Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Civil and Environmental Engineering

Sang Munn Kim

Source Trace Analysis: Investigating Hydraulic Limits and Cell Count in Trondheim Drinking Water Distribution System

Master's thesis in Civil and Environmental Engineering
Supervisor: Cynthia Hallé
Co-supervisor: Marius M. Rokstad, Michael B. Waak
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Preface

This MSc thesis is the product that marks the end of 2 year long MSc program for Civil and Environmental Engineering at Norwegian University of Science and Technology in Trondheim, while at the same time being the embodiment of the culmination of work that has transpired over my journey for higher education that initiated in 2015. The main topics for this thesis, source trace analysis and tracer study in drinking water distribution system, were introduced to me by my supervisors in fall 2021. It has since been subjects that have been in the background of my MSc program through preparatory work for MSc thesis during fall semester 2021 and MSc thesis during spring semester 2022. The endeavor has been incredibly enlightening and interesting but were also followed with several challenges. Nonetheless, I am incredibly grateful for getting the opportunity for completing my MSc degree with subjects and topics that have the overall aim of benefitting people with better water quality and health, which has contributed to a sense of importance in my work.

First and foremost, I want to thank my mom Benedikte for always being there with lots of support, positive energy and always being in her thoughts and prayers. I thank my girlfriend Julie for all the encouragement and comforts, as well as helping me with making some of the illustrations that were made for this thesis. I give huge thanks to my supervisor Cynthia for giving clear instructions and excellent follow-up for the past one year period, and for giving tremendous amount of assistance for work with automated flow cytometry, tracer study and other supporting work. I thank Marius for assisting with water distribution modelling which has been a huge contribution to this thesis. I thank Michael for providing with resources and introducing me to central pieces of ideas for this thesis which has been significant for shaping the objectives and the research questions. I thank Trine and Marina for training and giving instructions for the lab work, and for the tremendous amount of general assistance in the lab. Finally, I want to thank all the people here in NTNU and workers at VIVA that have helped with the preparation of automated flow cytometry and tracer study, whom the project would have not become possible if not for their assistance and contribution.

Sang Munn Kim

Trondheim, 10th of June 2022

Abstract

There are many challenges of maintaining satisfactory water quality in a water supply network. Drinking water in distribution systems are subject to water quality deterioration that are often related to hydraulic residence time. Water quality issues and pollution in a source can spread through distribution system, where the extent of the spread is determined by hydraulic limits of the source. Additionally, drinking water distribution systems with more than one water source form zones where water from different sources mixes with each other, dividing the distribution system into areas of mixing and no-mixing.

The main purpose of this thesis has been to demonstrate the feasibility of performing a type of water quality characterization study called source trace analysis, with aims to identify mixing zones and hydraulic limits of the two water sources in Trondheim drinking water distribution system. Parameters that are suitable for source trace analysis in drinking water distribution system in Trondheim was investigated through field work. Thereafter, simulation of source trace analysis in Trondheim distribution system with aims to identify mixing zones was performed using hydraulic modelling software EPANET. Furthermore, tracer study with NaCl combined with automated flow cytometry was performed to relate growth of bacterial cell counts in distribution system to hydraulic residence time. The purpose was to assess suitability of using bacterial cell count as a parameter for source trace analysis and investigate whether bacterial cell count can be used to determine water age.

The results from field work showed that conductivity and color are suitable parameter for source trace analysis, showing that source trace analysis with field data is feasible in Trondheim. Through modelling and simulation, hydraulic limits of the two water sources in Trondheim, as well as mixing zones in distribution system were identified. Bacterial cell counts were observed to be fluctuating within a range that differed between locations in the distribution system, suggesting that cell counts are stable in a location but also subject to change during distribution. Relating bacterial cell count to hydraulic residence time in order to determine bacterial cell count growth rate was attempted but did not give a meaningful result, mainly due to lack of data. More measurement of cell counts is needed at more locations before a bacterial cell count growth rate can be determined for water in Trondheim drinking water distribution system and remains for future work.

Keyword

Source Trace Analysis, Tracer Study, Water Distribution Model, Automated Flow Cytometry, Drinking Water Distribution System, Cell Count, Hydraulic Residence Time.

Sammendrag

Det er mange utfordringer ved å opprettholde tilfredsstillende vannkvalitet i et vannforsyningsnett. Drikkevann i vanndistribusjonsnettverk er utsatt for forverring av kvalitet forårsaket av reaksjoner ofte knyttet til hydraulisk oppholdstid. Vannkvalitetsproblemer og forurensning i en vannkilde kan spre seg gjennom distribusjonsnettverk, hvor omfanget blir bestemt av hydraulisk grense til kilden. I tillegg former vannforsyningsnett med mer enn en vannkilde, områder i nettet hvor vann fra forskjellig kildene møter og mikser med hverandre. Dette skaper områder i nettverket hvor det er blanding av vann fra flere kilder.

