Demonstrating the potential of salt tracer studies to improve Norwegian drinking water network models and water age estimates

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Sammendrag

«Tracer»-studier med salt kan potensielt forbedre norske vannettsmodeller og vannalder-estimater. Hygienisk sikkert drikkevann er et grunnleggende menneskelig behov. Drikkevannskvalitet påvirkes av råvannet, vannbehandling, samt prosesser og hendelser ute på vannettet. Det er vist at drikkevann med høyere alder, eller oppholdstid, kan ha forskjellig kvalitet fra drikkevann som nylig har gjennomgått vannbehandling. I denne studien ble vannalder estimert i Trondheim kommunes vannett ved bruk av datasimulering, samt vannettsmodellen til kommunen. Modellens nøyaktighet ble vurdert gjennom en «tracer»-studie med bruk av natriumklorid (NaCl). Empiriske estimater av vannalder var konsekvent høyere enn simulert ankomsttid for «traceren» ved alle målestasjonene. Likevel ble det funnet god korrelasjon mellom simulert og empirisk vannalder, noe som indikerer at ytterligere justering av vannettsmodellen kan forbedre nøyaktigheten. Dette arbeidet demonstrerte at «tracer»-studier med salt er en kostnadseffektiv, enkel, og trygg metode for å skaffe direkte estimater av vannalder, samt kalibrering av kommunale vannettsmodeller.

Summary

Hygienic drinking water is a fundamental human need. While traversing the drinking water distribution network, water age underlies many water-quality degradation processes, and water with extended age may differ from initial post-treatment quality. In this study, water age was estimated in the Trondheim municipal distribution network using a water network model and simulations. A full-scale sodium chloride (NaCl) tracer study was used to assess the model. Empirical water age estimates at monitoring sites were consistently longer than the simulated tracer peak arrival times. Nonetheless, simulated and empirical water age correlated well, indicating that additional adjustments to the water network model may improve accuracy. This work demonstrated that salt tracer studies are a cost-effective, simple, and safe method to directly estimate drinking water age and calibrate municipal water network models.

Introduction

The United Nations Sustainable Development Goals envision, among other things, good health, clean water and innovative infrastructure for society (United Nations, 2015). Drinking water infrastructure in Norway will require significant investment, approximately 220 billion Norwegian kroner, to update all existing infrastructure to a standard that satisfies these goals (RIF, 2019). Furthermore, after the enteric illness outbreak in Askøy, Norway in summer 2019 due to fecal *Escherichia coli* contamination, drinking water quality and water infrastructure have received more critical public interest, and many municipalities have given potential or existing vulnerabilities more consideration (Bruaset, 2008).

During the days or weeks that water travels through a municipal drinking water distribution network, water quality may degrade due to bacterial growth in the water, interactions of the water with pipe materials or biofilms, or with intrusion of external contaminants via breaks, leaks or planned maintenance activity (van der Kooij, 2000; Makris *et al.*, 2014; Chan *et al.*, 2019). Hydraulic characteristics like flow velocity as well as water residence time (or 'water age') are often critical factors in these events in addition to the subsequent propagation of contaminated water in the distribution network (Douterelo *et al.*, 2013; Haig *et al.*, 2018). Despite its importance, however, water age is difficult to measure or infer directly, especially in the Norwegian context where there are usually little or no chemical additives in finished water product. In contrast, practices common in some other countries, such as residual disinfection or fluoridation, may be utilized to help elucidate how long water has been in a distribution network in those countries.

In this investigation, we aim to demonstrate that a salt tracer, using brine already present at a water treatment plant (WTP) for onsite chlorine production, is an important assessment tool available for water age model calibration when other empirical indicators of water age are absent or unavailable. First, a water network model used by the municipal water authority of Trondheim, Norway, was adapted to EPANET, and then average water age was simulated throughout the municipal distribution network (Rakstang, 2020). Next, the model was used to plan a full-scale tracer study, in which water age was directly measured at six monitoring sites in the distribution network using conductivity to detect salt plugs. Finally, empirical observations of water age were compared to model predictions, revealing some of the challenges of this method but also opportunities for improving water age estimation in Norwegian distribution networks.

