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Inclusion of water age in conjunctive optimal operation of water and power networks

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ABSTRACT

Water distribution systems (WDSs) are vital infrastructures designed to deliver water safely to consumers. This complex system necessitates continuous operational decisions, often optimized for efficiency. WDSs rely on power grids (PGs) to operate pumps and treatment facilities. PGs, likewise crucial, require strategic management to meet demand and environmental standards. Integrating the operation of both systems has garnered attention for its potential cost, energy, and environmental benefits. By leveraging the interconnection, trade-offs can be assessed, leading to improved solutions. Past research primarily focused on cost or carbon emissions as well as on hydraulic and voltage constraints. However, this study examines the impact of power systems on water quality, particularly water age, a key operational concern. Incorporating PGs into the optimal operation problem may alter flow directions, thereby influencing water age. Through mathematical modelling, this study evaluates these effects and applies them to simple case studies, demonstrating the influence of PG operation on water quality. Results demonstrate how tank constraints affect water age and show that a conjunctive operation approach, although beneficial for reduction of cost and energy consumption, can be damaging for water quality.

Key words: optimal operation, power grids, water age, water distribution systems

HIGHLIGHTS

- The impact of a conjunctive WDS-PG optimal operation on water age is presented and analyzed.
- Although believed to be beneficial, the conjunctive operation approach is found to have damaging impacts on water age.
- Tank operation is found to serve as a reliable surrogate for water age control.
- Total operation cost is found to be a competing objective to minimal water age.

INTRODUCTION

Water quality modelling in water distribution systems (WDSs) presents a multitude of challenges stemming from the inherent complexity and variability of hydraulic and contaminant transport processes within these networks (Besner *et al.* 2001). Firstly, the spatial and temporal dynamics of water flow and mixing pose significant hurdles to accurate modelling (Kim *et al.* 2011). WDSs encompass a vast network of pipes, pumps, valves, and storage tanks, exhibiting intricate hydraulic behaviours influenced by factors such as pipe material, diameter, topology, and operational conditions. Capturing the transient flow patterns and residence times of water parcels as they traverse through this labyrinthine infrastructure requires sophisticated modelling techniques capable of simulating both steady-state and transient flow regimes with high fidelity. Moreover, the heterogeneous nature of water quality parameters, including chemical constituents, disinfection by-products (Boorman 1999), and microbial contaminants (Helbling & VanBriesen 2009), further complicates the modelling task, necessitating comprehensive consideration of reaction kinetics, mass transfer phenomena, and water quality standards compliance.

Water quality modelling is one of the major challenges for both researchers and practitioners in the field of water resource systems engineering. Several studies have dealt with the problem of including water quality considerations in an optimization process. Kurek & Ostfeld (2013) developed a multi-objective methodology to optimize the design of a WDS, using objectives of chlorine disinfectant concentrations and water age, alongside the traditional minimal cost objective. Similarly, Shokoohi *et al.* (2016) proposed a multi-objective optimal design problem that is based on water quality, using a water quality reliability index that integrates chlorine residual and water age. Tu *et al.* (2005) solved a problem of optimizing the distribution and

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quality of a regional water supply system, which relies on several different water sources of different qualities. Their method involved a genetic algorithm for the determination of flow directions and the application of a generalized reduced gradient to optimize the objective function afterwards. Yang *et al.* (2000) presented an optimization of a WDS's operation under blending constraints. The Battle of the Networks II (Marchi *et al.* 2014) constitutes another example of an attempt to address water age as part of a design and operation problem of WDSs and highlights the importance and relevance of the topic.

The link between WDSs and power grids (PGs) is multifaceted and symbiotic, underscoring the interdependency of critical urban infrastructure networks (Hamiche *et al.* 2016). WDSs rely heavily on the uninterrupted supply of electricity for various operations, including pumping, treatment, and distribution. Electric pumps are integral components of water distribution networks, facilitating the movement of water from sources to consumers, while treatment processes such as filtration, disinfection, and chemical dosing require consistent power supply to maintain water quality standards. Moreover, the monitoring and control systems employed in water infrastructure, such as supervisory control and data acquisition systems, depend on electricity to monitor flow rates, pressure levels, and water quality parameters in real time, enabling operators to detect anomalies, optimize system performance, and respond swiftly to emergencies. As such, any disruptions or fluctuations in PG operation can have profound implications for the functionality and resilience of WDSs, potentially leading to service interruptions, compromised water quality, and cascading impacts on public health, economic activities, and societal well-being.

