be lowered by 40-60% for a 30-year life span [16]. The next frontier in water system management and investment planning is digital twin modelling, which involves the creation of virtual copies of physical water systems in real time and calibrated with the data from water network sensors.



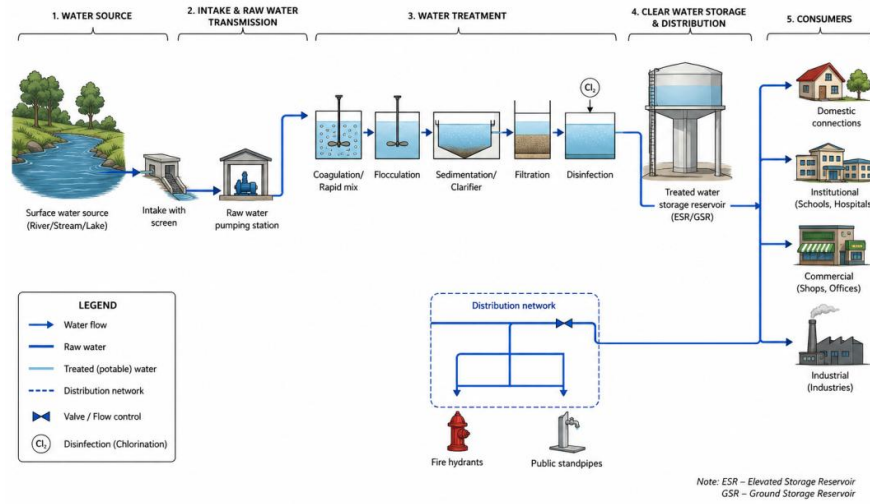


Fig. 1. Generalised schematic of an urban water supply system (adapted from case study design, Banda Town [2])

IV. RESULTS AND COMPARATIVE ASSESSMENT

Service Level Improvement

Comparative performance evaluation of existing system and proposed system in Banda town shows that there is a transformational improvement under the six critical service level indicators defined by the Ministry of Housing and Urban Affairs (MoHUA) [2],[35] in the town:

Table VI: Service Level Comparison — Existing vs. Proposed Water Supply System, Banda Town

S.No.	Indicator	Benchmark	Existing	Proposed
1	Coverage of water supply connections	100%	44.01%	100%
2	Per Capita Supply (LPCD)	135	77	135
3	Metering of connections	100%	0%	100%
4	Continuity of supply	24 hrs	1.5 hrs	24 hrs (24×7)
5	Quality of water (IS 10500)	100%	100%	100%
6	Balancing storage capacity	—	1.9 ML	4.29 ML
7	WTP treatment capacity	—	2 MLD	7.22 MLD

Source: Case Study Design Data; CPHEEO Benchmarks [35]; LPCD = Litres Per Capita per Day; MLD = Million Litres per Day

The proposed system is a shift from a seasonal intermittent and under coverage supply system to perennial continuous (24×7) fully metered supply system with 100% population coverage. Per capita supply increases by 75.3% (77 → 135 LPCD), and balancing storage by 125.8% (1.9 → 4.29 ML). Treatment capacity boosted by 261% (2 → 7.22 MLD) with a 10% hydraulic overload allowance for emergency situations.

Hydraulic Performance Validation

The 15 distribution nodes in all 15 wards had a minimum residual head of 7.0 m for single storey connections, which is in line with CPHEEO norms (7.0 m for single storey, 12.0 m for 2 storey and 17.0 m for 3 storey). When the single storey connection was tested under peak demand with a peak factor of 3.0 for population less than 50,000 [35] all 15 distribution nodes had a minimum residual head of 7.0 m. No negative pressure areas were found, therefore the risk of contamination ingress due to sub-atmospheric conditions was excluded [8].



