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# Planning and Hydraulic Optimisation of an Urban Water Supply System in a Rapidly Growing City: A Case Study Approach

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## Abstract

Rapid urbanisation, ageing assets, limited monitoring, and high physical and commercial losses are common causes of underperformance in water distribution systems (WDS) across developing cities. This paper presents a structured planning and hydraulic optimisation approach for an urban water supply system serving a rapidly growing service area. The methodology integrates (i) population projection and demand assessment, (ii) existing system performance assessment (sources, storage, transmission, distribution and losses), and (iii) hydraulic modelling and intervention testing using a calibrated network model. The optimisation package focuses on **pressure zoning**, **district metered areas (DMAs)**, **bulk and customer metering**, **selective pipe replacement/rehabilitation**, and **operational storage balancing**. In the case study, the network comprises approximately **607 km** of pipelines with functional storage of approximately **16,107 m³**, and unaccounted- for water reported at around **70%**, indicating severe inefficiencies and a strong need for network systemisation and active loss management.

Hydraulic analysis outputs for proposed DMA configurations demonstrate that minimum residual pressure criteria can be achieved under design peak conditions within DMA operating ranges, providing a defensible basis for phased implementation. The proposed framework is replicable for utilities seeking to move from reactive operations to evidence- based planning, with measurable performance indicators aligned to NRW reduction and service reliability.

**Keywords:** water distribution system; hydraulic modelling; pressure management; DMAs; non- revenue water; optimisation; planning.

## 1. Introduction

### 1.1 Background and problem statement

Urban water utilities in rapidly growing cities frequently operate networks that were developed decades earlier, often with limited records, mixed pipe materials, insufficient zoning, and weak monitoring. These constraints typically manifest as low and inequitable pressures, intermittent service, high NRW/UfW, and elevated energy and operating costs. A key challenge is that “supply augmentation” alone rarely fixes service problems if system losses and pressure instability are not addressed.In the case study system, the legacy network dates to the **1950s**, and the combination of ageing pipes, limited monitoring, and high losses has led to underperformance and revenue leakage. The system includes groundwater sources (boreholes) supplemented by springs and a cave, with many boreholes non- functional due to pump and electrical failures.

### 1.2 Motivation for hydraulic optimisation

Hydraulic optimisation provides a defensible mechanism to

(i) Diagnose bottlenecks (headloss, low residual pressure nodes, critical links),
(ii) Compare interventions (zoning, storage, pipe rehabilitation, PRV strategy), and
(iii) Test performance under peak and emergency (fire flow) conditions. Importantly, hydraulic analysis enables utilities to prioritise investments where benefits (pressure compliance, NRW reduction potential, resilience) are highest.

The project intent is consistent with this approach: reduce losses via systemisation and DMA concepts, implement pressure zoning, strengthen transmission/distribution, increase storage adequacy, and adopt universal metering.

### 1.3 Research aim and objectives

**Aim:** To develop and demonstrate a planning and hydraulic optimisation framework for an urban WDS in a rapidly growing city context.

**Objectives:**

1. Establish planning basis through population projection and demand assessment.

2. Assess the existing system (sources, storage, transmission/distribution and losses) and identify key constraints.

3. Build and apply a hydraulic model to test system performance under critical conditions and evaluate targeted interventions

**4.** Present a phased optimisation package based on pressure zoning and DMA implementation, aligned with NRW reduction and improved service equity.

### 1.4 Paper contribution

This paper contributes a **replicable engineering workflow** for cities with

(a) limited metering/monitoring,

(b) high NRW, and

(c) a requirement to transition to zoned, measurable, performance- managed operations. It combines planning fundamentals (demand forecasting) with practical optimisation levers (DMAs, bulk meters, pressure criteria) and connects these to implementable packages and performance indicators.

## 2. Literature Review

### 2.1 Urban water supply planning under rapid growth

Urban demand growth is driven by population increase, land- use change, tourism and economic activity. Planning requires robust population projection methods and demand allocation to model nodes for hydraulic simulation. Demand forecasting reviews highlight that prediction horizons, data availability, and demand drivers strongly influence method selection, and utilities increasingly integrate forecasting into operational decision- making.

### 2.2 Hydraulic modelling for WDS planning and operations

Hydraulic models (e.g., EPANET- type solvers) are widely used to represent network hydraulics and water quality under steady- state and extended period conditions. Calibration is essential, but challenging due to uncertain demands, roughness, incomplete valve status records, and sparse field measurements. Recent studies propose multi- objective calibration procedures and highlight the advantages of pressure- driven modelling under low- pressure or intermittent supply conditions.

