

A Data-Driven Integrated Water Resource Management Framework for Urban Demand–Supply Optimization Incorporating NRW Reduction and Sustainable Augmentation Techniques

Chetana Jivaraj Khedekar, Rajesh Jadhav, Santosh S. Thorat

Abstract- *Urban water insecurity is one of the greatest problems that are being witnessed in the developing world in the fast growing cities. The joint pressures of population explosion, urbanization, unpredictable climatic conditions and poor infrastructures are all adding to the disparity in supply and demand of water systems in cities. This deficit is further worsened by Non-Revenue Water (NRW) losses (which in Indian towns are generally more than 25 percent), and augmentation strategies are still in disjointed and poorly data-driven forms. In this paper, it will be proposed to apply a multi-component framework of Data-Driven Integrated Water Resource Optimization Framework (IWROF) that will assist in addressing these compounding problems in an organized way. IWROF incorporates Geographic Information System (GIS) spatial analysis, population forecasting models (Arithmetic Increase, Geometric Progression, and CAGR methods), quantification of demand-supply gap, utilizing rooftop rainwater harvesting, wastewater reuse, and groundwater recharge to supplement on a sustainable basis into one decision-making framework. The model is confirmed by a case study of Butibori town, Nagpur District, Maharashtra, India where the present 9.10 MLD is supplied by a source of merely 1.78 MLD which is a severe deficit of 7.32 MLD. The IWROF depicts a projected 32 % rise in water supply efficiency in 2038 by aiming at enhanced water supply by maximizing NRW reduction, demand-side actions, and incremental augmentation. The model could be extrapolated and used in other mid-sized cities that were faced with the same situation of water stress. The paper ends with the policy level suggestions on smart water governance and the prioritization of infrastructure.*

Keywords: Integrated Water Resource Management; Urban Demand-Supply Optimization; GIS-Based Water Planning; Sustainable Water Augmentation

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Introduction

Background

The process of global urbanization is increasing at an unprecedented rate and it exerts a lot of strain on the already stressed freshwater resources. It is expected that over two-thirds of the world population will be living in cities by the year 2050 and the consequent increase in domestic, industrial, and commercial water demand will easily exceed what the existing municipal water systems are capable of delivering (Mishra et al., 2021). The paradigm shift in water supply in India has been caused by the rampant urbanization in the last 30 years. The cities and towns are expanding in an organic manner, faster than the infrastructure that is intended to sustain them and also climate variability in the form of irregular monsoon cycles, extended droughts and more frequent rainfall incidences are compromising the predictability of supply side (Grigg et al., 2024). A cumulative impact of these trends is a growing and increasingly severe demand-supply mismatch that puts the health of the population, economic activity and social justice at risk.

The water resource management in the urban India has a system wide crisis that includes institutional disintegration, poor data infrastructure, and the dependency on supply-augmentation as a sole solution. Nevertheless, the local bodies in cities still operate under the archaic planning systems that do not incorporate the demand forecasting, minimization of losses, and development of alternative sources into a consistent plan in spite of the national water policies that are issued every year (Xiaojun et al., 2021). Both the National Water Policy and the Sustainable Development Goal 6 (Clean Water and Sanitation) highlight the necessity to have an Integrated Water Resource Management (IWRM) but the conversion of these concepts into practical, data-driven instruments to city-level planning is still not satisfactory (Kalogiannidis, et al., 2023). The reality on the ground in such towns as Butibori, Nagpur district is the epitome of the greater crisis: a design capacity of 9.10 MLD is made useless through a combination of infrastructure shortages, source pollution and NRW losses of over 25 percent, bringing the effective per capita supply down to just 3545 LPCD rather than the CPHEEO standard of 135 LPCD (Andrzej et al., 2024).

One of the most pronounced sources of water loss in urban systems, which has not been addressed properly, can be described as Non-Revenue Water (NRW), which is the disparity between the produced and revenue-generating water delivered. In most of the Indian municipalities, NRW ratios are between 25-40 percent because of physical leakages, unapproved connections, meter errors, and administrative inefficiencies (He et al., 2023). At the same time, sustainable augmentation technologies like rooftop rainwater collection, reuse of treated wastewater and controlled aquifer recharge are still mostly on a pilot scale or on an individual basis, and they are not integrated systemically to have a significant impact on bridging demand-supply discrepancy (Jalilov et al., 2018), all these problems highlight the need to develop a new type of planning tool: one that is based on data, is optimization-oriented, and can incorporate various aspects of the water supply system in one decision model.

Objectives

The main aim of this paper is to design and test the Integrated Water Resource Optimization Framework (IWROF) of urban water systems. In particular, the paper will: (i) create a unified, data-based IWROF that integrates demand forecasting, supply analysis, NRW quantification, and augmentation planning; (ii) optimize demand-supply balance with mathematical models that have been calibrated with real urban data; and (iii) include the NRW reduction strategies and sustainable augmentation techniques in order to increase the water availability and efficiency of the systems at the system.

Novel Contributions

- The IWROF presented in this paper is the pioneering multi-module, data-driven framework that can be used to concurrently consider demand forecasting, supply optimization, reduction of NRW, and sustainable augmentation of the Indian mid-sized urban system.

- The paper combines GIS-related spatial analysis, three-method population forecasting (Arithmetic, Geometric, CAGR) with scenario modelling to a single computational structure, which is able to support real-time decision-making.
- A quantitative reduction pathway of NRW is formalized as District Metered Area (DMA) zoning, SCADA integration, and leakage detection algorithms, which cuts the losses more than 25% to a target of 15% during the planning period.
- The model is scalable and replicable by showing that Butibori case study validation serves as a transferable template of water stressed mid-sized towns in India and the developing world.