All pipe segments were tested to ensure they were in the CPHEEO velocity band (0.60–3.00 m/s for distribution, 0.75–1.8 m/s for rising mains). The PWC analysis [29] has confirmed that the best cost-effective strategy for the phased installation of the pumps is the following: have 50% of the pumps stand-by at both the 15th year of pump commissioning and the 30th year of pump replacement, and size the pumps for the 15th year for the pump installations.

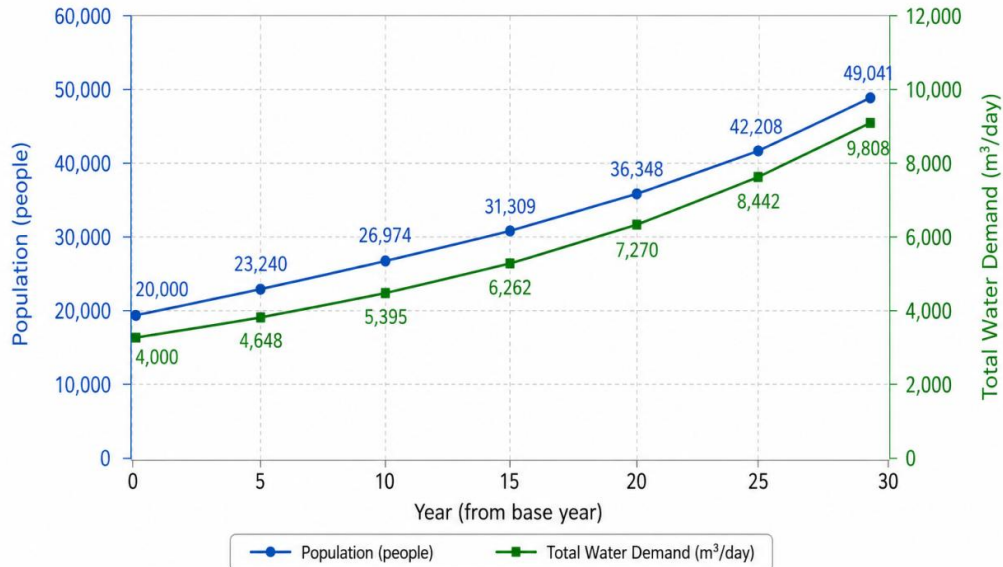


Fig. 2. Projected population and total water demand growth over the 30-year design horizon, Banda Town (Incremental Increase Method) [2]

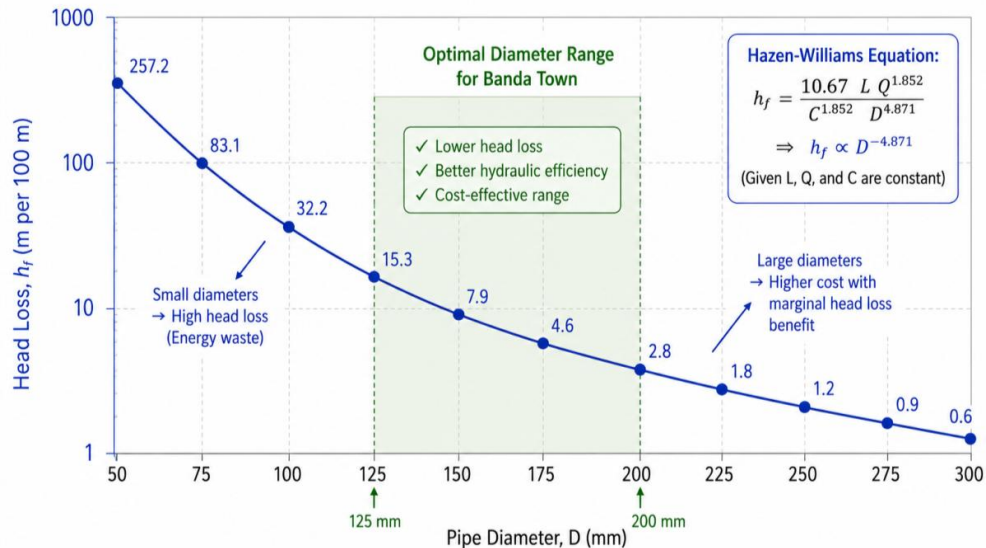


Fig. 3. Conceptual head loss vs. pipe diameter curve illustrating the Hazen-Williams exponential relationship and the optimal diameter range for Banda Town [8]