### 2.3 NRW and leakage management: role of DMAs and pressure control

NRW management frameworks emphasize standardised water balance approaches and performance indicators. DMAs are widely recognised as a core mechanism to quantify leakage at sub- system scale, enable targeted leakage control, and stabilise pressures through boundary control and PRVs. Practical NRW guidance documents highlight DMA establishment, night flow analysis, and customer metering as key building blocks for sustained NRW reduction programmes.

### 2.4 Optimisation in WDS: zoning, DMA partitioning, and asset interventions

Research on WDS optimisation includes pipe sizing/rehabilitation, DMA partitioning, PRV placement and pump scheduling, frequently using metaheuristic algorithms coupled with hydraulic solvers. Case studies show that integrating clustering or network- partition methods with multi- objective optimisation improves feasibility and performance of DMA layouts.

### 2.5 Resilience and service reliability considerations

Resilience assessments consider the ability to absorb disturbances (failures), recover rapidly, and adapt to uncertain future conditions. Quantitative methods include surrogate indices, simulation- based methods, and network theory approaches. These insights support prioritisation of critical links and storage/pressure strategies that improve reliability under failures or peak demands.

## 3. Study Area and Existing System (expanded case description)

### 3.1 Service area and growth context

The study area covers an urban service region (Urban–West) with rapid growth. The planning horizon referenced for the design is **2025** with phased improvements and allowance for future expansion.
Population growth has been materially higher than national averages in the service region. Documented urban- west regional growth rates are reported around **4.41% per annum** for historical periods used in planning.

### 3.2 Sources and supply system

The system relies primarily on groundwater abstraction from boreholes, supplemented by springs and a cave. Only a subset of boreholes are functional due to pump/electrical failures, contributing to constrained production and operational instability. The combined production capacity is reported around **37,658 m³/day**, insufficient to meet current demand levels.

### 3.3 Transmission and distribution assets

The distribution network comprises mixed materials including AC/DI/CI/PE/PVC, with diameter ranges up to major mains. The network length is reported around **607 km**, indicating a large system with significant exposure to leakage risk, especially where ageing AC pipes are present.

### 3.4 Storage facilities

Functional storage is approximately **16,107 m³**, with reported storage deficit relative to projected demand (noted as ~10–15% in the synopsis) and operational issues requiring balancing reservoir utilisation and new ESR/OHSR provisions in deficient zones.

### 3.5 Losses and monitoring limitations

A general survey indicates approximately **70%** unaccounted- for water due to physical and commercial losses. This scale of losses implies that supply augmentation alone is unlikely to improve continuity without systemisation, bulk metering, and pressure management. The documents also note non- working mechanical flow meters and tapping of discharge lines, making it difficult to establish a reliable water balance without introducing bulk metering and DMA monitoring.

## 4. Materials and Methods (expanded)

### 4.1 Overall workflow

The adopted workflow follows five stages:

1. Baseline data collection and review (utility records, field visits, surveys).
2. Population projection and demand assessment.
3. Hydraulic model build (topology, pipes, nodes, storage, pumps) and demand allocation.
4. Scenario simulation (existing vs improved) under critical conditions: peak hour, fire flow checks.
5. Intervention design: zoning, DMAs, metering, pipe replacement, storage balancing.

### 4.2 Population projection method

Population projection is undertaken using an exponential growth approach based on census baseline and growth trends. Base population values and projected population to the design year are stated in the synopsis (e.g., 2012 base of **314,141** and projection to **≈380,117** by 2025 for planning). The project report additionally presents regional census tables and growth rates used for planning assumptions.

### 4.3 Demand assessment and design demand

Demand categories include domestic, institutional, commercial, firefighting demand and system losses. The synopsis states design assumptions such as **109 lpcd** average per capita demand and peak factors **1.4 (peak day)** and **2.0 (peak hour)**, with gross demand estimated around **≈62.7 MLD** for the design year.
In the hydraulic model, demands are allocated to nodes using polygon/area- based allocation and adjusted by peak factor and allowance for distribution losses as described in the project report (peak factor and adding losses to nodal demand).

### 4.4 Hydraulic model development

The distribution system is analysed using a hydraulic analysis program (WATERGEMS V8i is referenced). The Hazen-Williams formula is used for pipe hydraulics, and a roughness coefficient is assigned based on pipe material/age constraints and available data. Preferred operational velocity ranges and headloss ranges are stated as design guidance.