In recent years, several studies have investigated the coupled optimization of power and water systems. Koh *et al.* (2022) explored the interaction between a reservoir system and the PG, demonstrating through a hard-coupling modelling framework that integrating water systems enhances renewable energy integration. Pereira-Cardenal *et al.* (2016) optimized a joint regional water–power system, focusing on irrigation, with emphasis on water systems for power generation and agricultural purposes rather than drinking water distribution. Zamzam *et al.* (2019) proposed an optimal operation problem aiming to minimize operation costs, but their assumptions, such as fixed energy prices for water operators and simplified constraints on WDSs, may not fully capture real-world complexities. Stuhlmacher & Mathieu (2020) formulated a problem to minimize flexibility costs by treating WDS as controllable loads, which may oversimplify the importance of WDS objectives. Oikonomou *et al.* (2017) suggested revealing energy prices to WDS operators for optimization, while Oikonomou & Parvania (2020) incorporated desalination plants into WDS optimization. Majidi *et al.* (2022) introduced a pumped-storage hydropower unit to reduce reliance on conventional generators, highlighting the need for comprehensive optimization methods for interconnected systems. Putri *et al.* (2023) proposed a predictive control algorithm for interconnected water and power systems, demonstrating significant benefits such as capital savings and reduced carbon footprint. Bhatraj *et al.* (2024) presented an optimization model for renewable energy–based microgrids coupled with water supply systems, emphasizing energy efficiency improvements. All mentioned studies often lack detailed modelling of the PG, particularly power flow equations, which is crucial for revealing optimal operation strategies for both networks. Furthermore, they seldom took into consideration water quality objectives of constraints.

In this work, we aim to analyze different conjunctive operational strategies and gain an understanding of their effect on water quality. We intend to link different operation strategies, water quality, and total operation cost and show the trade-offs that take place between the different objectives. We examine two simple conjunctive systems and use a non-linear optimization model to obtain results.

METHODOLOGY

For the purposes of this work, we select water age, which is defined as the time water travels throughout the system until it reaches consumers, as an indicator for water quality in the system. In general, low values of water age are most desired, as they indicate fresher water that are more suitable for consumption, as opposed to older water, which is often linked to bad water quality and certain water quality issues such as odd taste or odour, microbial growth, and reduced ability to control corrosion (EPA 2022).

A large amount of data was randomly generated using MATLAB and its EPANET toolbox. Out of the 50,000 randomly generated hydraulic simulations, 43,600 were hydraulically feasible (satisfy minimal pressure head constraints of 30 m at all network nodes). The simulations were generated by constructing random sequences of pump rotation speeds and inserting them into EPANET 2.2 to obtain hydraulic data. Upon examining the data, a clear relationship between tank operation and the maximal water age observed in network demand nodes has emerged. This relationship led us to believe that by constraining the operation of the tank, the maximal allowed water age in the system could be controlled. Constraining the operation of the tank would indirectly affect the operation of pumps, which will in turn affect the operation of the PG.

The full conjunctive optimal operation problem is presented by Shmaya *et al.* (2023) and is used for the purposes of this work as well. As part of that formulation, the constraint of tank head is given in Equation (1):

$$H_{\mathrm{tank},s}^{\min} \leq H_{\mathrm{tank},s}^{t} \leq H_{\mathrm{tank},s}^{\max} \tag{1}$$

By constraining the minimal tank level with several different bounds, we aim to create a field of solutions, each with a certain optimal cost and maximal water age value, out of which a system operator could choose the best strategy according to the desired outcome of the operation. By dividing the range of feasible tank heads to increments, we repeatedly solve the conjunctive optimal operation problem, modifying the lower bound of the tank head constraints each time. Each of the solutions is then simulated using EPANET 2.2 to determine the maximal observed water age in the system's demand nodes. The values of total cost are then plotted against the corresponding minimal tank constraint and maximal observed water age, to create the field of solutions that will serve the operator in the decision-making process. This methodology is demonstrated in the flow chart in Figure 1.

RESULTS

Case study I

The layout of case study I is presented in Figure 2. The system comprises of a WDS, supplying water from a source to three consumers, and includes one pump and one tank. The pump is supplied with power through a PG, which comprises three buses. Bus 1 constitutes a conventional generator, whose generation is not limited. Bus 2 constitutes a solar generator, which is available only during daylight hours and whose generation capacity is constrained by a profile, used by Jahid *et al.* (2018) and given at Figure 3 along with the used water demand pattern. The PG also includes one power consumer with a constant demand at bus 3, connected to both generators.

Table 1 presents properties of both the WDS and the PG of case study I.

For case study I, the increment size was set to 0.1 m, which results in 71 solutions in total. The results are presented in Figure 4. The results of the conjunctive optimal operation are compared here to the results of optimizing the independent WDS, to provide an insight into the way that the PG affects conditions inside the WDS.