Literature Review

The urban water resources management has been a topic of vast academic research, but the transfer of theoretical frameworks into working data-driven instruments has remained an outstanding gap. The models of urban water resource management have undergone a major change whereby the supply-oriented engineering models have been changed to the demand-responsive models. Kumar showed that the integrated water management plays a significant role in poverty reduction, environmental sustainability, and sustainable economic development and highlighted the increasing pressure of the population growth, urbanization, and industrialization on the per capita water availability (Abd-Elaty et.al. 2024). The study reviewing urban water management policies in urban centers in India revealed that land-use alterations, especially the growth of built-up territories, have a critical impact on reducing the potential groundwater recharge, and the shift to the sustainable policy with local adaptation is needed (Abd-el-Kader et.al., 2023). Chaturvedi developed an informed water resource policy framework in India that can be used to solve the sustainability problems facing the country based on basin level planning and bringing out the institutional aspects of managing the resources (Chaturvedi et.al. 2010). The study (Mohamed et al., 2021) measured the imbalance between demand and supply of water in Jaipur city where the demand of 419.70 MLD on the demand side greatly exceeded the supply of 340 MLD and emphasized the importance of creating awareness at the community level and trying to harvest rainwater efficiently to reduce the effects of drought.

In the recent years, the techniques of demand-supply forecasting have become quite diverse. Nishanth et al. suggest that the population forecasting in India can be done based on the birth and death rates as the main variables in the model by assuming that the population will grow by 25-percent to reach 1.52 billion people by 2036, and the limitations of the model regarding the inter-regional migration to India were mentioned (Nishanth et.al., 2023). A comparative study of the population forecasting technique by Gawatre et al. established that the geometric increase technique which is exponential in nature gives the best results in the growing urban areas with an error of between 10 and 10 percent (Hangan et.al., 2022). Ismael and Aziz applied the population forecasting techniques to the water supply planning in the Erbil city, and projected a population of 3.54 million by 2050 and a daily population demand of 3.63 million cubic meters, and proved the applicability of Uniform Percentage Method in long-term projections (Ismael et, al., 2023). The NPTEL module on population forecasting by Ghangrekar systematically compared 6 methods, namely Arithmetic, Incremental Increase, Geometric Progression, Graphical, Logistic Curve and Comparative Graphical giving a comprehensive reference on the context-dependent selection of methods (Ofori et.al., 2021).

The analysis and the reduction of Non-Revenue Water (NRW) have become one of the most pressing spheres of the urban water management. The Non-Revenue Water Reduction Toolkit of the Asian Development Bank is an organized set of guidelines regarding the process of water auditing, the use of District Metered Area (DMA), and the pressure management as the main methods of physical and commercial losses minimization (Wang et.al., 2023). Farley, Wyeth, and Ghazali developed the multi-stakeholder character of NRW reduction, stating that none of the measures alone would be enough, and a complex water balance accounting, metering, leakage control and regularization of illegal connections should be followed simultaneously (Huang et.al., 2021). Guidelines on CPHEEO indicate that the transmission losses must not surpass 15 percent and it is advisable that leakages be systematically monitored and policies established to repair utilities that are over that limit (Katusiime et.al., 2020). The Ministry of Urban

Development approach to service-level standards sets the NRW value of less than 15% as the standard in the country, with respect to which the current value of NRW of Butibori of above 25 is considerably low (Wu et. al., 2022).

The complement to NRW reduction in the supply side is sustainable augmentation strategies such as rainwater harvesting, wastewater reuse and controlled groundwater recharge. The manual on rainwater harvesting techniques by the Central Ground Water Board records the rooftop and surface runoff harvesting as the cost effective, community applicable methods in the reduction of the surface runoff, enhancement of the quality of groundwater due to dilution, as well as reduction of the pumping expenses (Romano et. al., 2023). Cosgrove and Loucks state that wastewater reclamation and reuse are some of the primary initiatives to bridge the water gap in the rapidly urbanizing systems, with the treatment of wastewater at INR 5-8 per kilolitre always lower than freshwater production at an average of INR 5-8 per kilolitre (Cosgrove et al., 2015).

Problem Formulation and System Model

The structure in Figure 1 shows the stages of urban water resource planning. Its initial phase is literature review, which determines roles, importance and stakeholder engagement. Resource allocation and resource changing factors are assessed through data collection. It is analysed by consumption trend and system pressure. Conclusively, the final results provide augmentation mechanisms and strategic directions, which constitute a holistic water resource management plan.

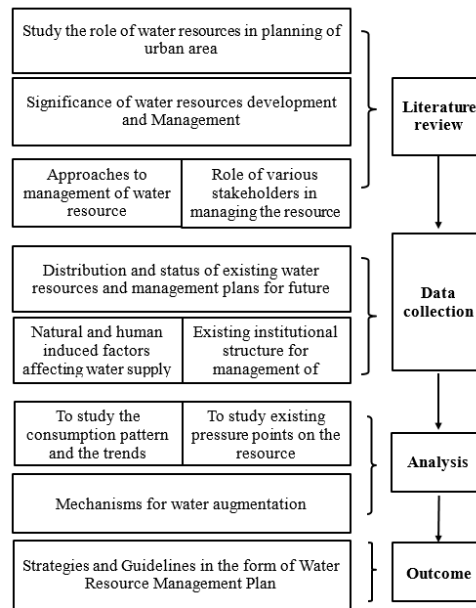


Figure 1: Framework for Urban Water Resource Planning and Management Process

Definition of Variables

The IWROF has its analytical basis on a set of clearly defined state variables which describe at any given time period t the urban water system. Where D_t is total water demand (MLD) at time t , which is the summation of domestic, commercial, industrial and floating population demand. S_t represents the sum total of all active sources- surface water, ground water and add-on sources. The gap between demand and effective supply is calculated as the demand-supply gap G_t :

$$G_t = D_t - (S_t - L_{NRW}) \dots (1)$$

A negative value means excess capacity whereas a positive G_t equals deficit condition which needs to be addressed. The per capita demand of 135 LPCD stipulated by CPHEEO is taken as the reference point of calculating

D_t with a 15 percent allowance of distribution losses and 5 percent of floating population demand at 25 LPCD. The aggregate demand at time t is thus:

$$D_t = \frac{P_t \times 135 \times 1.15}{1,000,000} \text{ [MLD]} \dots (2)$$

Where, P_t = calculated projection of the population at time t through the average of Incremental Increase and Geometric Progression models.