Materials and Methods

Description of the municipal drinking water system

Trondheim, Norway, has a population of approximately 205 000 (Statistics Norway, 2020). Municipal drinking water originates from two nearby lakes, Jonsvatnet to the east (primary supply) and Benna to the southwest (secondary and reserve supply) (City of Trondheim, 2017). Jonsvatnet, by way of Vikelvdalen water treatment plant (VIVA), provides water to about 99 % of the city population and is also the reserve supply for the nearby municipality of Melhus (population 16 700). Raw water from Jonsvatnet is withdrawn from a lake depth of 50 m and then travels 4 km by tunnel to VIVA. Water first passes through a granular limestone bed to increase water hardness for corrosion control. Disinfection includes 0.1 mg/L free chlorine (HOCl), produced by electrolysis of a NaCl brine to NaOCl (i.e., the chloralkali process), and ultraviolet (UV) irradiation (40 mJ/cm^2). Under normal operation, production at VIVA is about 750 L/s (23.7 × 10^6 m^3/year). The distribution network includes 800 km of pipe, 12 elevation basins, 20 pump stations and 7000 manholes. Secondary water supply from Benna is withdrawn via two parallel intakes from a depth of 32 m, travels by tunnel 1.5 km, and is disinfected at Benna WTP with UV irradiation (40 mJ/cm^2) and about 0.1 mg/L free chlorine. Normal production is 150 L/s to Trondheim (4.7 × 10^6 m^3/year, via 24 km pipeline) and 50 L/s to Melhus (1.6 × 10^6 m^3/year).

Water network model and simulation studies

The City of Trondheim maintains a water network model using MIKE URBAN software

(DHI Group), which was exported to EPANET 2.0 software (U.S. Environmental Protection Agency) for simulation studies. This model consisted of approximately 9500 nodes and 10 800 links, with 48 different daily demand multiplier patterns to represent water consumption variations in the distribution network. The model was built with a traditional top-down approach (Blokker *et al.*, 2016), meaning water demands were clustered into the 9500 nodes rather than 51000 individual building connections (City of Trondheim, 2017). Custom scripts in MATLAB software (MathWorks, Inc.) were used to perform water age and chemical tracer simulations with EPANET, utilizing the 'epanet-MATLAB' package (Uber, 2013).

Water age simulation

For water age simulations, both WTPs were assumed to be operational. Reservoir nodes at Jonsvatnet and Benna were designated the origin ($t = 0$). During initial simulations, water age stabilized at approximately 120 days (2880 h), so this duration was used in subsequent runs. Time-step intervals were 10 min. Final simulations determined the average and maximum water age for each node, with averages representing the mean of the final 48 h in simulation time. Water ages were visualized using QGIS 3.4.15 software (QGIS Development Team, 2020).

Tracer simulation

Propagation of a chemical tracer through the distribution network was simulated for approximately 1 week. Only VIVA operation was simulated, matching conditions during the full-scale study (i.e., Benna WTP was not in service). To model NaCl, chemical reaction coefficients in EPANET were set to zero. Additional model nodes were inserted closer to the inlets and outlets of selected storage basins to improve simulation results at those locations. A node inside the simulated VIVA introduced 20 mg/L tracer for 1 h, and in later comparisons to the full-scale study, 30 min was added to simulated values to account for the chlorine contact basin at VIVA, which has a 30 min residence time. Hydraulic and water quality calculations used a 5 min time step.

Notably, conductivity predictions in the simulation represented the change in conductivity due to the tracer, in contrast to the actual conductivity. Therefore, in subsequent comparisons against measurements from the tracer study, simulated values were transformed by either adding the median observed conductivity at each site (sites 2 to 6) or minimum conductivity (site 1), which were assumed to represent the background.