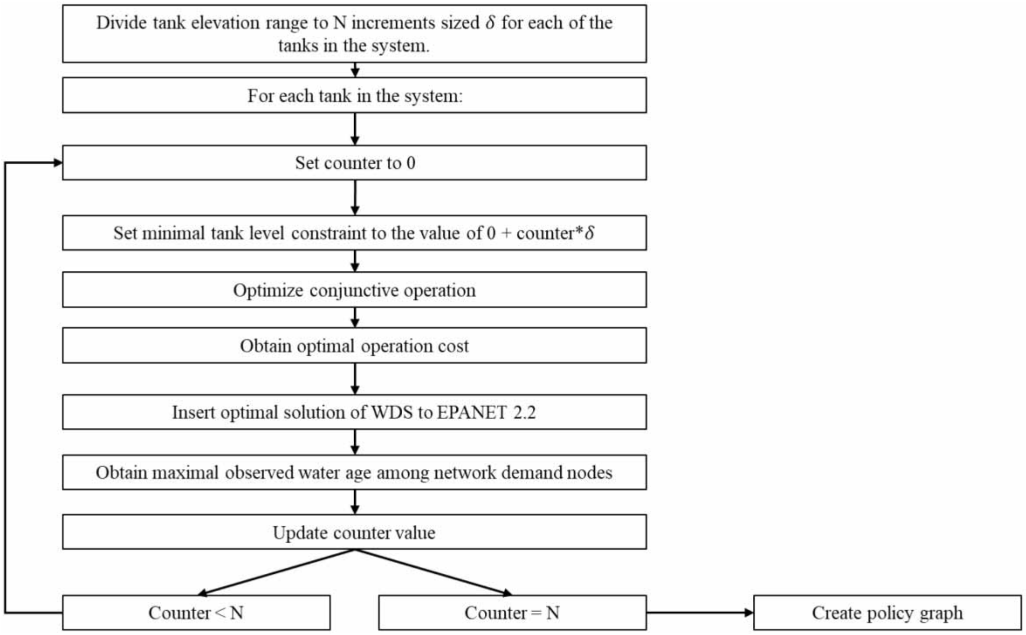


Figure 1 | Flow chart summarizing the proposed methodology.

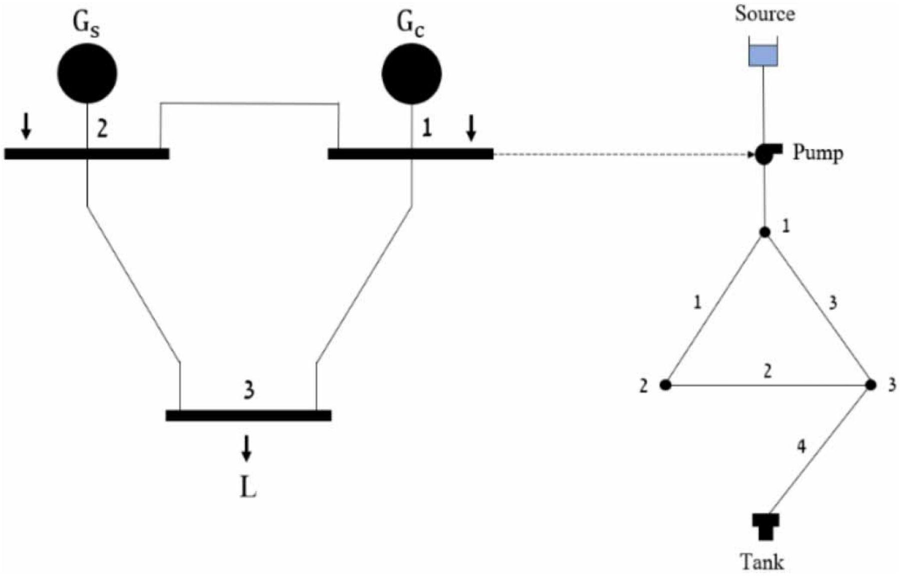


Figure 2 | Layout of case study I.