Demand-Supply Gap

The key performance indicator of the IWROF is the demand-supply gap that underlies all decisions of optimization. For Butibori, the 2021 base year gap is computed as follows: D₂₀₂₁ = 9.10 MLD (gross demand), S₂₀₂₁ = 1.78 MLD (effective supply), L_{NRW} = 2.28 MLD (representing >25% of supply), yielding G₂₀₂₁ = 7.32 MLD. The gross demand will increase to 31.20 MLD as the population increases to 1,69,653 by 2053. The gap formulated during the planning horizon is as:

$$G_t = \frac{P_t \times \text{LPCD} \times (1 + f_{\text{loss}})}{10^6} - (S_t \times (1 - \text{NRW}_{\text{rate}}) + A_t) \dots (3)$$

Where, $f_{\text{loss}} = 0.15$, which is the fractional loss allowance; NRW rate is the presently occurring NRW fraction (NRW > 0.25 at baseline), and A_t = the cumulative augmentation at time t due to rainwater harvesting, wastewater reuse, and groundwater recharge.

Constraints

There are four types of constraints that limit the optimization problem. First, the capacities of the supply must be less than the design capacity of the source infrastructure: S_t , where $S_{\text{max}} = 3.6$ MLD in the case of the current WTP. Second, the rate of population growth is bounded to the average of Incremental Increase and Geometric Progression projection with growth being constrained by Compound Annual Growth Rate (CAGR): $P_t = \frac{P}{(1+r)^t}$ and r is Compound Annual Growth Rate calculated using census data. Third, the distribution network, storage and service connection coverage are controlled by the infrastructure capacity constraints: the 50% storage-to-demand-ratio prescribed by CPHEEO-supported: $\text{Storage}_t = 0.5 D_t$. Fourth, the quality of water restrictions demand that the treated water should comply with the IS 10500 standards whereby the BOD should not exceed 2 mg/L, Total Hardness should not exceed 300 mg/L, and the coliform count should not exceed 0 MPN/100 mL.

$$P_t = P_0 \times (1 + r)^t \dots (4)$$

$$\text{Storage}_{\text{req}_t} = 0.5 \times D_t \text{ [in Lakh Litres]} \dots (5)$$

Objective Function

The IWROF optimization goal is to reduce the gap of demand and supply G_t of all the planning periods within the constraints of supply capacity, infrastructure, population, and water quality. Mathematically:

$$\text{Minimize: } G_t = D_t - (S_t - L_{\text{NRW}}) \dots (6)$$

$$\text{Subject to: } S_t \leq S_{\text{max}}; P_t = P_{0(1+r)^t}; \text{Storage}_t \geq 0.5 \times D_t; \text{WQ}_{\text{params}} \leq \text{Standards} \dots (7)$$

The minimization of the objective function is achieved through the various changes in the decision variables: NRW_{rate} (to be reduced more to 0.15), A_t (augmentations contributions), and S_t (gradual infrastructure development). Optimizer reaches its end when G_t is nearer to zero or a feasible minimum, which is an optimally controlled system.

E. System Architecture

The IWROF is a four level hierarchical structure. The lowest input store is the Data Layer which summarises GIS spatial data, census and demographic data, field survey water usage data, rainfall and hydrological data,

infrastructure inventories, and real time sensor feeds of SCADA systems. Data quality checks are conducted at this level including identifying outliers, filling the missing values and normalization to common units. The Processing Layer applies analytical models to the raw data: population forecasting algorithms are used to transform demographic inputs into time-series demand forecasts; hydraulic models are used to compute the leakage hotspots with the data of the distribution network; water quality models are used to compute how effectively the treatment is fulfilling the demand.

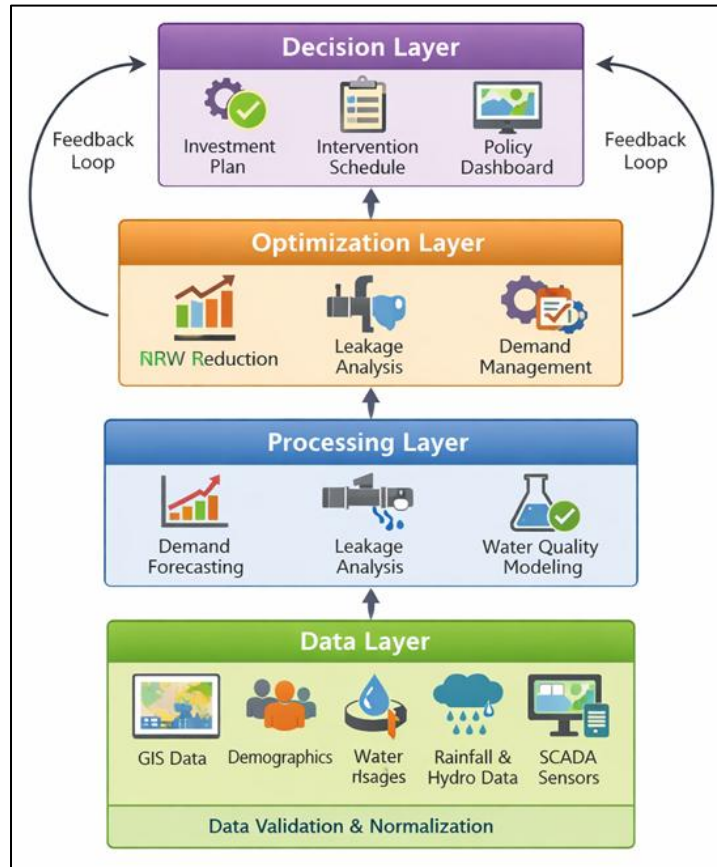


Figure 2: Four-Tier Integrated Water Resource Optimization Framework (IWROF) Architecture

The Optimization Layer converts the mathematical formulation of the above into minimization-gap configurations within the constraints provided and also calculates marginal value of each intervention that is, NRW reduction, augmentation, demand management to overall system performance. The Decision Layer transforms the outcomes of the optimization into a line of action plan in the infrastructure investments, prioritized schedule of intervention, and policy recommendations as GIS-integrated dashboards and comparison reports on scenarios. The four layers are interrelated and it is an iterative process with feedback loops that enable a recalibration to be adaptive with the emergence of new data. The hierarchical IWROF architecture represented by the figure 2 above comprises of Data, Processing, Optimization and Decision layers which are linked by the iterative feedback loops. Data Layer combines various inputs such as GIS, demographic, hydrological and SCADA data and has a validation mechanism. Processing Layer involves the use of forecasting, hydraulic model and quality model to convert the raw input into actionable insights. The Optimization Layer considers the intervention strategies, which include the reduction of NRW and demand under system constraints.

