Abstract

Water distribution networks (WDNs) are recognized as critical urban infrastructure, and their efficient management is vital for the socio-economic progress and overall well-being of modern urban-centric societies. Performance management of city-wide WDNs enforces major challenges on the utility operators and decision-makers, particularly in the developing economies, which in turn propels extensive research scope targeted towards real-field application. The present research stems from the necessity of enhanced performance assessment methodologies concerning hydraulic efficiency, energy sustainability, and leakage control in WDNs. In this context, generalized frameworks for quantitative evaluation of hydraulic, energy, and leakage behavior in urban WDNs were developed. An inherently simple and versatile global composite metric, Hydraulic Performance Index (HPI), was proposed for performance assessment and benchmarking of diverse WDNs, including intermittent systems. The efficacy of the HPI-based framework to account for hydraulic and operational constraints, service levels, and leakage conditions was illustrated through case studies, and a qualitative performance scale was introduced to categorize and benchmark WDNs. A review-based analytical survey concerning the status quo of energy metrics proposed for WDNs was conducted to ascertain their suitability for energy efficiency assessment of WDNs. An abridged list of Energy Performance Indices (EPIs) comprising five system EPIs and ten operational EPIs was synthesized through logical deduction and reasoning, which was deemed sufficient to quantify the baseline WDN energy efficiency. A novel Energy Sustainability Score (ESS) was formulated, and a generalized framework was designed for operational energy benchmarking of WDNs. Furthermore, an integrated framework for hydraulic and energy benchmarking of WDNs was framed based on the combined impact of global composite metrics, HPI and ESS, and its applicability was illustrated on both pumped and gravity-based WDNs. By virtue of the robust and flexible design of the indices, these frameworks could be directly implemented or tailored to suit the requisites of specific utilities using hydraulic models or data-driven approaches for benchmarking. Subsequently, the efficacy of EPANET 2.0 for leakage modeling and calibration was verified through an extensive experimental study on a realistic network prototype. The potential capability of configuring improved leak models using the leak parameters (emitter coefficient and emitter exponent) was ascertained. The localized and global sensitivity of hydraulic parameters to system leakage was also analyzed. Finally, a comprehensive sensitivity-based methodology to ascertain the scope of leakage management by retrofitting existing deficient networks with sensors was devised. A multi-criteria decision-making (MCDM) model for selecting the optimal number of sensors and their relative positions within the WDN was framed, entailing the simultaneous maximization of Euclidean distances among the sensor positions and the corresponding leak-induced pressure residuals obtained at these sensors. The developed performance assessment methodologies were coupled with hydraulic models using the EPANET-MATLAB programmer's toolkit, and their applicability and usefulness were demonstrated using a numerical network, real-world WDN, or experimental network, as applicable. The straightforward and generalized frameworks are expected to benefit the decision-makers for enhanced performance management and offer guidance towards the capacity building of WDNs in the long run. The outcomes of this research also aim to provide key insights for the decision-makers to better understand system performance and hydraulic modeling, with noteworthy applicability in the resources-strained and deficient utilities prevalent in developing economies.

KEYWORDS: Water supply system; Water-energy nexus; Hydraulic modeling; EPANET 2.0; Performance benchmarking; Hydraulic performance; Energy efficiency; Leak management; Leak modeling; Sensitivity analysis; Multi-criteria decision-making; Asset management.