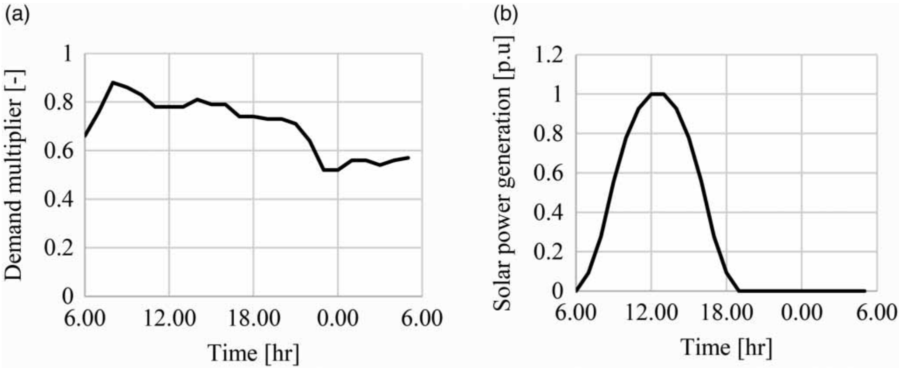


Figure 3 | Water demand pattern (a) and solar generation profile (b) (Jahid *et al.* 2018).

Overall, it can be observed that water age is damaged when applying the conjunctive approach to the system – while most scenarios in the independent WDS operation problem result in maximal water age of less than 9 h, most scenarios examined with the conjunctive approach led to maximal water age that exceeds 10.5 h. This emphasizes the competition between the two objectives of better water quality and reduced operational cost, constituting a clear link between the quality of water in the WDS to the operation of the PG.

A steady increase in total pump power is observed for the independent WDS operation problem. As tanks in the system are more strictly constrained, a reduced amount of the energy that they contain can be exploited, resulting in increased power capacities for pumping purposes. A decrease in maximal water age value is also observed, reaching its minimal value in the scenario of constraining minimal tank level at 7 m, meaning that no water is allowed to flow out of the tank. Water ages most significantly in tanks, since large amounts of water are not mixing with fresher water. By not using the tank, the effect of the older water it contains on the system's maximal water age is mitigated.

The maximal water age curve in Figure 4(b) can be divided into three main areas, each presenting a different trend – a horizontal line, showing no impact of tank level constraint modifications between 0 and 3.5 m; a monotonic increase between 3.5 and 5.6 m; and a monotonic decrease between 5.6 and 7 m. Figure 5 depicts tank level curves for five different constraints, one from each region of the graph, along with constraints that constitute the boundaries between those areas.

Tank operation policies differ in the two problems. As the objective function of the independent WDS operation problem is defined as minimization of pump power demand, tank operation policy is quite trivial – the entire volume of water in the tank

Table 1 | Case study I properties

System	Component	Attribute	Value
WDS	Link	Diameter (mm)	600
		Roughness (-)	110
		Length (km)	3
	Node	Base water demand (m^3/h)	475
		Pressure demand (m)	30
		Elevation (m)	0
	Tank	Elevation (m)	35
		Diameter (m)	25
		Maximal level (m)	7
	Tank link	Diameter (mm)	500
		Length (km)	0.5
	Pump	η (-)	0.85
		Curve coefficients	200; 1×10^{-5}
		Rotation speed range (rpm)	[0,50]
		α_{pq} (-)	$\frac{1}{3}$
PG	Transmission line	Impedance (p.u.)	$0.1j$
	Capacitor	Admittance (p.u.)	$0.055j$
	Bus	Minimum voltage bound (p.u.)	0.95
		Maximum voltage bound (p.u.)	1.05
	Reference bus	Reference voltage (p.u.)	1
	Load	Base power demand (p.u./h)	$2.8653 + 1.2244j$

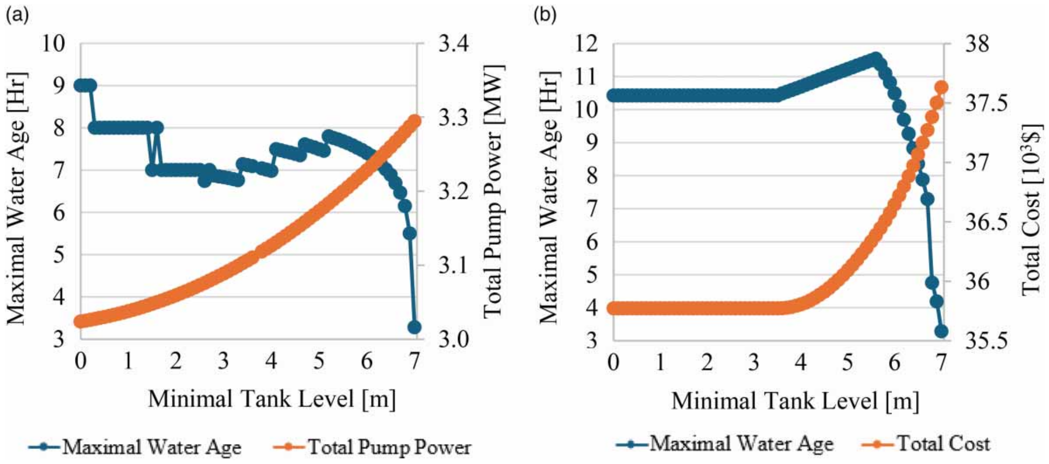


Figure 4 | Water quality analysis results for case study I in the independent WDS operation problem (a) and the conjunctive operation problem (b).