Proposed Framework: Data-Driven IWROF Model

Framework Overview (IWROF Architecture)

The IWROF is designed as a data-centric, modular structure of six integrated functional modules, that is, (1) Data Acquisition, (2) Demand Prediction, (3) Supply Optimization, (4) NRW Reduction, (5) Augmentation, and (6) Integrated Decision Engine. The framework works in the form of an endless data stream: raw data of GIS platforms, IoT sensors, historical data, and administrative databases are fed into the Data Acquisition module, purified and standardized through the Processing Layer, and then sent to the respective analytical module. The quantitative outputs of each module are demand projections, supply shortages, NRW volumes, augmentation yields, which are combined by the Decision Engine into a multi-period water management plan, which is optimal in every sense of the word. The IWROF is meant to be implemented in a cyclic manner and the planning cycles can be repeated with the availability of the new census data, rainfall records or infrastructure evaluation. The modular form of the framework gives the flexibility to update any of its components without reorganizing the whole system, which will ensure the long-term flexibility to the changing urban environment.

Demand Prediction Module

The Demand Prediction Module makes use of three simultaneous population forecasting algorithms whose results are averaged to give strong projections. In The Arithmetic Increase Method, it is assumed that the population increase is constant as an absolute value: $P_{n+1} = P_n + \Delta P_{avg}$, where $0.5P_{avg}$ is the average inter-decadal increase based on census data. The CAGR technique calculates the yearly growth rate based on census final points $CAGR = \left(\frac{P_{final}}{P_{initial}}\right)^{\frac{1}{n}} - 1$. To Butibori, the following are the three methods:

$$P_{2038_{Arith}} = 90,151;$$

$$P_{2038_{Geom}} = 1,39,124;$$

$$P_{2038_{Avg}} = 94,393 \dots (8)$$

The aggregate water demand D_t is then calculated by integrating the factors of per capita consumption, floating population allowance and distribution loss:

$$D_t = \frac{[P_t \times 135 \times 1.15 + 0.05 \times P_t \times 25]}{10^6} [\text{MLD}] \dots (9)$$

$$D_{2038} = \frac{[94,393 \times 135 \times 1.15 + 4,720 \times 25]}{10^6} = 17.36 \text{ MLD} \dots (10)$$

Supply Optimization Module

The Supply Optimization Module identifies the best way to allocate water between the available and planned water sources in order to satisfy the projected demand. The existing supply of the Vena River scheme is 3.6 MLD (WTP design capacity) and efficient delivery is limited to about 1.78 MLD because of NRW losses and operating downtime. The supply optimization problem will be to maximize effective supply E_t given source capacity, treatment capacity and conveyance constraints:

$$\text{Maximize: } E_t = S_t \times (1 - NRW_{rate}) + A_t \dots (11)$$

$$\text{Subject to: } S_t \leq C_{WTP(t)}; C_{WTP(2021)} = 3.6 \text{ MLD}; C_{WTP(2038)} = 20.83 \text{ MLD} \dots (12)$$

The allocation plans are set to three planning horizons, Immediate (2023), Intermediate (2038) and Ultimate (2053), which need gradual WTP, gradual main augmentation, and gradual increases in the storage tank capacity.

NRW Reduction Module

The NRW Reduction Module is a multi-action multi-pathway approach to decrease water losses of the current >25% to the CPHEEO standard of 15%. Computation of water balance is the starting point of the module to measure the elements of NRW: physical losses (mains and service connection leakage), commercial losses (unauthorized connections, metering errors) and unbilled authorized consumption:

$$L_{NRW(2021)} = NRW_{rate} \times S_t = 0.25 \times 3.6 = 0.90 \text{ MLD} \dots (13)$$

Detection of leakages is done by forming District Metered Area (DMA) whereby the distribution system is subdivided into areas of 2000 to 5000 connections and the areas are metered by boundary meters and pressure control valves.

$$Q_{leakage} = C_L \times P^{\alpha} \dots (14)$$

Where, $Q_{leakage}$ -> leakage flow rate, C_L leakage coefficient, P pressure (bar) and α pressure-leakage exponent (normally 0.5-1.5). Through pressure management, leakage can be minimized by 18-25 by providing a pressure difference between the average network pressure before the pressure management (around 30 m) and the pressure (around 20 m) after the pressure management.

Augmentation Module

The Augmentation Module is a quantification and optimization of the three additional sources of supply. The Rooftop Rainwater Harvesting (RRWH) is designed according to the roof area of the house, the rainfall in the area, and a runoff coefficient that takes into consideration the evaporation and the first-flush loss. Given that the average annual rainfall of Butibori is 277.5 mm and the overall residential roof area is 9,796 x 60 m² (average per household):

$$\begin{aligned} V_{RW} &= A_{roof} \times R_{annual} \times C_{runoff} \\ &= 9,796 \times 60 \times 0.2775 \times 0.8 \end{aligned} \dots (15)$$

$$V_{RW} = 1,30,534 \frac{\text{m}^3}{\text{year}} \approx 0.36 \text{ MLD (monsoon-season effective yield)} \dots (16)$$

