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DEVELOPING A MODELING ALGORITHM FOR HYDRAULIC PROCESSES AND WATER QUALITY IN WATER SUPPLY SYSTEMS

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Abstract

In this article, the issues of comprehensive modeling of hydraulic processes and water quality dynamics for the efficient management of water supply systems under modern conditions are examined. The main objective of the study is to develop an integrated hydraulic–chemical modeling algorithm that accounts for real-time flow velocity, pressure, reservoir level, concentrations of reactive substances, and the propagation of tracer compounds. The article analyzes hydraulic processes using the EPANET 2.2 software environment and models pressure losses across pipe diameters, variations in flow velocity, flow distribution at nodes, and the temporal dynamics of water quality indicators (residual chlorine, turbidity, and tracer concentration) based on the operational data of the Nurafshon city water supply network.

Keywords: Water supply system, hydraulic processes, water quality modeling, EPANET 2.2, Hazen–Williams formula, Darcy–Weisbach formula, hydraulic analysis, quality indicators, residual chlorine, mathematical model, algorithm development, flow velocity, energy saving.

Introduction

Population growth, the expansion of industrial enterprises, and the acceleration of urbanization processes require more efficient management of water supply systems and a deeper understanding of the hydraulic processes within them. Modern water supply networks are complex multi-parameter systems in which factors such as pressure fluctuations, flow velocity, pipe diameters, network configuration, reservoir levels, and daily consumption variability operate in an interconnected manner.

Real-time monitoring and analysis of these parameters are essential for maintaining stable water quality, optimizing the hydraulic regime, and developing energy-efficient management strategies.

Deterioration of water quality, reduction of residual chlorine, water stagnation in pipelines, and the risk of secondary contamination are among the most pressing issues faced by many urban water supply utilities. In particular, changes in water quality caused by reduced renewal rates at distant points of the network may lead to deviations of drinking water delivered to consumers from hygienic standards. Therefore, integrated modeling of hydraulic and water quality processes, as well as forecasting water conditions across all elements of the network, is considered one of the most important directions in modern water supply management.

In recent years, the use of hydraulic modeling software such as EPANET has expanded the ability to determine pressure, flow rate, and water quality parameters of water supply networks through computer simulation. However, in practical conditions, the classical coefficients of the Hazen–Williams or Darcy–Weisbach formulas do not fully reflect the actual operational state of the network. Factors such as pipe aging, changes in material roughness, pressure fluctuations, temperature, pump operating regimes, and the decomposition rate of reactive substances have a significant impact on the accuracy of hydraulic calculations.

Main part

The methodology of this study is based on comprehensive modeling that integrates hydraulic processes and water quality dynamics within water supply networks. The methodology includes the following stages: data collection for the network, development of the hydraulic model, application of water quality models, algorithm development, and validation of the results. Each stage was carried out using modern mathematical approaches, the EPANET 2.2 software package, and real operational data.[1-4]

Full model parameters based on the Hazen–Williams formula operating in real-time conditions in the Nurafshon city water networks.

Pressure head. Water density $\rho \approx 1000$ [kg/m^3].

$$H\uparrow(t) = z\uparrow + \frac{P\uparrow(t)}{\rho g} \quad H\downarrow(t) = z\downarrow + \frac{P\downarrow(t)}{\rho g}$$

Hydraulic gradient:

$$S(t) = \frac{H\uparrow(t) - H\downarrow(t) - h_{loc}(t)}{L}$$

Here, the local losses $h_{los}(t) = \frac{\zeta V(t)^2}{2g}$ are expressed by (ζ – local loss coefficient).

Working form of the main flow model (Hazen–Williams).

$Q_{HW}(t) = 0{,}278\, C(t)\, D^{2{,}63} S(t)^{0{,}54}$ [6,7]

Here, D is in meters, and Q is taken in liters per second (L/s). Real-time correction.

$C(t) = C_0 * k_{new}(t)$

Here, k_new (t) is the real-time coefficient.

The real-time coefficient k_new (t) incorporates changes in pipe condition, operating regime, and sensor data (pressure, velocity, and observed flow). Three parameters were taken into account in the water supply systems of Nurafshon city.