is exploited to reduce pump power demand as much as possible, and once it is empty, it is filled up to meet the tank closure constraint. In the conjunctive operation, however, the tank is incentivized to be filled mid-day due to the availability of free solar power. In addition, it does not reach its lower bound constraint. This explains the flat section of the curve between 0 and 3.5 m – even though the constraint value is modified, the optimal solution is not affected, since the constraint is not binding. As the minimal tank level constraint reaches the minimal tank level obtained for the original problem, water age begins to rise.

Defined as a weighted average, water age is affected by two parameters – the quantity of the water mixing in nodes and its age. Water age in a system would be damaged most significantly by large amounts of old water mixing in nodes with small amounts of younger water, and it could be improved by either ensuring constant mixing with younger water or limiting the

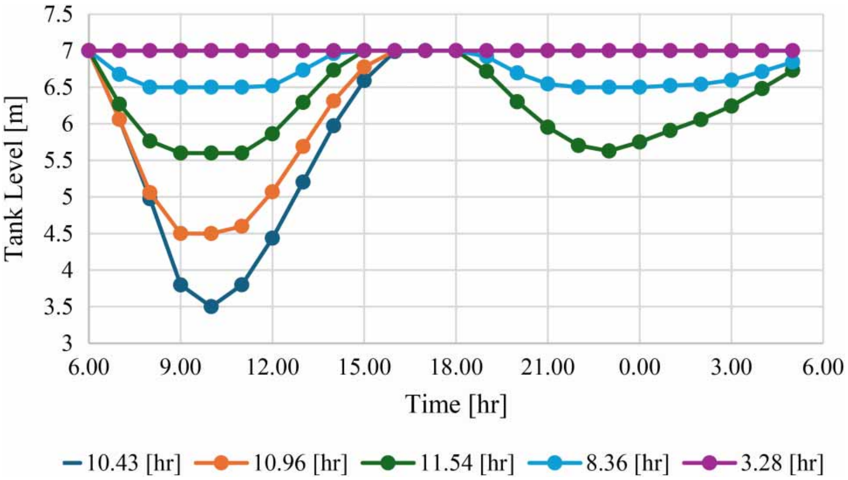


Figure 5 | Tank level operation curves for different tank level constraints in the conjunctive optimal operation problem of case study I.

amount of old water entering the system. Smaller amounts of water that are supplied from the tank in the morning result in older water entering the system at 18:00, when the tank is used for the second time in a day. This causes for the water age rise between the 3.5 and 5.6 m constraint values. This trend is mitigated when the constraint value keeps increasing. At this point, although the water supplied from the tank is older, its amount is small enough that it does not damage the water age in a dramatic way.

These claims are supported by Figure 6, which presents water age curves for node 3 in the water system, at which the maximal water age is obtained.

Since the tank operation policy is similar, the curves attain a similar shape, with a spike in water age occurring at 18:00, when the tank is emptied for the second time. However, by limiting the minimal tank level to 6.5 m, water age was able to be kept under 9 h, and under 4 h for not using the tank at all throughout the simulation.

Case study II

The layout of case study II is presented in Figure 7. The system comprises a WDS with seven junctions, two tanks, and two pumps. The pumps are supplied with power by a 14-node PG, which is a slightly modified version of the 13-bus grid IEEE benchmark (Mohammed 2022). The water demand pattern and solar generation profile used for this case study are the same as those shown in Figure 2. The properties of the case study are given in Table 2.

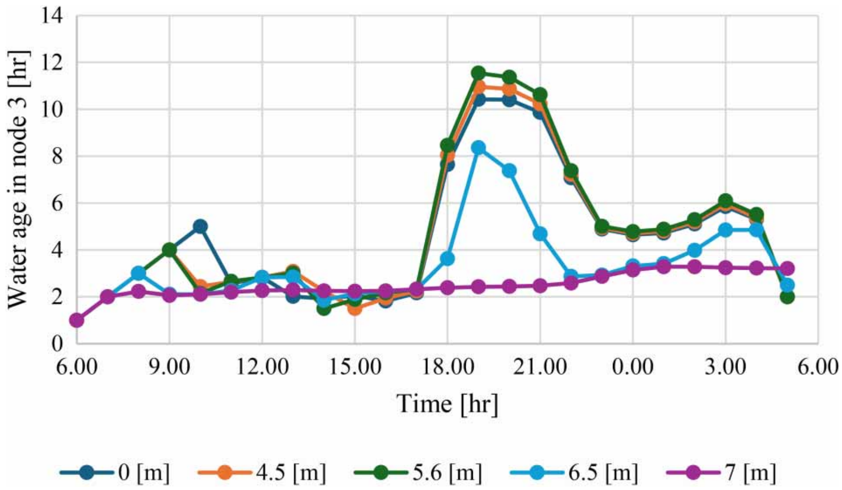


Figure 6 | Water age curves for node 3 for different tank level constraints in the conjunctive optimal operation problem of case study I.