Economic and Social Implications

An economic perspective takes into account the lifetime cost of a pipe installation, with the aim of reducing this cost while maintaining hydraulic performance, which is achieved through the use of PWC-optimised pipe diameter selection. All house connections are metered, leading to better demand accountability and revenue recovery [11]. Mechanical sludge dewatering (centrifuge) is an alternative to open lagoon disposal that decreases the environmental liability and remediation costs.

The project has a direct impact on the well-being of 9,896 households (2025 projection), by providing continuous, pressurised, safe water – thereby improving equity across all 15 wards, including historically marginalised areas, reducing waterborne disease risk and eliminating the burden of household water storage, on-going use and maintenance, and transport [2],[20]. Under the proposed design, it is possible to reach the Jal Jeevan Mission Target of Functional Household Tap Connections (FHTC) at quality, quantity and regularity [35].

V. CHALLENGES AND LIMITATIONS

Technical Issues

Despite having well-established methodologies, there are some technical issues in water supply planning for medium sized towns in India. There is a natural uncertainty in population forecasts over longer time horizons; for example, changes in migration over time, municipal boundary changes, and land-use changes can render even well-constructed forecasts incorrect [13]. The Geometric Method is shown to overestimate by $2.6\times$ relative to the Incremental Method by 2055 (see Banda); if not used with care, this can lead to catastrophic over-design.

The assumption of 135 LPCD remains under doubt for the whole design period. Thomas et al. [10] and Sharma and Kansal [22] show the relationship between consumption patterns and income, service quality, and lifestyle changes, which suggest a possibility of underestimation or overestimation of future demands with fixed per capita norms. The design calls for 10% loss of water in the system, but in Indian utilities, NRW is typically in the range of 30-50% which reduces the availability of services offered by the water system [20].

Data quality limits the ability of hydraulic modelling: No GIS-based network records, demand characterisation data, or pipe condition data are available, which means that the hydraulic modelling has to rely on simplified schematic representations [5]. Extended period simulation (EPS) is not often performed in small utilities, even for towns relying on run-of-river intakes, which can be particularly sensitive to seasonal source variability, and is required for a steady-state hydraulic model to completely capture this variability.

Research Gaps

In spite of a large body of literature, there are still several gaps in the literature. In Indian context, multi-variable dynamic demand models are very limited, which incorporates population, income, land-use change, and climate variables [1],[3]. Most studies assume that per capita demand remains fixed; however, empirical evidence indicates consumption growth of 2-4% per capita, above the baseline, in rapidly urbanising towns. The effect of climate change on demand (temperature-induced consumption) and supply (monsoon variability and ground water depletion) is not well incorporated into the conventional planning frameworks from CPHEEO [3],[20].

Research on energy efficiency in water supply systems is sparse for small and medium-size Indian water supply systems: solar pumping LCC studies, gravity-flow optimisation studies and/or VSD implementation studies are rare. Evidence of health, productivity, and welfare benefits of 24 \times 7 supply conversion is lacking and is a requirement for municipal investment decisions. The contextual nature of developing country utilities and a lack of literature to provide the tools to account for institutional capacity, willingness to pay, and the scarcity of data are emphasised by Khati and Vairavamoorthy [20].

Future Research Directions

Potential Improvements in Planning Methodology

Demand forecasting frameworks for the future need to be built that are climate adaptive, incorporating multiple variables such as the population forecast, hydrological risk modelling, socio-economic trajectories and land-use change



scenarios [1],[3]. Real-time consumption data input as the design process unfolds would enable adaptive infrastructure planning, which would adjust capacity commitments as uncertainty dissipates [13]. If data infrastructure is created, comprehensive urban water data can be used to train machine learning models such as neural networks or gradient boosting that can significantly enhance the accuracy of forecasts.