For the first case (Case 1), linear correction (analytical model)

$$k_{new}(t) = \mathrm{sat}\,(1 + a\,[P_\Delta(t)] + b\,[V_\Delta(t)]\,, k_{min}\,, k_{max})$$

$$P_\Delta(t) = P\uparrow(t) - P_{ref}\,, \qquad V_\Delta(t) = V(t) - V_{ref}$$

Here, a and b are the parameters to be identified, and P_ref and V_ref are the reference values around the operating point.

sat (x , $k_{min}, k_{max},$) – fizik chegaralash $k_{min} = 0.5$ dan $k_{max}1.5$ gacha.

For the second case (Case 2), relative degree correction (dimensionless)

$$k_{new}(t) = \mathrm{sat}\,(\left(\frac{P\uparrow}{P_{ref}}\right)^a * \left(\frac{V(t)}{V_{ref}}\right)^a \; k_{min}, k_{max})$$

Here, **α** and **β** are the exponents to be identified.

Uchunchi hol For the third case (Case 3), flow-based adjustment (directly from measurement).

First, the baseline flow is calculated with k_new = 1:

$$Q_{HW,orig}(t) = 0{,}278 * C_0 * D^{2{,}63} * S(t)^{0{,}54}$$

$$k_{new}\,(t) = \mathrm{sat}\,(\frac{Q_{obs}\,(t)}{Q_{HW,orig}\,(t)}\,, k_{min}\,, k_{max}\,)$$

Measurement model and smoothing (optional but recommended)

For sensor noise in real-time conditions:

$\widetilde{P(t)} = P(t) + VP\,(t)\,,\ \widetilde{V(t)} = V(t) + v_V(t),\ \widetilde{Q(t)} = Q(t) + v_Q(t).$

Discrete smoothing (EMA) $\widetilde{x_k} = \mu\widetilde{x_{k-1}} + (1 - \mu)\,\widetilde{x_k} \qquad 0 < \mu < 1$ [8,10]

This is applied to $\acute{P}$, $\tilde{V}$, $\tilde{Q}$ (or a simple moving average).

Discrete (real-time) set of equations

At each k-step ($t_k = k\,\Delta t$)

1. Elevation and gradient:

$$H_{\uparrow,k} = Z\uparrow + \frac{P_{\uparrow,k}}{\rho g}\ \ ,H_{\downarrow,k} = Z\downarrow + \frac{P_{\downarrow,k}}{\rho g}$$

$$S_k = \frac{H_{\uparrow,k}\ - H_{\downarrow,k}\ - \frac{\zeta V_k^2}{2g}}{L}$$

k_new according to the selected case.

First case $k_{new,k} = \{\mathrm{sat}\big(1 + a\big(\,P_{\uparrow,k} - P_{ref}\big) + b(V_k - V_{ref}), k_{min}\,,\ \ k_{max}\big)$

Second case $k_{new,k} = \{\mathrm{sat}\left(\left(\frac{P_{\uparrow,k}}{P_{ref}}^{a}\right) + \left(\frac{V_k}{V_{ref}}^{b}\right), k_{min}\,,\ \ k_{max}\right)$

Third case $k_{new,k} = \{\mathrm{sat}\big(Q_{obs,k} /\ Q_{HW,orig,k}\,, k_{min}\,,\ \ k_{max}\big)$

Flow prediction: $C_k = C_0\ k_{new,k} \quad Q_{HW,k}\ = 0{,}278\ \ C_k\ \ D^{2.63} S_k^{0.54}$

Limits, units, and scope of application.

D (m) , L (m) , Q (L/s) or 0,00278 with the coefficient (m^3/s).