Tracer study

Water age was estimated in the full-scale distribution network using a salt tracer, as previously demonstrated (Skipworth et al., 2002). Salt-saturated brine (NaCl) was already present at VIVA for production of free chlorine via electrolysis. Salt was selected as a tracer because it is safe for consumers, cost effective, and easy to measure in real-time as conductivity. In addition, the onsite brine system was mostly automated and required little personnel time. The brine was injected directly downstream of filtration for 1 h, dosed to achieve approximately 20 mg/L NaCl and corresponding to a conductivity spike of about 30 µS/cm (at 20ºC) (Figure 1). By injecting at the inlet of the chlorine contact basin, complete mixing was ensured prior to distribution. In total, 161 L of brine was injected, equivalent to 57.6 kg of NaCl. The average 20ºC conductivity of finished water product at VIVA in 2019 was 132 µS/cm, and with the additional spike due to the tracer, the final conductivity was expected to be well below the Norwegian drinking water standard of 250 µS/cm (Helse- og omsorgsdepartementet, 2019).

Six monitoring sites were selected: effluent of VIVA, two storage basin inlets, and three pumping stations (Figure 2). Manual measurements were taken every 5 min at VIVA (site 1) using a WTW LF 537 conductivity meter. In the distribution network (sites 2 to 6), conductivity was measured every 5 min using either Ponsel conductivity probes (SN-PC4EB-5713) and

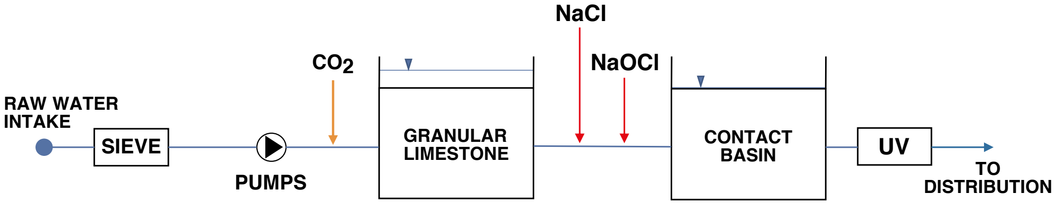

Figure 1: NaCl tracer injection point at Vikelvdalen water treatment plant (VIVA).

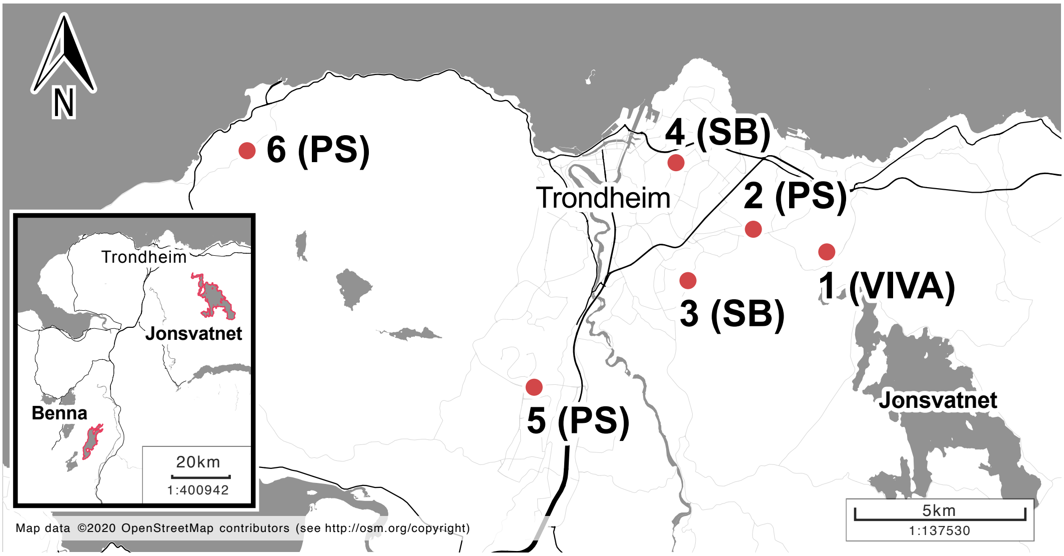

Figure 2: Conductivity monitoring sites during the full-scale tracer study. VIVA = Vikelvdalen water treatment plant, PS = pumping station, SB = storage basin. Map data: OpenStreetMap Contributors (2020).