In Indian distribution network practice, steady state simulation should be replaced by extended period simulation (EPS) which allows modelling of pressure, quality, and demand patterns across daily and seasonal periods [5]. Satellite-based built-up area growth analysis is a viable data independent approach to population projection which can be used in any environment where there are census data limitations.

Opportunities for Future Work

The biggest near term opportunity is in smart infrastructure deployment. In Indian utilities, real-time monitoring of pressure, quality surveillance and automatic leakage detection for NRW reduction (30-50%) could be achieved with SCADA-IoT integrated sensor networks without any investment in new infrastructure, directly improving system performance [15],[20]. There is a need for studies of the cost-effective architectures of IoT for small utilities with limited operational budgets.

The techno-economic package of solar powered pumping combined with battery storage and demand-response control should be evaluated and tested thoroughly for 30,000-70,000 population range characteristic of Banda and other similar towns. Sludge valorisation is an economic co-benefit solution that minimizes landfill pressure and allows the reuse of WTP sludge in the production of bricks, fill aggregates and/or agriculture soil amendment. For peripheral wards where populations are dispersed, decentralised modular treatment systems (DMS, e.g. compact package plants, constructed wetlands) could be used as supplements to the centralised WTPs, which could lower the costs of transmission infrastructure [31].

The new frontier for water network operations and capital investment planning is digital twin modelling, which involves creating real-time virtual models of physical water networks that are calibrated. Pilot implementations in Indian metros should be scaled up to medium-sized towns and open-source toolkits should be created to minimize the adoption challenges for resource-constrained utilities.

VI. CONCLUSION

The review has summarised the current state of knowledge on population projection, estimation of water demand, and demand-based hydraulic design of water supply systems in urban areas, with a detailed case study of the Banda town, Sagar District. The main findings are:

Selection of the population projection method is crucial: The bandwidth of the medium sized Indian towns comes closest to the growth stabilisation in medium sized Indian towns; hence, the design population for Banda is 57,333 as calculated by Incremental Increase Method. The Geometric Method provides the design population of 1,49,934, which is unrealistic.

Demand-based design avoids hydraulic failure: Civil infrastructure components are designed for the 2055 ultimate demand (8.59 MLD) and electro-mechanical components are phased into intermediate years (2040) to achieve the optimum capital cost and hydraulic adequacy with long-term operations.

The economics of pipes are controlled by the Hazen-Williams exponent ($D^{4.87}$): The diameter sensitivity of head loss in pipes requires strict optimisation of pipes within each segment in a PWC – selection of diameters that keep velocities between 0.60 and 3.00 m/s (CPHEEO norms) ensures both hydraulic efficiency and system longevity.

The use of computational modelling is crucial: WaterGEMS V8i has been able to verify that there was no negative pressure at any node and the minimal head of 7.0 m was maintained throughout the network even under peak demand, which would not have been possible using manual modelling in a 15-ward network with 9,896-connections.

The redesigned system is transformative: Per capita supply grew by 75.3% (77 LPCD to 135 LPCD), coverage expanded to 100% from 44%, continuity from 1.5 hrs/day to 24×7, storage capacity increased by 126% and will provide equitable, safe and sustainable water supply to 9,896 households till 2055.



Some recommendations for planners and policymakers are outlined below: (i) pre-implement multi-method projection verification prior to design completion; (ii) require water utilities larger than 3 MLD to have a hydraulic model (WaterGEMS or EPANET); (iii) incorporate climate sensitivity in demand forecasting to ensure infrastructure is future-proofed; (iv) mandate smart metering and IoT deployment for NRW reduction; and (v) consider solar-powered pumping for medium-sized utilities as a cost-competitive alternative to grid-connected pumping. Incorporating these into the AMRUT 2.0 and Jal Jeevan Mission would significantly help India's water security agenda in cities.