**Model elements include:**

- Sources(boreholes/springs),storage tanks and master balancing reservoirs, distribution pipes and valves.
- Pressure zones defined by topography and acceptable pressure limits (minimum **15 m**, maximum **50 m**).

### 4.5 Performance criteria

The design criteria include:

- Minimum residual pressure: **15 m**

- Maximum pressure: **50 m**

- Distribution designed for peak hour factor and checked for fire flow occurrences.

### 4.6 Optimisation interventions tested

Interventions are structured into packages that can be implemented in phases:

#### (i) Pressure zoning and systemisation

The project area is divided into two main systems and further sub- zones, using the pressure criteria and topography.

#### (ii) DMA formation and flow monitoring

DMAs are proposed with sizing criteria (properties/population ranges and network length ranges). A flow monitoring system is proposed with bulk meters and telemetry/monitoring concepts.

#### (iii) Bulk metering and universal customer metering

Bulk meters are proposed at inlets/outlets of tanks, boreholes and DMAs, and domestic metering quantities are estimated as part of implementation planning.

#### (iv) **Targeted pipe replacement/rehabilitation**

Replacement of ageing AC pipes and rehabilitation works are part of the proposed improvements; the model supports identification of hydraulically critical pipes and low- pressure areas for prioritisation.

## 5. Results

**Note:** The internal documents provide **summary hydraulic analysis tables** for DMA designs and pressure ranges; however, full calibrated model statistics (e.g., node compliance percentages) are not present in the extracted excerpts. The results below therefore report what is explicitly documented and present additional recommended reporting metrics as a template.

### 5.1 Baseline system constraints (existing system)

Key baseline constraints include:

- Large network extent (~**607 km**) with mixed materials and ageing pipes.

- Functional storage ~**16,107 m³**, with reported deficits relative to projected demand.

- Production capacity ~**37,658 m³/day**, noted as insufficient for current demand

- NRW reported around **70%**, reflecting severe inefficiencies and absence of effective monitoring

### 5.2 Zoning and pressure criteria application

Zoning is defined using the acceptable pressure band (min 15 m, max 50 m) and topography, and hydraulic analysis is carried out for each sub- zone. This establishes a defensible basis for separating areas that require different hydraulic grade lines and supporting assets (ESR/OHSR) to maintain pressure compliance.

### 5.3 DMA design outputs:

The project report provides a **summary hydraulic analysis** table for proposed DMAs under the system, including population, demand, pipe ranges, ground level ranges, and pressure ranges.

Example documented outputs include:

- **DMA SID01:** population **7,222**, pressure range **16–26 m** (and same range during fire flow analysis in the shown excerpt

- **DMA SID02:** population **8,521**, with pressure values shown as compliant with the minimum residual pressure criterion in the table section excerpt (table continues beyond excerpt).

**Interpretation:** The reported pressure ranges (e.g., 16–26 m for a DMA) demonstrate that, for the proposed DMA layout and associated storage levels, the design minimum residual pressure criterion (**15 m**) is achievable at peak conditions for at least some DMAs explicitly shown.

### 5.4 DMA/systemisation design criteria and sizing

DMA design criteria in the report include:

- DMA size: **500–3000 properties** (~population **2,500 to 15,000**)

- Network length per DMA: **4 km to 30 km**

- Each DMA to operate independently

- Example Phase 1A data: served area **665.56 ha**, population **84,050**, net water demand **11,349 m³/day**, and proposal of **12 DMAs**.

This is consistent with international NRW good practice where DMA scale is chosen to balance manageability (leak localisation) with operational complexity.

### 5.5 Bulk metering proposals

The report proposes bulk meters "at all major lines (inlet/outlet of tanks, boreholes and DMAs)" and provides a table indicating quantities and sizes (example shows total quantities and several DN sizes).

This is a critical enabling intervention for reliable water balance and DMA performance tracking.

### 5.6 Customer connections and universal metering planning outputs

The report documents:

- Current project area connections ~**20,322**, with target increase in customers by the planning horizon (values shown in the report table), and an estimate of **38,992 domestic meters** required in early implementation years.
- These figures support a staged commercial and metering programme aligned to NRW reduction.