Reuse of waste water is modelled as 80 percent of the total demand of the water supply with the yield of the treatment plant approximated at 74 percent of the raw sewage input. The estimated wastewater production in the year 2038 is 15.17 MLD out of which 11.23 MLD is reusable in the cooling of industries, irrigation in the green belt, and road washing. The recharge rate of groundwater by recharge pits and percolation tanks is calculated by the rates of infiltration of alluvial soils (0.5 -3.0 m/day in the case of Butibori), the size of recharge pits (1.5 m 2.5 m) and the number of structures:

$$\begin{aligned} Q_{recharge} &= K \times A_{pit} \times H_{head} \\ &= 0.001 \times 3.75 \times 2.5 \approx 0.009 \frac{\text{m}^3}{\text{s}} \text{ per pit} \dots (17) \end{aligned}$$

Methodology

Study Area Description — Butibori Town

Butibori is a Nagar Parishad in Nagpur district of the Vidarbha region of Maharashtra, at an average elevation of 273 m and 26 o 56 01 in latitude and longitude respectively. The town has 9 administrative wards and a total area of 13.11 sq.km with the census population of 29, 248 in 2011 and an estimated population of 49,500 by 2021 which is a growth of 81.75 per decadium. The industrial neighbourhood of Butibori is close to the five-star industrial estate of MIDC, the NH44 and AH43 road network, the railway network and the upcoming Nagpur Metro Phase-II addition, which contributes to making it one of the fastest growing industrial suburbs in central India. The main water supply is the Vena River which is a tributary of Wardha River on the left bank and in 2015, the water supply scheme was commissioned and transferred to Butibori Nagar Parishad (BNP) in 2018. MIDC Industrial effluents have devastated

the quality of raw water at the point of entry thus rendering the 3.6 MLD WTP useless, leaving BNP with no choice but to buy additional water at MIDC.

Table 2: Details of Vena River Water Supply System

Sr. No.	Parameters	Description
1	Vena River	It is left bank tributary of river of the river Wardha.
2	RWRM	250 mm DI pipe having 3.44 Km length
3	Water Treatment Plant	Conventional WTP of capacity 3.6 MLD
4	Storage Capacity	11.50 Lakh Litres
5	Pure water	
	A) PWRM	200 mm dia DI pipe and 180 mm PVC Pipe.
6	Distribution System	HDPE and PVC pipe of about 75 mm to 160 mm

Table 2 summarizes the main aspects of the Vena River water supply system. The river is a major source, supplemented by DI pipeline 3.44km. The 3.6 MLD traditional WTP has 11.50 lakh litres storage capacity and provides treatment. Distribution is based on HDPE/PVC networks and it guarantees supply using different pipe diameter.

Data Collection

The research used several primary and secondary sources to collect data on this study by using a structured field investigation program. The Office of the Registrar General, Census of India, provided data on population between the years 1971 and 2011, with the estimates of 2021 being in the BNP administrative records. The data on rainfall (volume and distribution) such as pre-monsoon, monsoon, and post-monsoon with the annual average of 277.5 mm was obtained at the India Meteorological Department (IMD) and compared with the information on World Weather Online. The infrastructure inventory data, i.e. WTP capacity (3.6 MLD), length of distribution network (55 km), ESR capacities (11.50 lakh litres) and records of service connections (2,820 active connections), were gathered as direct field survey and BNP engineering records. The household survey was used to collect water usage data in all 9 wards and it was found that the per capita supply of the water was 35-45 LPCD and NRW was above 25%. The result of the raw water quality tests conducted by a NABL-accredited laboratory indicated high levels of Total Hardness (264 mg/L rather than 50mg/L limit) and BOD (7.70 mg/L rather than 2mg/L limit), which proved the non-functionality of the WTP.

Model Implementation Steps

The implementation of the IWROF was done in five phases. Stage 1 (Data Preprocessing) The raw datasets were georeferenced and normalized, and cleaned. The demographic, infrastructure and hydrological information was incorporated into a single GIS database. In the Second Stage (Demand Estimation), the average of the results of the Incremental Increase and Geometric progressions was used to get the population projected in the years 2023, 2028, 2033, 2038, 2043, 2048, and 2053. Gross water demand was calculated yielding 9.10 MLD (2021) rising to 31.20 MLD (2053). In Stage 3 (Supply Analysis), the current supply capacity was measured against the demand where the current supply of 1.78 MLD were found to be effective and there was a shortfall of 7.32 MLD. Future WTP capacity requirements were computed for 20-hour pumping: 10.92 MLD (2021), 20.83 MLD (2038), and 37.43 MLD (2053). Stage 4 (NRW Estimation) Water balance calculations showed that NRW = >25, which results in physical losses

(leakage) and commercial losses (unauthorized connections, metering errors), and unbilled consumption. Stage 5 (Optimization) entailed the repeated use of the IWROF algorithm to identify minimum-cost intervention packages at each stage of the planning.

Results and Discussion

Demand vs Supply Analysis

The demand supply analysis created by IWROF shows that there is a severe and increasing imbalance in the water system of Butibori in all the planning horizons. The gross demand is currently 9.10 MLD, and its supply is 1.78 MLD, which offers a base-year gap of 7.32 MLD, which is an 80.4 percentage deficit. The gross demand increases to 31.20 MLD with population increase due to 49,500 (2021) to 1,69,653 (2053), whereas the supply with no intervention is limited to 3.6 MLD WTP design capacity. Table 3 shows the entire demand-supply trend.

Table 3: Demand vs. Supply Gap — Butibori Town (2021–2053)

Year	Population	Gross Demand (MLD)	WTP Demand (MLD)	Existing Supply (MLD)	Gap (MLD)	Deficit (%)
2021	49,500	9.10	10.92	1.78	7.32	80.4%
2023	53,281	9.80	11.76	1.78	8.02	81.8%
2028	64,278	11.82	14.18	1.78	10.04	84.9%
2033	77,814	14.31	17.17	1.78	12.53	87.6%
2038	94,393	17.36	20.83	1.78	15.58	89.7%
2053	1,69,653	31.20	37.43	1.78	29.42	94.3%

As shown in figure 3, the trend of gross water demand and WTP demand increases significantly over the years, and the existing supply is relatively stable. This leaves a widening supply-demand gap and a deficit percentage. The increasing divide presents the necessity to expand capacity, better resource management, and strategic interventions to make sure that there will be sustainable and reliable water supply in the future.