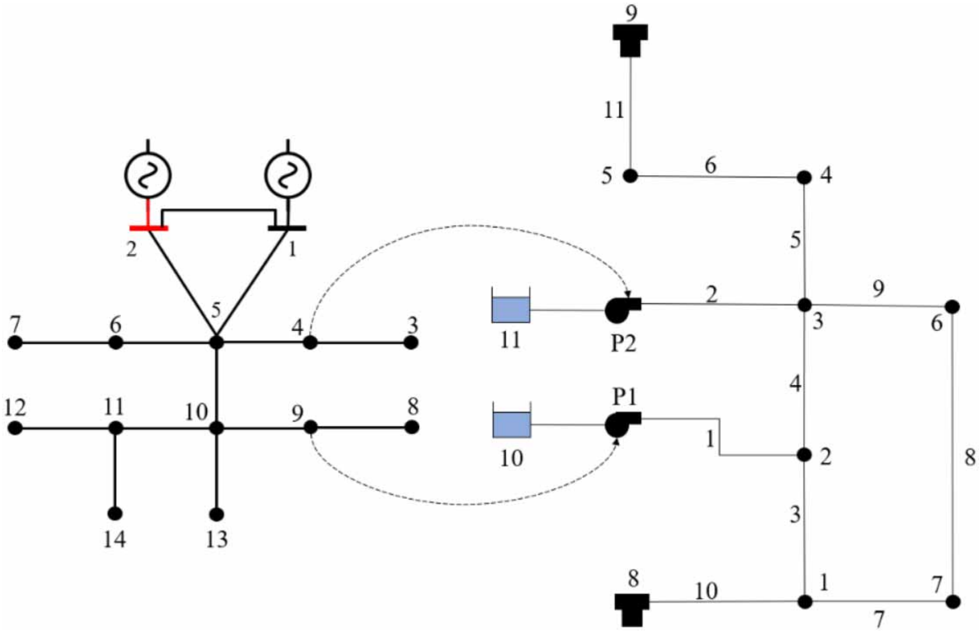
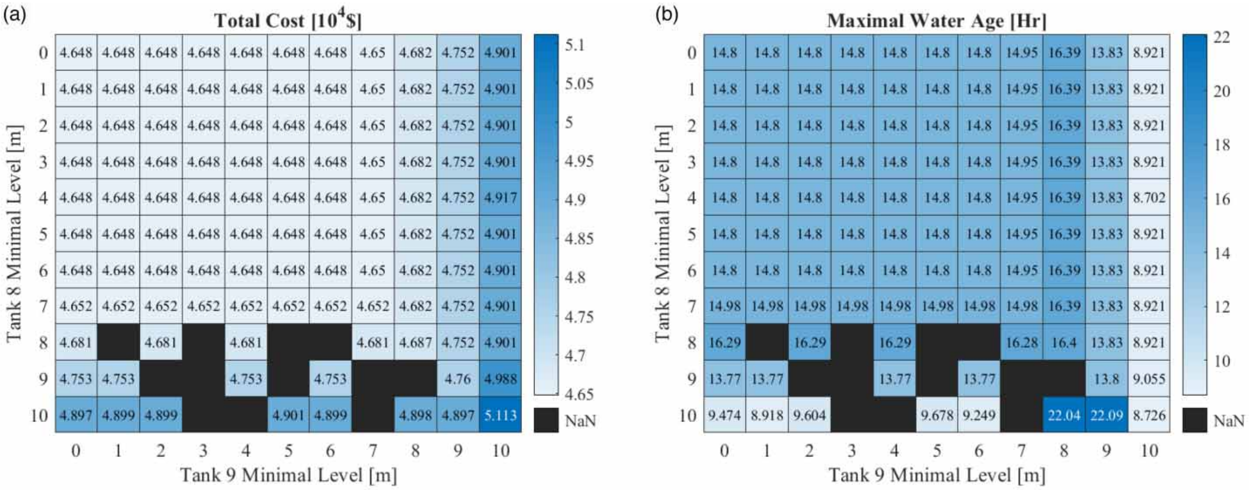


Figure 7 | Layout of case study II.