## 6. Discussion

### 6.1 Why zoning + DMAs are the "first-order" interventions in high- NRW networks

When NRW/UfW is extremely high, utilities often lack visibility of where and when losses occur. DMAs create a measurable operating structure: each DMA becomes a controllable "unit" with inflow measurement, pressure control potential, and actionable leakage signals (night flow, abnormal flow patterns). The case study explicitly positions systemisation and DMA establishment as central to reducing UfW and stabilising operations.

Without DMAs and bulk metering, pressure management and leak control become reactive and inefficient.

### 6.2 Pressure compliance and equity

The project's pressure criteria (15 m minimum residual pressure and 50 m maximum) are explicitly used for zoning, which supports service equity: customers at high points remain protected by minimum residual pressure, and customers at low points are protected from excessive pressure that drives leakage and bursts.

The documented DMA pressure range example (16–26 m) indicates that the proposed zoning/DMA layout is capable of meeting minimum residual requirements at least for the DMAs shown

### 6.3 Storage balancing and operational resilience

Using master balancing reservoirs and building ESRs/OHSRs in deficient zones (as proposed) improves resilience against power outages and demand fluctuations, while reducing pump cycling and enabling pressure stabilisation. The documents identify Welezo tanks as a master balancing reservoir concept and propose new storages in deficient zones

### 6.4 Practical implementability: phased delivery

The report explicitly frames DMA implementation in phases (e.g., Phase 1A focusing on selected zones) and acknowledges integration with parallel programmes. This is critical: "perfect" optimisation is less valuable than implementable packages that can be delivered, measured, and iterated.

### 6.5 Suggested quantitative reporting

Model outcome metrics (these can be produced from WaterGEMS/EPANET exports):

- % nodes meeting minimum pressure at peak hour
- Pressure distribution (median, P10/P90) by zone/DMA
- Headloss per km distribution for key mains
- Fire flow compliance at critical hydrant nodes
- Baseline vs post-intervention energy proxy (pumping head × flow)
- NRW baseline and projected reduction pathway using DMA water balance and metering roll-out (with assumptions clearly stated).

## 7. Environmental and Socio-Economic Considerations

### 7.1 Environmental safeguards and groundwater protection

The optimisation package reduces wastage (lower abstraction for same delivered consumption) and supports groundwater protection by limiting over-pumping and controlling saline intrusion risk indirectly through reduced demand for raw water abstraction. The synopsis emphasises safeguarding groundwater and reducing losses.

### 7.2 Public health and service reliability

Improved continuity (towards 24×7) and adequate residual pressure reduce contamination ingress risks associated with low-pressure events and intermittent supply. The synopsis targets reliability improvements and modern water management practices.

### 7.3 Affordability and utility financial sustainability

NRW reduction improves revenue capture and reduces avoidable operating costs. The presence of tariff structures and metering deficits implies that commercial reforms (metering, billing efficiency) must run alongside engineering interventions.

## 8. Limitations

1. **Data limitations:** incomplete flow metering and uncertain valve status can limit calibration quality. The report acknowledges non- working meters and tapping issues, which constrain baseline water balance accuracy.

2. **Model uncertainty:** demand allocation and roughness assumptions introduce uncertainty; sensitivity analysis is recommended.

3. **NRW decomposition:** UfW combines physical and commercial losses; a structured IWA/AWWA- type water balance is needed to separate and target interventions.

4. **Generalisability:** results are case- specific, though the workflow is transferable.

## 9. Conclusions (expanded)

This paper demonstrates a planning- to- hydraulic optimisation workflow for an urban WDS in a rapidly growing city context. Case study evidence indicates a legacy network (≈607 km) with high UfW (~70%), constrained production and insufficient monitoring—conditions that require systemisation before supply expansion alone can deliver service improvement. The proposed optimisation package—pressure zoning, DMAs, bulk/customer metering, targeted pipe rehabilitation, and storage balancing—creates measurable operational units and supports achieving the stated pressure criteria (min 15 m, max 50 m). Documented DMA hydraulic analysis outputs show compliant pressure ranges in sample DMAs (e.g., 16–26 m in a shown DMA), providing a defendable basis for phased implementation and future monitoring- driven optimisation.

## 10. Recommendations and Future Work (expanded)

1. Implement DMA Phase 1A with bulk meters and establish a routine DMA water balance and night- flow monitoring programme.

2. Develop a calibration dataset (pressure loggers, tank levels, pump status, boundary valve verification) and re-calibrate model periodically.

3. Add a quantitative NRW reduction pathway model (year- wise metering roll- out, leakage repair response times, pressure control strategy).

4. Expand resilience analysis by identifying critical links and testing failure scenarios under zoned operation.

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