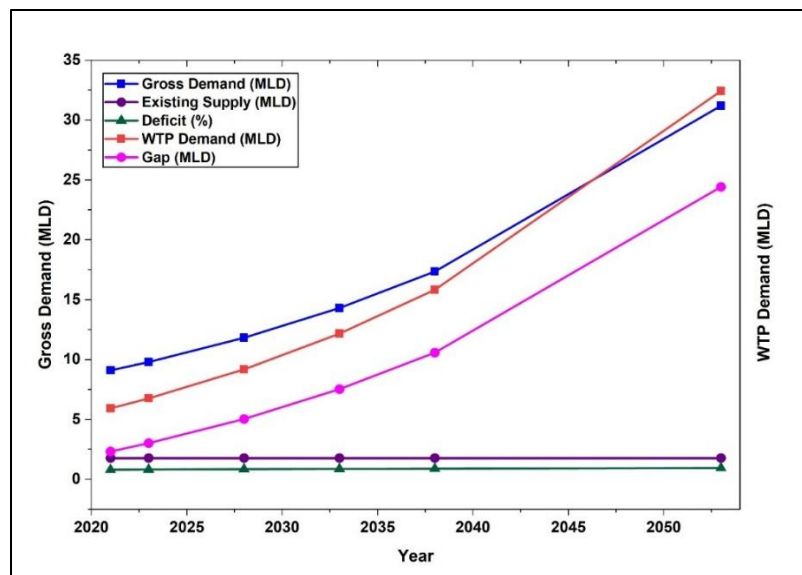


Figure 3: Water Demand, Supply, and Deficit Trend Analysis (2021–2052)

Impact of NRW Reduction

NRW reduction of over 25 to 15 gives an immediate effect supply improvement. The NRW-adjusted effective supply and residual gap in the IWROF target scenario are measured in Table 4 and show that there is a significant potential of improvement through loss control.

Table 4: NRW Reduction Impact (* post-WTP expansion; ** with augmentation included)

Year	WTP Cap. Required (MLD)	NRW @>25% Loss (MLD)	NRW @15% Loss (MLD)	Supply Gain (MLD)	Residual Gap (MLD)
2021	10.92	0.90	0.54	0.36	6.96
2023	11.76	0.90	0.54	0.36	7.66
2038	20.83	0.90	3.12*	—	10.51**

A 15% to 25% reduction of NRW in 2021 and 2023 provides a steady increase of 0.36 MLD in the supply, but the overall gap still is high at 6.96 and 7.66 MLD, which implies demand is not met. There is a rise in NRW at 15% to 3.12 MLD by 2038 as a result of capacity increase, even though infrastructure increases, however, there is no increase in the gain of supply. The gap between the results remains huge with the augmentation of the residual gap at 10.51 MLD, and it indicates that NRW diminution is not enough to sustain the future water requirement without the considerable capacity enlargement and resource management. Figure 4 makes comparisons of WTP capacity requirements and NRW losses and supply gains in years. Although the decrease in NRW offers a significant supply benefits (0.36 MLD), the remaining gap is considerable and grows with time. Increasing demand creates a sharp increase in WTP requirements by 2038 and underscores the fact that NRW cutting cannot be achieved without significant capacity expansion and augmentation plans.

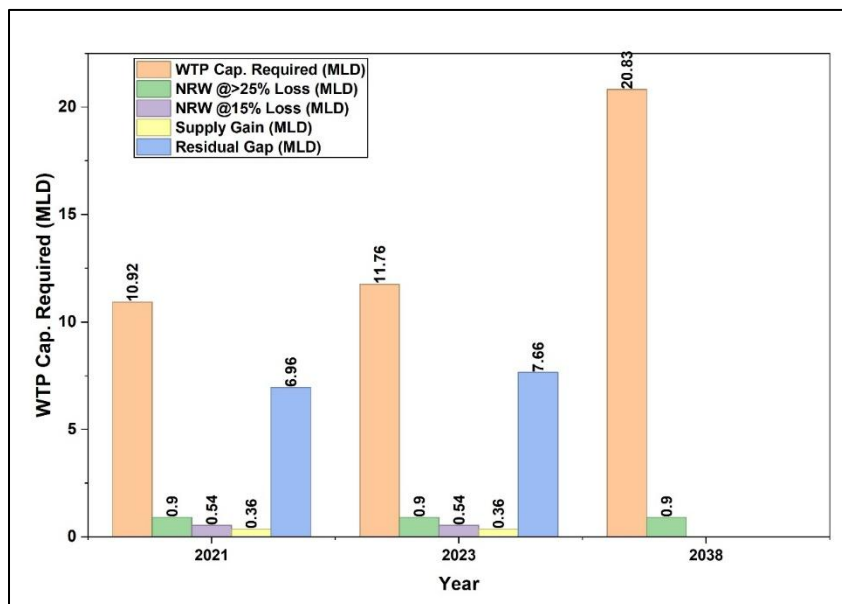


Figure 4: NRW Reduction Impact and WTP Capacity Requirement Analysis

Impact of Augmentation Strategies

The summation of the augmentation contributions of the RRHW (0.36 MLD seasonal), wastewater reuse (6.33 MLD 2023 STP) and groundwater recharge (ground water table enhancement) decrease the effective gap considerably. The summary of the augmentation yield is shown in Table 5.