Campbell Scientific data loggers (CR200X and CR300) or a WTW Multi 3630 handheld logger equipped with a TetraCon 925-3 probe. All meters were calibrated with a NaCl standard prior to data acquisition. As there was a limited number of probes available relative to the number of monitoring sites, several probes were manually relocated during the tracer study. Relocation was scheduled based on when the tracer peak was expected during preliminary simulations.

Results

Water age simulation

The average estimated water age was less than 4 days for over half of the Trondheim distribution network (51.2 %) when both VIVA and Benna WTP were in operation (Figure 3). Nearly 73.1 % had a water age less than 8 days. In 25.9 % of the network, however, average water age may exceed 8 days. Furthermore, maximum water age (not shown) may exceed 8 days in 39.1 % of the distribution network. Extended water ages appeared to be most prevalent in the city center, which is also among the most densely populated areas of Trondheim. Certain nodes in the distribution network were observed to give water age in excess of 60 days, which may be attributed to local dead-ends or other special, low-flow cases. These nodes are likely outliers, as surrounding nodes were often not in agreement.

Tracer simulation and full-scale tracer study

Time points corresponding to the simulated and actual conductivity peaks were identified using the maximum conductivity value. When a conductivity "plateau" existed (i.e., for some simulated peaks), the mean time point was taken among the maximum conductivity values. Simulated condu-