REFERENCES

- [1]. N. Agarwal, P. Srivastava, and R. Menon, "Integrated urban water demand forecasting using hybrid statistical models," *J. Water Resour. Plan. Manag.*, vol. 150, no. 2, p. 04023089, 2024.
- [2]. P. Sharma, R. Verma, and T. Singh, "Population projection and demand assessment for urban water supply planning," *J. Urban Water Manag.*, vol. 15, no. 1, pp. 1–12, 2024.
- [3]. V. Bansal, M. Arora, and S. Kapoor, "Climate-sensitive population forecasting for sustainable urban water infrastructure design," *Sustain. Cities Soc.*, vol. 92, p. 104489, 2023.
- [4]. R. Patel, D. Chaudhary, and S. Meena, "Assessment of population growth and water demand in medium-sized towns of India," *Int. J. Urban Water Stud.*, vol. 9, no. 1, pp. 25–34, 2023.
- [5]. P. S. Reddy, D. Kumar, and A. Sharma, "Hydraulic performance assessment of urban water distribution systems under projected demand scenarios," *Urban Water J.*, vol. 20, no. 6, pp. 587–599, 2023.
- [6]. S. Verma, A. Gupta, and P. Kulkarni, "Demand-based design of urban water supply system using CPHEEO guidelines," *J. Civil Infrastruct. Water Eng.*, vol. 14, no. 2, pp. 89–98, 2023.
- [7]. R. Kumar, S. Verma, and P. Singh, "Urban water supply planning based on population forecasting techniques," *Int. J. Civil Eng. Res.*, vol. 13, no. 1, pp. 45–54, 2022.
- [8]. S. Mishra, V. Tripathi, and A. Pandey, "Urban water supply system design and performance analysis," *Water Eng. Manag. J.*, vol. 18, no. 2, pp. 87–96, 2022.
- [9]. R. Sahu, K. Patel, and S. Dubey, "Demand forecasting approaches for tier-II Indian cities: A comparative analysis," *Int. J. Civil Eng. Technol.*, vol. 13, no. 3, pp. 112–123, 2022.
- [10]. J. Thomas, L. Mathew, and K. Joseph, "Long-term municipal water demand estimation incorporating socio-economic indicators," *Water Policy*, vol. 24, no. 4, pp. 615–628, 2022.
- [11]. S. Chatterjee, D. Mukherjee, and P. Roy, "Urban water demand management and planning in India," *Int. J. Water Resour. Dev.*, vol. 37, no. 4, pp. 589–603, 2021.
- [12]. [12] A. Kulshreshtha, R. Singh, and V. Jain, "Peak demand estimation and infrastructure sizing in Indian municipal water systems," *J. Water Supply Res. Technol.—AQUA*, vol. 70, no. 5, pp. 685–696, 2021.
- [13]. S. Nair, M. Iqbal, and P. Choudhury, "Scenario-based planning for urban water supply systems under demographic uncertainty," *J. Infrastruct. Syst.*, vol. 27, no. 3, p. 04021029, 2021.
- [14]. Singh, R. Yadav, and N. Srivastava, "Population projection models for infrastructure planning in Indian cities," *J. Mun. Eng. Plan.*, vol. 7, no. 4, pp. 201–210, 2021.
- [15]. Das, S. Roy, and A. Ghosh, "Evaluation of water demand management strategies in rapidly growing urban centers," *Environ. Dev.*, vol. 35, p. 100523, 2020.
- [16]. J. Gupta and S. R., "Planning and designing water supply systems in rapidly urbanizing areas," *J. Environ. Eng. Plan.*, vol. 12, no. 1, pp. 65–74, 2020.
- [17]. Tripathi, N. Verma, and P. Saxena, "Urban population growth modeling for water supply master planning," *Int. J. Urban Sustain. Dev.*, vol. 12, no. 2, pp. 179–191, 2020.
- [18]. R. Yadav, D. Mishra, and K. Soni, "Water demand in urban areas: Forecasting," *Int. J. Water Resour. Plan.*, vol. 5, no. 2, pp. 140–149, 2020.
- [19]. M. Joshi, A. Singh, and S. Tiwari, "Evaluation of population forecasting methods for water supply projects," *J. Water Supply Sanit.*, vol. 11, no. 4, pp. 233–241, 2019.