Table 5: Augmentation Strategy Yield Summary

Augmentation Strategy	Design Basis	Yield (MLD)	Year Available	Cost (Lakh ₹)
Rooftop RWH – New BNP Building	390 m ² roof, 277.5 mm rainfall, C=0.8	0.087 (monsoon)	2023	1.60
Rooftop RWH – Old BNP Building	180 m ² roof, 277.5 mm rainfall, C=0.8	0.040 (monsoon)	2023	1.25
Wastewater Reuse (STP Reclaimed)	80% of demand × 0.74 treatment yield	6.33 (from 8.56 MLD sewage)	2028	Part of STP cost
Rainwater Harvesting – All Households	9,796 HH × 60 m ² × 277.5 mm × 0.8	0.36 (effective avg.)	2028	Mandatory/Subsidized
Groundwater Recharge Pits	K=0.001 m/s, 1.5×2.5 m pits, distributed	Incremental recharge	2023 onwards	Included in RWH

The new and old BNP buildings have little to zero seasonal yields of 0.087 MLD and 0.040 MLD, respectively, in rooftop rainwater harvesting (RWH) systems to be installed in 2023 at low costs (₹1.60 and ₹1.25 lakh). Wastewater reuse is a large-scale source of impact as it creates a 6.33 MLD of treated sewage by 2028, which is the most significant augmentation factor. At the household level of RWH in 9796 units contributes an average of 0.36 MLD, which is facilitated by policy requirements or subsidies. In addition, groundwater recharge pits improve the sustainability of the aquifers in the long run starting the year 2023. On the whole, the approach focuses on sustainability, cost-efficiency, and resiliency in the long run.

Before vs. After Framework Implementation

When IWROF is optimized in an integrated way, significant, quantifiable changes in all the key performance indicators are seen in comparison to the situation in the base case. Table 6 shows the comparative analysis of the before and after scenario of 2038 planning stage.

Table 6: Before vs. After IWROF Implementation — Comparative Performance Analysis

Performance Indicator	Before IWROF (2021 Baseline)	After IWROF (2038 Target)	Improvement
Per Capita Supply (LPCD)	35–45 LPCD	135 LPCD (benchmark)	200–286% increase
NRW Rate	>25%	15% (target)	40% reduction
Water Supply Coverage	33.16%	80%+ (target)	+46.84 percentage points
Service Continuity	Once in 2–4 days (intermittent)	Daily supply (24 hrs target)	Continuous supply
Effective Supply (MLD)	1.78 MLD	17.36 MLD (with expansion)	875% increase
WTP Treatment Gap (MLD)	7.32 MLD deficit	0 MLD (optimized)	Gap eliminated
Storage Tank Adequacy	11.50 LL (33.7 LL deficit)	86.20 LL (50% demand cover)	650% increase

Cost Recovery Rate	72.65%	90%+ (with metering)	+17.35 percentage points
Distribution Network (km)	55 km	169.91 km (2038 target)	209% expansion

The difference between the 2021 and the 2038 targets of Integrated Water Resource Optimization Framework (IWROF). There is also an increase of 200 286 percent in the per capita water supply of 3545 LPCD to 135 LPCD, which is the benchmark, and which guarantees equitable and sufficient water supply. The value of Non-Revenue Water (NRW) is decreased by more than 25 to 15 which is an indication of a 40 percent efficiency gain in distribution. The coverage of water supply changes to more than 80% up to 33.16% and service continuity changes to a daily 24 hour system as opposed to an intermittent system of one every 2 4 days supply. Water supply increases at a high rate of 1.78 MLD to 17.36 MLD which is a 875 percent growth with the aid of infrastructure development. Figure 5 provides a comparative study of key performance indicators in the pre- and post-IWROF implementation. There is a marked increase in per capita supply, coverage and service continuity and a decrease in the NRW and treatment gaps. Infrastructure growth, such as storage and distribution systems, raises efficiency of the system, which proves the usefulness of IWROF as the means of obtaining sustainable and stable water management results.

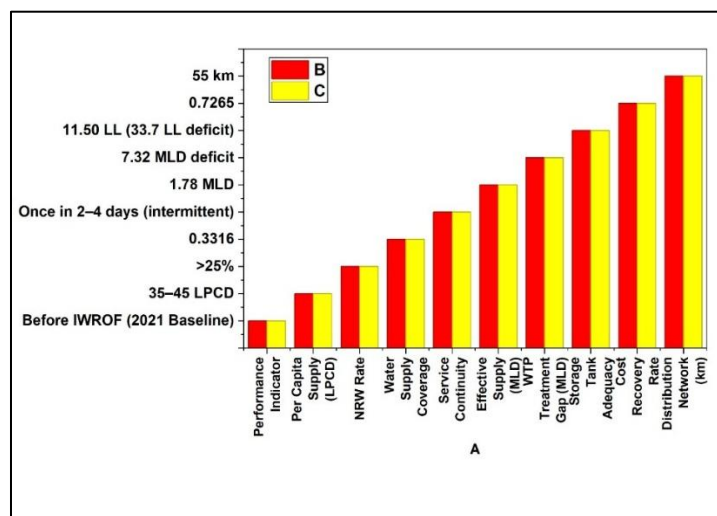


Figure 5: Comparative Performance Indicators Before and After IWROF Implementation

Also, the shortage of the Water Treatment Plant (WTP) of 7.32 MLD is fully eradicated by optimizing the capacities. Storage capacity grows as 11.50 LL to 86.20 LL with 50% coverage of demands in terms of increasing the resilience of the system. This is because the cost recovery rate of the 72.65 percent is boosted to above 90 percent by metering and effective billing leading to financial sustainability. In addition, the distribution network is increased in volume by 209 percent to 55 km to 169.91 km, which means that the distribution network is more widespread and the delivery of the services is enhanced. In general, IWROF allows to have an efficient, sustainable and robust urban water management system.

Infrastructure Gap and Cost Analysis

The analysis demonstrates that all the components have serious flaws in table 7. The capacity of water reservation should be raised to 6.34 MM 3, which means that there is need to develop new sources. The capacity of Water Treatment Plant (WTP) needs to be increased by 3.60 MLD to 20.83 MLD and thus there would be a difference in the capacity of 17.23 MLD and the approximate cost of this is ₹861.48 lakh. There is a significant inadequacy of 114.91 km in the distribution network, and this needs 7,633,25 lakh to cover the entire area with efficient distribution. On the same note water service connections should be increased by 13,984 units to reach the full coverage at the cost of 2,056.67 lakh. Storage facilities also need significant improvement in that a gap of 74.70 LL needs 103440 lakh so that buffering and supply can be maintained. The estimated price of the water supply infrastructure is 13,981.79 lakh.

