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Automated Reverse Osmosis Permeate Blending and Pressure-Dependent Pump Optimization in Topographically Complex Water Distribution Networks

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Research Article

Keywords:

Posted Date: September 14th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10755687/v1

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Abstract

In topographically complex water distribution networks (WDNs), maintaining uniform water quality and optimal hydraulic pressures presents a significant operational challenge. This paper proposes an integrated algorithmic framework combining automated Reverse Osmosis (RO) permeate blending with pressure-dependent Variable Speed Drive (VSD) pump optimization. By dynamically adjusting the blending ratio of RO permeate and raw groundwater using real-time Electrical Conductivity (EC) feedback, the target mineralization and pH balance are maintained without unnecessary remineralization overhead. Concurrently, hydraulic control algorithms optimize pump operation across distinct elevation zones, mitigating over-pressurization and reducing specific energy consumption by up to 22.4%. The model was validated using simulated IoT sensor telemetry based on topographical characteristics typical of Eastern Georgian water supply systems.

1. Introduction

Water distribution networks serving regions with highly variable topography often encounter coupled hydraulic and water quality management challenges. Elevated zones require significant pumping heads to maintain minimum operational residual pressures, whereas low-elevation zones suffer from excess pressure, increased background leakage, and higher pipe burst frequencies. Simultaneously, reliance on Reverse Osmosis (RO) desalination or high-grade filtration processes necessitates mineral stabilization to deliver non-corrosive, aesthetically pleasing, and potable water.

Traditional static RO permeate blending systems operate on fixed bypass ratios, which fail to compensate for fluctuations in feed water salinity, pressure drops across membrane modules, or dynamic hydraulic demand patterns. This work introduces an automated, real-time closed-loop control system that dynamically integrates permeate-raw water ratio modulation with dynamic VSD pump speed selection based on continuous Wireless Sensor Network (WSN) telemetry.

2. System Architecture & Methodology

2.1 Automated Permeate Blending Control

The water treatment architecture utilizes a dynamic bypass stream diverted from feed groundwater prior to high-pressure RO membrane units. The target water blend is defined by a target Electrical Conductivity (EC_target) and target Total Dissolved Solids (TDS_target). The volumetric blending ratio α = Q_permeate / Q_total is modulated via a motorized proportional control valve governed by a Proportional-Integral-Derivative (PID) feedback loop:

$$\alpha(t) = K_p \cdot e(t) + K_i \int e(\tau)\, d\tau + K_d \cdot \frac{de(t)}{dt}$$

Where e(t) = EC_target − EC_measured(t). Real-time telemetry ensures that water quality parameters remain tightly bounded within health and aesthetic standards, minimizing chemical re-mineralization

requirements.

2.2 Pressure-Dependent Hydraulics and Pump Optimization

In topographically complex terrain, system head constraints are elevation-dependent. The hydraulic optimization algorithm continuously reads pressure transducer data located at key Critical Pressure Nodes (CPNs) within high, intermediate, and low hydraulic zones. The pump speed ratio N / N_0 is iteratively adjusted to satisfy minimum pressure thresholds P_min at all nodes while minimizing total power consumption W_pump:

Minimizing $W_{pump} = \Sigma [(\gamma \cdot Q_i \cdot H_i) / \eta_i(N_i)]$

Subject to: $P_j \geq P_{min}, \forall j \in Nodes$

3. Performance Evaluation & Results

The proposed framework was tested under simulated operational scenarios representing multi-zone hydraulic distribution networks. Table 1 outlines key system parameter boundaries and operational benchmarks observed during trial simulations.

Table 1
Operational parameters and energy optimization benchmarks across elevation zones

Zone Elevation	Target Pressure (kPa)	Baseline Energy (kWh/m³)	Optimized Energy (kWh/m³)
Low Zone (0–40 m)	250–300	0.48	0.36
Mid Zone (40–90 m)	350–400	0.72	0.58
High Zone (90–150 m)	500–550	1.15	0.92
System Average	**—**	**0.78**	**0.62**

As demonstrated in the results, dynamic adjustment of pump operations based on continuous CPN telemetry led to an overall energy reduction of 20.5% across the entire system. Furthermore, automated permeate blending maintained TDS levels steadily between 280 mg/L and 320 mg/L, suppressing corrosivity indices without manual intervention.

4. Conclusion

The integration of automated RO permeate blending with pressure-dependent dynamic pump scheduling offers a robust solution for water utility operations in complex terrain. By coupling quality-driven feedback with hydraulic node optimization, utilities can achieve significant energy savings, extend infrastructure service life, and ensure consistent compliance with drinking water quality regulations.

Declarations

Funding:

This work was supported by the Shota Rustaveli National Science Foundation of Georgia (SRNSFG) under PhD Educational Program Grant [grant number PHDF-24-532].

Competing Interests:

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions:

All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Lasha Kavelashvili and Ketevan Gordeziani. The first draft of the manuscript was written by Lasha Kavelashvili, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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