- [20]. [20] K. Khatri and K. Vairavamoorthy, "Challenges for urban water supply and sanitation in developing countries," *Water Environ. J.*, vol. 33, no. 3, pp. 362–369, 2019.
- [21]. D. Mehta, K. Shah, and H. Trivedi, "Demand-oriented planning of urban water supply infrastructure," *J. Sustain. Urban Dev.*, vol. 6, no. 3, pp. 155–164, 2019.
- [22]. D. Sharma and A. Kansal, "Water demand estimation in Indian cities using regression-based techniques," *J. Environ. Manage.*, vol. 245, pp. 250–259, 2019.
- [23]. Bhattacharya, P. Saha, and S. Mitra, "Urban infrastructure planning using demographic projection models," *Procedia Eng.*, vol. 208, pp. 456–463, 2018.
- [24]. R. Kulkarni, M. Pawar, and V. Desai, "Practices on water demand estimation by Indian municipalities," *Urban Plan. Dev. J.*, vol. 14, no. 2, pp. 98–106, 2018.
- [25]. P. Narayanan and V. Srinivasan, "Linking land-use change and water demand forecasting in urban India," *Water Resour. Manag.*, vol. 32, no. 9, pp. 3055–3068, 2018.
- [26]. S. Rao, L. Kumar, and P. Ramesh, "Effect of population growth on urban water supply schemes," *J. Water Infrastruct. Dev.*, vol. 10, no. 3, pp. 177–186, 2018.
- [27]. P. Deshmukh, S. Patil, and R. Jadhav, "Urban water supply design based on population forecast and demand analysis," *J. Civil Eng. Urban Dev.*, vol. 5, no. 3, pp. 145–153, 2017.
- [28]. V. Iyer, A. Nair, and P. Krishnan, "The role of population projection in infrastructure planning," *Infrastruct. Dev. Rev.*, vol. 9, no. 2, pp. 78–89, 2017.
- [29]. S. Jain, P. Agarwal, and V. Singh, "Design optimization of water distribution networks under future demand growth," *J. Hydroinformatics*, vol. 19, no. 6, pp. 987–1002, 2017.
- [30]. M. Gokila Vani, K. Subramanian, and R. Kumar, "System dynamics approach for urban water demand forecasting," *Water Resour. Manag. J.*, vol. 30, no. 7, pp. 2105–2118, 2016.
- [31]. World Health Organization, *Guidelines for Drinking-Water Quality*, 4th ed. Geneva, Switzerland: WHO Press, 2016.
- [32]. Banerjee, R. Sharma, and S. Kulshrestha, "Planning of urban water supply under population uncertainty," *J. Urban Infrastruct. Plan.*, vol. 8, no. 2, pp. 112–120, 2015.
- [33]. Malhotra, N. Gupta, and R. Mehra, "Population forecasting techniques for municipal infrastructure," *J. Infrastruct. Syst.*, vol. 20, no. 3, pp. 112–120, 2014.
- [34]. K. Prasad, M. Rao, and V. Reddy, "Design parameters of urban water supply systems in India," *Indian J. Environ. Eng.*, vol. 4, no. 2, pp. 56–64, 2013.
- [35]. CPHEEO, *Manual on Water Supply and Treatment*, 3rd ed. New Delhi, India: Ministry of Urban Development, Government of India, 2012