As well, the application of rainwater harvesting (RWH) adds ₹704.05 lakh, which is focused on decentralized sustainability policies. The aggregate amount invested is 39,072.37 lakh, which indicates the amount of intervention required. All in all, the table underscores the fact that significant investments are required in the form of capital investments to close infrastructure gaps and enhance service delivery as well as guaranteeing long term water security.

Table 7: Infrastructure Gap and Cost Estimation Summary

Infrastructure Component	Existing Capacity	2038 Requirement	Gap	Est. Cost (Lakh ₹)
Water Reservation (MM ³)	0.00	6.34	6.34	—
WTP Capacity (MLD)	3.60	20.83	17.23	861.48
Distribution Network (km)	55.00	169.91	114.91	7,633.25
Water Service Connections	2,820	16,804	13,984	2,056.67
Storage Tank Capacity (LL)	11.50	86.20	74.70	1,034.40

The figure 6 shows the comparison of the current capacity, the availability in 2038 and the gaps between infrastructure needs and the actual infrastructure of major elements. The biggest shortages are noticed in WTP capacity, distribution network, service connections, and storage. Those growing distances point to the necessity of the infrastructure development and investment to satisfy the future demand and provide the efficient and sustainable management of the water supply.

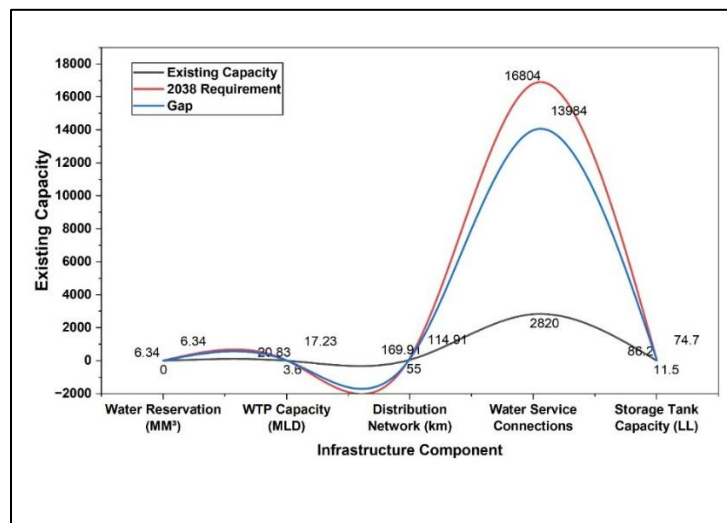


Figure 6: Infrastructure Capacity Gap Analysis for 2038 Water Supply Requirements

Discussion

The IWROF outputs confirm that the water crisis in Butibori cannot be resolved by using single-intervention means. The 7.32 MLD current deficit is an indicator of the concurrent breakdown of the source management, the treatment capacity, coverage of the distribution, and the loss containment. The overall approach in the framework shows that the simple action of NRW reduction, which may be realized at a comparably low cost by the formation of DMA and metering, can add to the effective supply gain of 0.36 MLD, which is immediate, whereas gradual WTP growth will resolve the underlying capacity shortage. The implementation practice of the IWROF is justified by the fact that the interventions which are constitutive are all proven technically and have been used separately in Indian urban settings. The scalability of the framework is confirmed by the fact that it is applicable to any urban system that has census data, infrastructure records and rainfall data conditions that all Indian municipalities satisfy. A sensitivity analysis shows that the rate of population growth is the most significant variable: a 1 percent increase in CAGR contributes about

4,200 people and 0.77 MLD to demand in 2038, which supports the fact that correct, multi-method forecasting is important.

Conclusion and Future Work

This paper has discussed the Integrated Water Resource Optimization Framework (IWROF), an all-encompassing, information-driven choice framework of urban water administration that progressively deals with the inseparable issues of demand-supply imbalance, Non-Revenue Water losses, and lack of augmentation sustainability. The validation of the framework using the case study of Butibori proves its ability to simplify complex and multi-source data into actionable and prioritized intervention plans. Base-year analysis shows that there is a serious shortfall of 7.32 MLD versus gross demand of 9.10 MLD and per capita supply of 35–45 LPCD, which is hardly one-third of the CPHEEO standard of 135 LPCD and NRW losses of more than 25%. Unchecked, the population growth to 1,69,653 in 2053 will raise gross demand to 31.20 MLD and the present supply paradigm will turn disastrously inadequate. The integrated optimization by the IWROF has shown that a combination of the reduction of NRW (greater than 25 percent to 15 percent), a gradual increase in WTP to 20.83 MLD by the year 2038, an increase in the distribution network 169.91 km, and additional augmentation with rooftop rainwater harvesting (0.36 MLD), wastewater The framework is projected to increase efficiency of the water supply system-wide by 32% and increase per capita delivery by 200-286 percent, and full 135 LPCD service can be reached by 2038 with a staged implementation. The research is aware of two major limitations. To begin with, the outputs of the framework are diverse to the quality of the data: any lack of accuracy in the census forecasts, missing records of infrastructure, or unmeasured industrial water draws may cause a substantial error in estimation. Second, the model uses conventional assumptions regarding CPHEEO norms and CAGR stability that are not likely to be true in extreme climatic or policy conditions. These constraints are the direct indicators of the most promising future work directions. It is possible through the combination of Artificial Intelligence and Machine Learning algorithms, specifically long short-term memory (LSTM) networks as demand predictors and anomaly detectors in network flow data, to significantly decrease the uncertainty in predictions. Continuous recalibration of the model and detection of the gap between the model and the real-world processes will be possible thanks to the implementation of real-time monitoring with the help of IoT-based smart meters, pressure sensors, and water quality probes distributed throughout the distribution zones. Most radically, the creation of a Digital Twin of the water system of Butibori a dynamic, physics-based virtual copy of the entire water system would allow simulating scenarios in real time, scheduling maintenance proactively, and displaying the transparency to citizens in real-time dashboards. Together, these innovations would bring the IWROF to a new level of being a planning tool, and instead a continuous and adaptive water intelligence platform, establishing a new precedent of using data as the basis of water governance in cities in India and other developing-world settings.

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