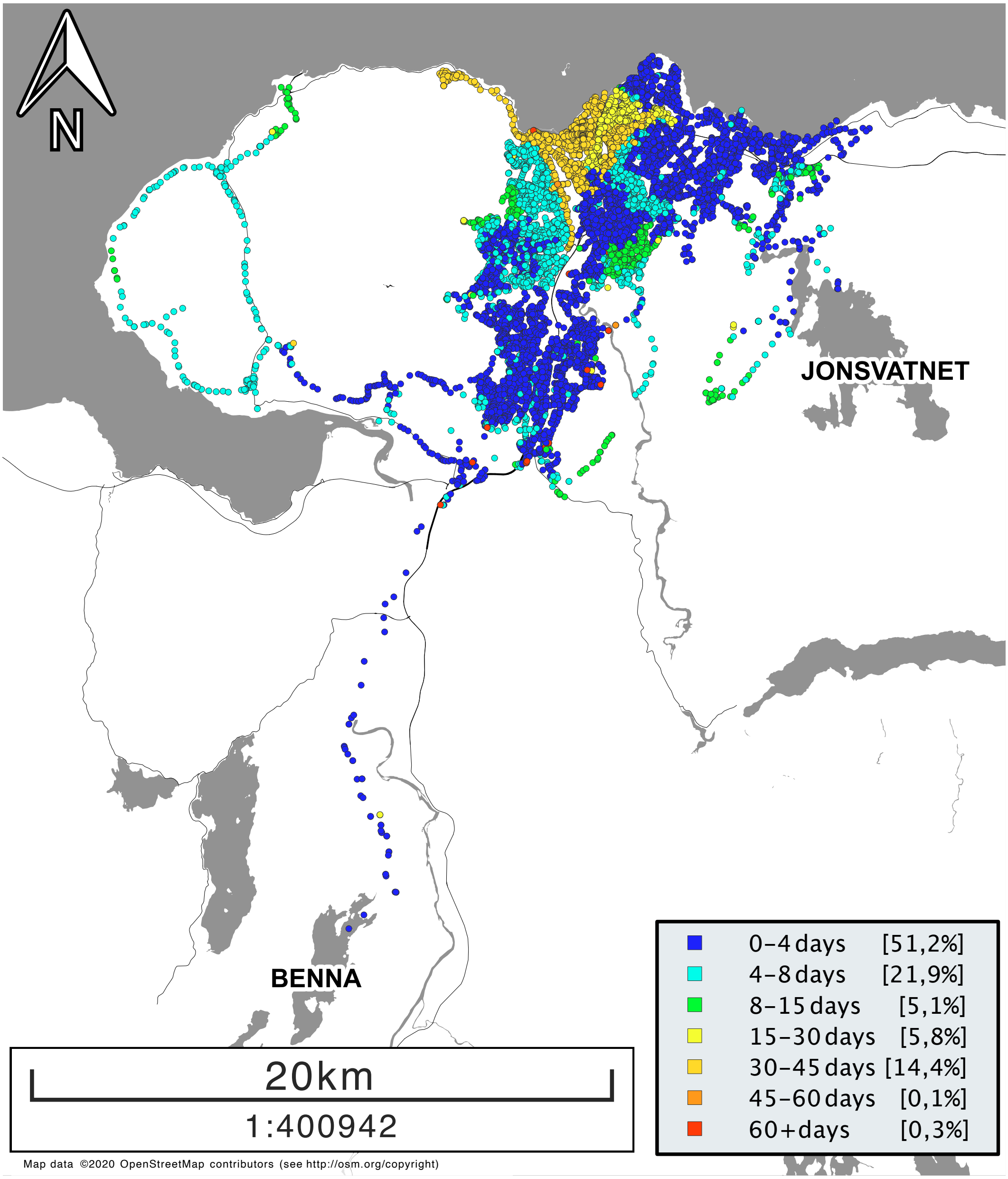

Figure 3: Average water age in the drinking water distribution network at day 120 of simulation, using the mean of the final 48 simulated hours. Map data: OpenStreetMap Contributors (2020).

ctivity peaks at sites 1 to 5 correlated well with observed peaks during the full-scale tracer study (R = 0.995, 95 % confidence: [0.924,1.000]; P =0.0004 using Pearson's product-moment correlation), but the simulated arrival times were consistently too early (Figure 4). Fitting the points by linear regression in R software (R Core Team, 2020), with intercept forced at $t = 0$, the slope was 1.66. This indicated that the further out in the distribution network (relative to VIVA), the greater the difference between simulated and actual conductivity measurements (Figure 5).