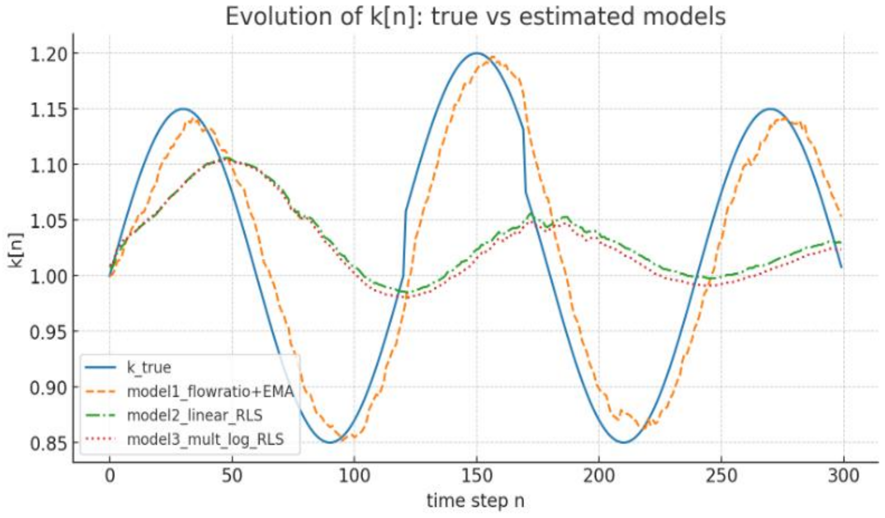
$k_{min}\,, k_{max}$ - physically reasonable range is from 0.5 to 1.5.

$S_k > 0$ should be ensured (pressure head decreases in the direction of flow).

μ is selected based on the given fittings; if none are present, then $\mu = 0$.

The real-time coefficient **k_new(t)**, which enriches the Hazen–Williams model with real-time measurements, and the corresponding online adaptive **C(t)** were determined in a complete mathematical form.

Думал на протяжении 6s



The graph compares the true value of the Hazen–Williams coefficient k[n] with the results of three adaptive estimation algorithms. Model 1 (Flow Ratio + EMA) responds quickly to changes but exhibits higher dynamic errors. Model 2 (Linear RLS) reacts more slowly to variations but provides more stable results. Model 3 (Multiplicative-log RLS) is the most stable and insensitive to noise; however, due to its high inertia, it adapts to changes with a delay.

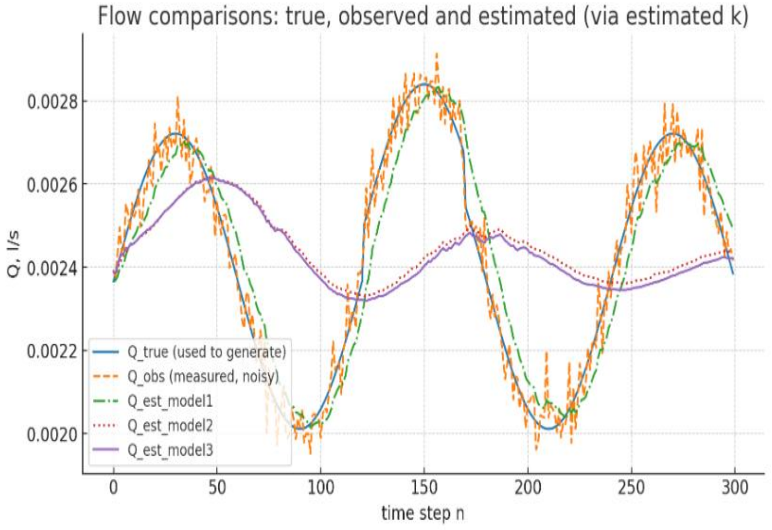


Figure 2. Comparison of flow estimation models.

This figure illustrates the comparison of the actual, observed (measured), and model-estimated values of flow (Q, L/s) over time.

CONCLUSION

This study proposed an effective scientific approach for integrated modeling of complex hydraulic and water quality processes in water supply systems. The newly developed modeling algorithm enables accurate assessment of the actual operational conditions of the network, prediction of water quality, and optimization of system performance.

The following key conclusions were reached:

- The new correction coefficient k_new(t) significantly improved the real-condition accuracy of the classical Hazen–Williams and Darcy–Weisbach equations.
- By integrating hydraulic and water quality models, the ability to predict parameters such as pressure, flow rate, water stagnation, and residual chlorine in real time was achieved.

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