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Inclusion of Water Age in Conjunctive Optimal Operation of Water and Power Grids †

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Abstract: Water distribution systems (WDSs) are critical infrastructure systems designed to safely supply water to consumers. As complex systems, they require constant operational decision-making, which is often the result of an optimization process. WDSs require power for pumping and the operation of water treatment facilities. Power is supplied through power grids (PGs)—essential infrastructure which must be strategically operated as well, under constraints. This work is focused on the effects of PG operation on water quality, which is a major operational challenge of WDSs. The inclusion of the PG as part of the WDS optimal operation problem has the potential of influencing flow directions in the WDS, which in turn affects water quality. In this work, a model for the optimal operation of water and power networks is constructed, including water age considerations. The model is applied to a simple case study, containing a small WDS connected to a small PG. The results demonstrate the effect of PG operation on water quality.

Keywords: optimization; optimal operation; water distribution systems; power grids; water age

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1. Introduction

In recent years, the problem of conjunctively operating water and power systems has attracted growing attention in the research community. By taking advantage of the connection between the systems through WDS power demand, trade-offs between the systems could be assessed and leveraged for obtaining better operation solutions that would benefit operators and the environment. These works mainly focused on objectives such as determining cost and environmental impact; hydraulic, pressure and demand constraints on the WDS side; and voltage, generation and demand constraints on the PG side [1–3].

Water quality constitutes a significant challenge for WDS operators [4]. This work is focused on the incorporation of a water quality model into a conjunctive optimization model for operating PGs and WDSs to demonstrate the interrelationship between power flow and water quality. Water age is chosen as a representative parameter that would reflect how water quality is affected by the PG.

2. Methodology

We consider a simple joint system comprising a 3-node WDS with one pump and one tank and a 3-bus PG with one conventional generator, one solar generator and one external power load, as examined by [5]. In this work, we aim to develop a surrogate model to allow for a simple incorporation of water age considerations into this model. Using random pump rotation speed sequences and EPANET 2.2, a large number of hydraulic simulations were performed. Hydraulicly feasible scenarios were screened, and the maximal water age observed among network nodes in each one of them was extracted. Then, a linear regression model was fitted to the data, linking the system's hydraulic states to the maximal water age

in demand nodes. In order to determine the regression variables, different combinations of link flows were examined, and those resulting in the best fitness were chosen. For the examined system, the chosen variables were pump flow, the flow in link 3 and the tank elevation, resulting in the linear regression model described in Equation (1):

$$MWA = c_0 + \sum_{t=1}^{T} c_1^t Q_p^t + \sum_{t=1}^{T} c_2^t Q_3^t + \sum_{t=1}^{T} c_3^t H_{tank}^t, \quad (1)$$

where *MWA* is the maximal water age among network nodes [hr]; c_i represents the regression coefficients; t is the timestep; T is the simulation period; Q_p^t is the pump flow $[\frac{m^3}{h}]$; Q_3^t is the flow in link 3; and H_{tank}^t is tank elevation. Since the model contains 3 variables with 24 values over the time period, it includes a total of 73 regression parameters.

The fitted regression model was then meant to be inserted into the conjunctive optimization model, allowing for the representation of the maximal water age in the system through a linear analytical expression. The conjunctive operation model could then be optimized using an off-the-shelf optimizer IPOPT through MATLAB.

The objective of the conjunctive optimal operation problem is the minimization of power generation costs. Generally, the water age tends to rise more significantly in tanks. Increased pumping helps reduce water age in demand nodes, and therefore, the inclusion of water age constraints is expected to act as an incentive to pump larger amounts of water, which will in turn affect the optimal operation strategy of the conjunctive system, linking the operation of the power grid to water quality considerations.

Figure 1 summarizes the proposed methodology in a flow chart.

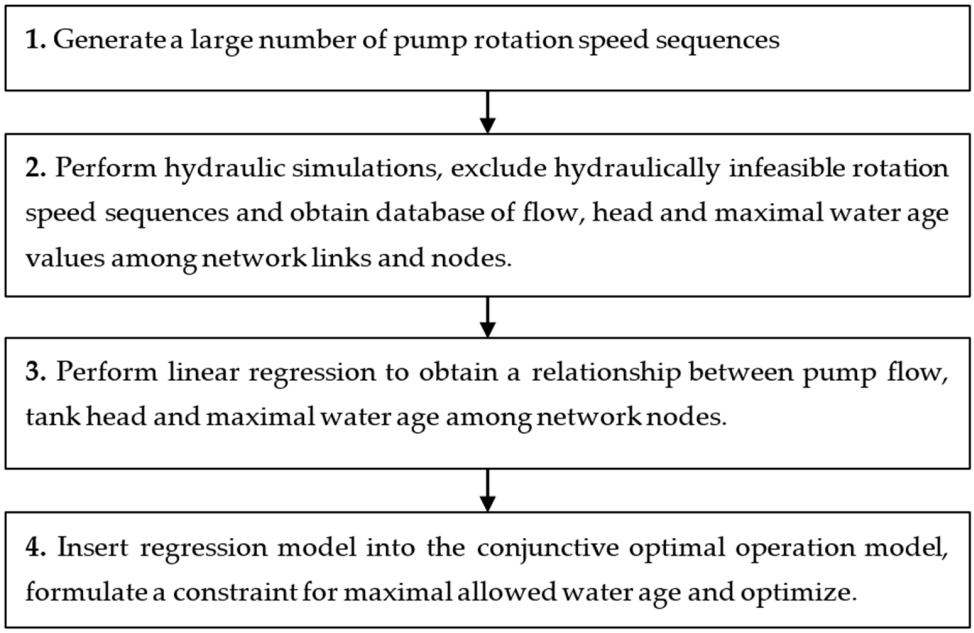


Figure 1. A flow chart summarizing the proposed methodology.