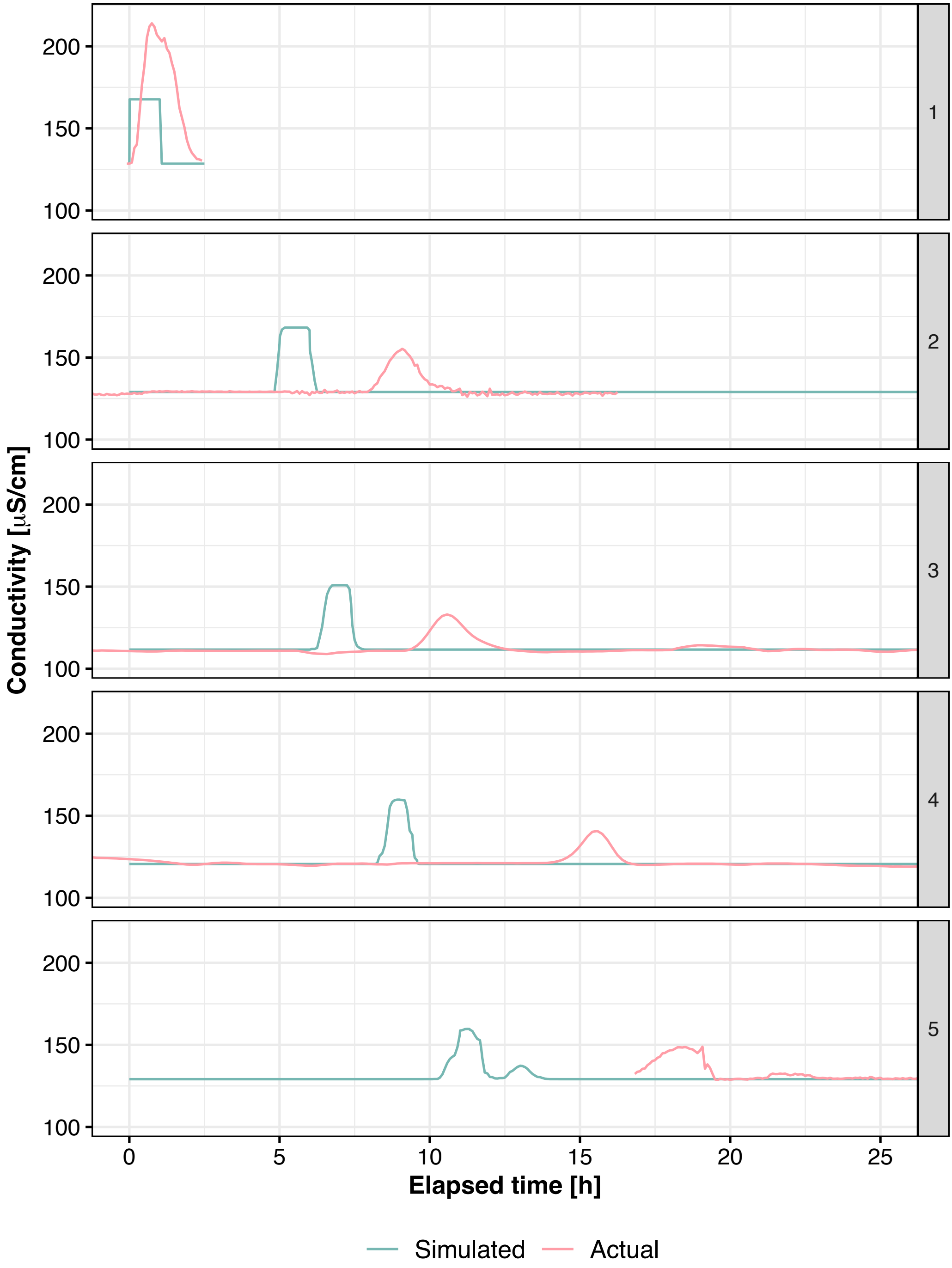

Figure 4: Actual conductivity measured at sites 1 to 5 versus simulated conductivity due to a salt tracer.

A conductivity peak was expected at site 6 at about 41 h but was never observed during approximately 160 h of monitoring. The simulated peak was only 4 to 5 µS/cm relative to baseline conductivity, however, and therefore the conductivity meters may have been unable to detect such a small peak. Site 6 was also the most distally located site in this study and

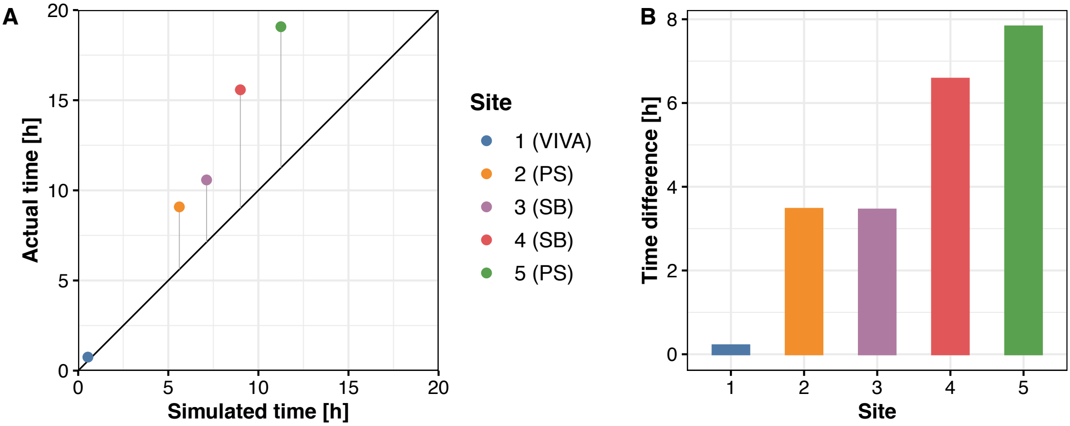

Figure 5: Disparities in actual versus simulated arrival times of a salt tracer at sites 1 to 5: (A) Disparities relative to unity (y = x) and (B) difference in actual peak arrival time relative to simulated peak arrival time. VIVA = Vikelvdalen water treatment plant, PS = pumping station, SB = storage basin.

likewise received water that had been influenced by several different storage basins during its transit.

Discussion

This work demonstrated that tracer studies are possible in the Norwegian drinking water context, where other "traditional" water age indicators like residual disinfectant or fluoride are typically not relevant. The use of salt-saturated brine from the chlorine production process at VIVA further demonstrated that existing infrastructure and equipment, when paired with conductivity meters capable of data-logging, are a cost-effective, simple, and, importantly, safe means of directly measuring water age in a full-scale distribution network. Though there were disparities in the simulated and empirical water ages, they correlated well, indicating that additional adjustments to the water network model may improve accuracy.