Table 2 | Case study II properties

System	Component	Attribute	Value
WDS	All links	Diameter (mm)	600
		Roughness (-)	120
	Links 3, 4, 5, 6, 7, 9	Length (km)	2
	Link 8		4
	All nodes	Pressure demand (m)	30
		Elevation (m)	0
	Nodes 4, 5	Base water demand (m^3/h)	150
	Node 6		300
	Node 7		400
	Tanks	Diameter (m)	20
		H_{min} (m)	30
	Tank links 10, 11	Diameter (mm)	750
		Length (km)	0.4
	Pumps	η (-)	0.85
		Curve coefficients	200; 1×10^{-5}
		Rotation speed range (rpm)	[0,50]
		α_{pq} (-)	$\frac{1}{3}$
PG	Transmission line	Impedance (p.u.)	$0.003 + 0.01j$
	Bus	Voltage magnitude (p.u.)	1
	Reference bus	Minimum voltage bound (p.u.)	0.95
		Maximum voltage bound (p.u.)	1.05
	Loads (buses 3, 7, 8, 12, 13, 14)	Base power demand (p.u./h)	$0.5 + 0.175j$

Since this case study includes two tanks, the problem must be solved for all combinations of tank constraints, which significantly increases the running time. Due to the complexity of the case study and long running times, relatively large increments of 1 m were set for the tank minimal level constraint. As the system now contains two tanks, the results must be shown in the form of heatmap charts, as shown in Figure 8. Points for which convergence was not achieved are marked in black.



(a) Total Cost [10^4\$]

	0	1	2	3	4	5	6	7	8	9	10
0	4.648	4.648	4.648	4.648	4.648	4.648	4.648	4.65	4.682	4.752	4.901
1	4.648	4.648	4.648	4.648	4.648	4.648	4.648	4.65	4.682	4.752	4.901
2	4.648	4.648	4.648	4.648	4.648	4.648	4.648	4.65	4.682	4.752	4.901
3	4.648	4.648	4.648	4.648	4.648	4.648	4.648	4.65	4.682	4.752	4.901
4	4.648	4.648	4.648	4.648	4.648	4.648	4.648	4.65	4.682	4.752	4.917
5	4.648	4.648	4.648	4.648	4.648	4.648	4.648	4.65	4.682	4.752	4.901
6	4.648	4.648	4.648	4.648	4.648	4.648	4.648	4.65	4.682	4.752	4.901
7	4.652	4.652	4.652	4.652	4.652	4.652	4.652	4.652	4.682	4.752	4.901
8	4.681		4.681		4.681			4.681	4.687	4.752	4.901
9	4.753	4.753			4.753		4.753			4.76	4.988
10	4.897	4.899	4.899			4.901	4.899		4.898	4.897	5.113

(b) Maximal Water Age [Hr]

	0	1	2	3	4	5	6	7	8	9	10
0	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.95	16.39	13.83	8.921
1	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.95	16.39	13.83	8.921
2	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.95	16.39	13.83	8.921
3	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.95	16.39	13.83	8.921
4	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.95	16.39	13.83	8.702
5	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.95	16.39	13.83	8.921
6	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.95	16.39	13.83	8.921
7	14.98	14.98	14.98	14.98	14.98	14.98	14.98	14.98	16.39	13.83	8.921
8	16.29		16.29		16.29			16.28	16.4	13.83	8.921
9	13.77	13.77			13.77		13.77			13.8	9.055
10	9.474	8.918	9.604			9.678	9.249		22.04	22.09	8.726

Figure 8 | Heatmaps describing maximal water age (a) and total operation cost (b) for water quality analysis of case study II.

Solving the conjunctive optimal operation problem for case study II requires significant computational resources. The problem was solved here 121 times, modifying the value of minimal tank constraints each time. Not all problems have converged to a feasible solution, which can be observed by the black squared marks shown in Figure 8. Nevertheless, a similar trend occurs, as the cheapest solutions are obtained for not constraining the tank operation at all, and the lowest water age and maximal cost obtained for the scenario in which the tanks are not employed. The water age obtained in the solution of the original problem is 14.8 h, and it is reduced to only 8.73 h by constraining tank levels. The rise of total cost reflects the way the PG is affected by the constraining of the tanks. This result means that the desire for a reduced water age value in the WDS will force the PG to operate in a more expensive, less favourable pattern – which demonstrates the competition between the objectives.

Figure 9 presents water age curves for nodes 5 and 7 of the WDS, which are the most remote nodes in the system, which are most affected by the rise in water age. This figure presents the curves for four different sets of constraints on minimal tank level.