3. Preliminary Results

A total of 50,000 hydraulic simulations were randomly generated, out of which 43,600 were hydraulically feasible (satisfy minimal pressure constraints). A linear regression model linking pump flow, flow in an additional link in the network and tank head to the maximal water age among network nodes resulted in an R^2 value of 0.86. Upon inserting it into the optimization model, it did not present sufficient accuracy, preventing water age considerations to constrain the problem and influence the optimal solution.

Examining both the system and the generated data, a clear relationship between tank operation policy and the maximal water age was revealed. By introducing an additional

constraint on the minimal tank level, the water age was affected quite significantly, as can be observed in Figure 2.

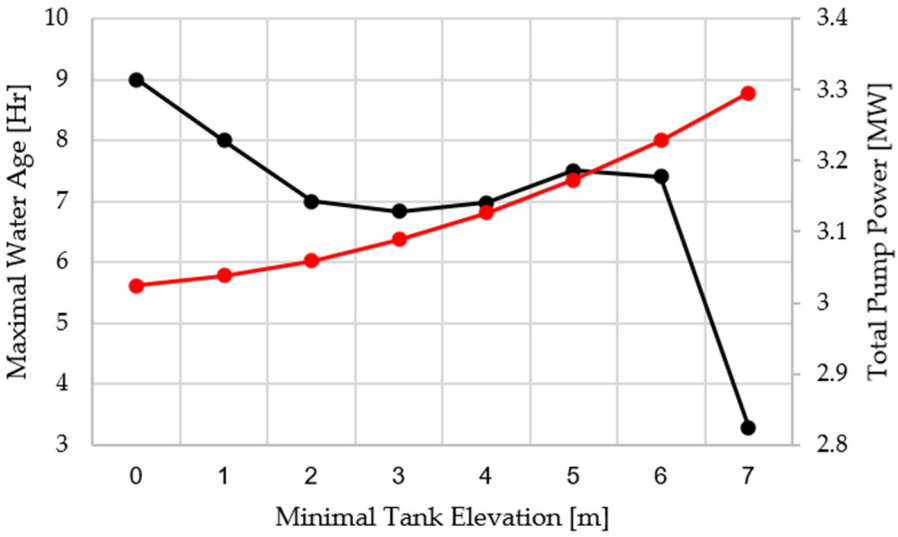


Figure 2. Maximal water age (Black) and minimal total pump power (Red) observed for different minimal tank level constraints.

4. Discussion and Conclusions

This work is aimed at presenting the influence of water quality constraints on the conjunctive optimal operation problem of water and power networks. As a part of this, we aimed to develop a surrogate model that would allow for the inclusion of water age constraints as part of a deterministic, non-linear optimization model. The surrogate model was to be based on a linear regression model fitted to a large number of random simulation data generated by EPANET 2.2.

As mentioned, the R^2 value of the fitted linear regression model was relatively high, pointing to a somewhat strong prediction ability. This result can support the claim that a linear regression model could be used to predict water age and serve as a much simpler surrogate model that will allow us to solve the highly complex water–power conjunctive optimal operation model under water age constraints. However, the regression model still shows inaccuracies which pose challenges for including it in an optimization process and prevents us from completing step 4 of the methodology, as described in Figure 1. The model does not cover a wide enough range of operation scenarios, which is translated into larger prediction errors for the result of the optimal operation problem. These larger errors result in the inability of the linear regression model to influence the optimization process and constrain the operation. Including a significantly larger number of simulations for the linear regression database may help but will be accompanied by significantly longer running time.

A more prominent relationship between the minimal tank level and maximal water age was revealed, pointing to a different possible direction for constructing a regression model that would result in higher accuracy. The percentage of water supplied from the tank out of the total water demand in the system or perhaps critical timesteps in which higher percentages of water demand are supplied from the tank could both possibly serve as better predictors which would more accurately approximate how damaging the use of stored water could be to water age in the system. As expected, the total pump power value increases as tank operation is more constrained, and the points in the graph could serve as different operation strategies for the desired water age and pump power of tank operation. From the standpoint of the conjunctive operation model, a more constrained tank operation is likely to result in higher pumping capacities which in turn will result in increased power production and generally more expensive operation. Questions that

we aim to answer are how flexible the operation of the conjunctive system is, and could it maintain low operational costs while satisfying desired water age constraints? These questions are left open and are likely to be answered by the development of a more accurate surrogate water age prediction model.

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