One significant factor contributing to the discrepancy was likely water production at VIVA (i.e., demand from the distribution network). During the first 24 h of the tracer study, the actual production volume at VIVA was only about 45 % of the simulated volume via EPANET (31×10^3 m^3 versus 68×10^3 m^3). In terms of flow rate, the simulated production at VIVA averaged 790 L/s during the 24 h period, which was near the 750 L/s estimated from total annual production in previous years. The actual measured production, however, averaged only 360 L/s during these 24 h. The reduced production would result in slower movement of water in the distribution network. To correct for such a discrepancy, the demand nodes and patterns may need adjustment, which was beyond the scope of this project. However, the high level of correlation between observed and simulated arrival times indicated that an accurate estimate of the water ages could be easily obtained by adjusting the total demand in the model. It was also unclear whether this discrepancy was temporary due to, for example, water usage changes during the COVID-19 pandemic and/or a national holiday that had occurred just prior to the study, in addition to normal seasonal variations.

Another influential factor was likely the starting conditions in the water network model and tracer simulation, such as initial filling levels in storage basins. If the model assumes different filling levels than actual conditions, flow estimates will be inaccurate. Starting the tracer simulation after the model had been first run for several simulation days, similar to what was done for the water age map, may reduce basin level starting effects.

Due to special circumstances, some sites may have been more prone to error than others. By accounting for a pumping station that had been deactivated during the tracer study and closing a water main from one of the storage basins, two modifications relevant for site 4, the peak arrival time at site 4 increased by approximately 30 min. This highlighted the need for good "on-the-ground" knowledge of distribution network operation (e.g., communication with municipal operators, technicians or engineers).

To improve future tracer studies, localized tracing, e.g. in low-demand areas or at the distal/ peripheral ends of the distribution network, may help avoid situations like experienced at site 6. Additionally, conductivity measuring equipment, if connected with the SCADA system found at every pumping station and storage basin, could greatly increase the number of measurement sites and enable real-time conductivity monitoring in addition to flow rate monitoring.

For future research and development connected with the water network model, implementation of stochastic demand patterns could be combined with an effort to expand and transition the model into an "all nodes and all pipes" type, as described by Blokker *et al.* (2010). Smart residential water meters could provide an opportunity for specific statistical water consumption data.

Contextualizing the water ages estimated here, previous work has indicated that the assimilable organic carbon (AOC) in Trondheim drinking water ranges from 70 to 110 µg/L as acetate (Waak et al., 2018; Johansen, 2018), while others have suggested that non-chlorinated drinking water with AOC above 10 µg/L is not biologically stable (van der Kooij, 2000). Water temperature is not ideal for bacterial proliferation of thermophilic organisms in the Trondheim distribution network (often <10ºC), but potentially problematic bacteria like *Legionella* have nonetheless been observed at such temperatures (Wullings and van der Kooij, 2006). Furthermore, in water containing residual free chlorine (HOCl) or chloramine (NH_2Cl), additives that mitigate bacterial growth, growth and associated water chemistry effects have been observed in 10 days or less (Masters *et al.*, 2015). Likewise, the longer water is in contact with pipes and pipe-associated biofilms, the greater the potential for water quality problems (Makris *et al.*, 2014). Because the simulated water age was consistently underestimated, actual water age may be greater than shown here for a significant part of the network. In addition to further calibration of the water network model, future work may investigate drinking water quality in context of water age and water movement patterns in the network.

Conclusion

Water age was estimated in Trondheim's distribution network using a water network model. Estimates indicated that the majority of nodes (73.1 %) in the model averaged below 8 days, but some areas of the distribution network may have significantly higher water ages. A full-scale tracer study was conducted for the first time in Trondheim and was successful with a relatively low salt tracer dose. During this study, actual water age was longer than model predictions, because simulated water demand was higher than the actual demand during the tracer study. Future work could improve calibration of the water network model as well as the manner in which the salt tracer is monitored. Water age and movement patterns could also be linked to water quality data to identify and address potential water quality challenges.

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