As expected, when tanks are not constrained at all, the highest water age values are obtained. The maximal water age is 14.8 h, which takes place in node 5. As the constraint is modified, water age begins to decrease. No significant improvement

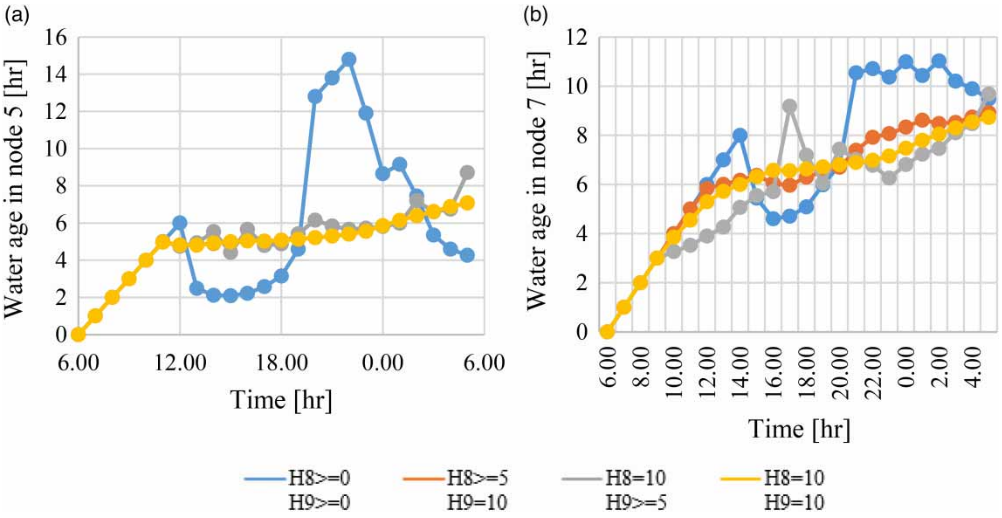


Figure 9 | Water age curves for nodes 5 (a) and 7 (b) for four different sets of minimal tank level constraints in the conjunctive optimal operation problem of case study II.

is observed when comparing the last three sets of constraints. The last set, in which flow out of the tanks is fixed to zero, does result in the lowest water age value, but the difference is negligible and does not exceed several minutes.

In general, it can be determined that the conjunctive approach damages water quality in the system, as it helps cut pump power costs, and subsequently reduces the amount of water supplied by pumps, leading to higher tank water supply, which is of lesser quality. The results illustrate the effect of the PG operation on water quality and presents water quality and power generation costs as competing objectives in the optimal operation problem. By applying the mentioned analysis to the conjunctive optimal operation problem, this competition is revealed in a clearer way – as tank operation is more constrained, water age generally improves, and total operation costs increase. The creation of visual operational tools such as those shown in Figures 4 and 8 can help operators assess how to best operate tanks in their systems to minimize operation costs, while maintaining a desired water quality.

CONCLUSION

This work focused on the examination of water quality response to the conjunctive optimal operation problem. Since the operation of the PG has the potential of influencing flow directions in the WDS, decisions made regarding power generation result in different water quality outcomes. Water age was chosen to represent a water quality indicator to be monitored in the WDS.

As analytical water quality calculations are extremely complex, the first part of this study was focused on the development of a surrogate method that would allow the simple incorporation of water quality in the optimization model. Several attempts were made to construct a linear regression model by examining large amounts of data, generated randomly by EPANET 2.2. After failing to develop a stable and reliable regression model, and upon examining the obtained data, it was decided to consider the minimal tank level constraint as a surrogate predictor for water age.

Results show that generally, as the minimal bound for the tank level rises, water age in the system reduces. This way, a nonlinear conjunctive optimal operation problem could be formulated and solved for a range of minimal tank level constraint values, and by inserting the solutions into EPANET 2.2 and extracting the maximal water age value for each of them, an operational 'map' could be obtained, tying tank operation, maximal water age, and total operation cost.

The results reveal a complex problem, and they differ depending on the system that is solved. The consideration of a network containing two tanks or more can result in a very large number of optimization problems to be solved, which can be very challenging computationally, and optimal solutions are not guaranteed for any set of constraints, even for a relatively small systems such as those examined in this work.

The analysis and control of water quality in WDSs poses significant challenges and lies at the very front of water resources engineering research these days. Future studies could combine different existing models for water quality prediction into the conjunctive optimization model to more accurately characterize the effects of the PG operation on water quality, consider more complex PG with storage components, or examine the effects of different PG objectives on water quality. Such studies will help reveal the link between power systems to water quality and have the potential to lead to better infrastructure management.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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