Hovedformålet med denne oppgaven har vært å undersøke gjennomførbarheten til en type vannkvalitetsstudie kalt kildesporing med mål om å identifisere områder med miksing og identifisere hydraulisk grense for de to vannkildene som eksisterer i Trondheim vanndistribusjonsnettverket. Parameter som er velegnet for kildesporing i distribusjonsnettverket i Trondheim ble undersøkt gjennom feltarbeid. Deretter ble det gjort en data-simulasjon på kildesporing ved å benytte hydraulisk modelleringsprogram kalt EPANET. Videre ble det gjennomført et tracer studie med NaCl kombinert med automatisk flowcytometer for å finne sammenheng på celle vekst i vanndistribusjonsnettverket med hydraulisk oppholdstid. Målet var å vurdere om celler i drikkevann kan bli brukt som en parameter for kilde sporing og om celle tall kan bli brukt til å bedømme vann alder i drikkevannsnettverk.

Resultater fra feltarbeid viser at konduktivitet og vannfarge er velegnet parametere for kildesporing, noe som demonstrerer at kildesporing gjennom felt arbeid er gjennomførbar i Trondheim. Ved modellering og simulering ble hydraulisk grense for to vannkildene i Trondheim avdekket, i tillegg til områder som opplever miksing. Celler i drikkevann ble observert til å fluktuere innen en rekkevidde som er relativt stabilt, men forskjellige områder i distribusjonsnettverk ble observert til å ha forskjellige celletall. Dette foreslår at celletall endrer seg i distribusjonsnettverket og er karakteristisk for sted til sted. Forsøk på å danne et forhold mellom cellevekst og hydraulisk oppholdstid mislyktes, hovedsakelig på grunn av at det krevde mer data enn det som ble samlet. Det kreves derfor mer data for at hastigheten på cellevekst i drikkevann kan bli fastslått for distribusjonsnettverket i Trondheim. Dette gjenstår for fremtidig arbeid.

Nøkkelord

Kildesporing, Tracer Studie, Vann-Netts Modellering, Automatisk Flowcytometer, Vanndistribusjonsnettverk, Celletall, Hydraulisk Oppholdstid.

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List of Abbreviations

CMFR – Completely Mixed Flow Reactor

DCC – Damaged Cell Count

DWDS - Drinking Water Distribution System

DWTP - Drinking Water Treatment Plant

EPS – Extended Period Simulation

FCM - Flow Cytometry/Cytometer

HNAC – High Nucleic Acid Count

ICC – Intact Cell Count

LNAC – Low Nucleic Acid Count

MRT – Mean Residence Time

NOM – Natural Organic Matter

PFR – Plug Flow Reactor

RTD – Residence Time Distribution

TCC - Total Cell Count

VIVA – Vikelvdalen Vannbehandlingsanlegg (Vikelvdalen Water Treatment Plant)

WDM - Water Distribution Model

1 Introduction

Having access to safe drinking water is one of the fundamental human rights set by the United Nations and is deemed one of the most important physiological necessities for human beings [11]. In 2012, it was estimated that around 780 million people around the globe lacks access to safe drinking water and around 760 000 children dies yearly due to diseases that can be related to unsafe water, unsatisfactory hygiene and sanitary condition [12]. Cities in developed countries commonly relies on water supply networks for providing safe drinking water to its inhabitants. This normally entails a single great network that supplies an entire city. As such, water supply networks have tremendous amount of impact on public health as people in cities often have their main and only water source from these networks. The impact is exacerbated by the fact that majority of the population in developed countries tend to live clustered in cities. This is also the case in Norway where only 2% of the population are reported to have private water source that are detached from the existing networks [13]. At the same time, it is documented that a small proportion of waterworks are responsible for providing water to the majority of the population [12]. Correspondingly, study by *Guzman-Herrardor B et al.* [14] for waterborne outbreaks in Nordic countries in period 1998 – 2012, observed that outbreaks in larger water supply networks have greater impacts as more people are connected to these networks. It is therefore imperative for public health that drinking water in water supply networks meets the regulatory requirements for safe drinking water at all times.

A typical water supply networks are made up of raw water source, drinking water treatment plant (DWTP) and distribution system. Drinking water distribution system (DWDS) consists of various water infrastructure units such as storage tanks, water tower and pumping stations. These units are usually all connected with each other with several kilometers of pipes which has the function to distribute water to recipients. One problem with this layout is that, due to its interconnectivity, a single location in the distribution system has the potential to spread undesirable contamination to a great extent. Between 2003 – 2012, it was reported 28 cases of waterborne outbreaks in Norway where 16 cases were related to incidents in water supply networks [13]. Two outbreaks, one in the city of Bergen in 2004 and one in the municipality of Røros in 2007, resulted in respectively 6000 and 1500 people becoming ill [13]. Pollution in raw water source have been observed to be the most frequent reason for waterborne outbreaks, but contamination from within water distribution system is also a likelihood and have been evidenced in Norway, such as in the most recent major waterborne outbreak in Askøy municipality in 2019 [13, 15]. The incident affecting around 12 000 people and leading to estimated 2000 people getting sick, was caused by *Campylobacter* originating in an underground storage tank. The leading explanation of the contamination is that the water in the storage tank was exposed to bacteria caused by leaching of fecal matter from birds/animals after rainfall that had seeped through the cracks [15]. Past events of waterborne

outbreaks in large water supply network reveals the need of commitment to have continuous work of management and maintenance to protect and ensure clean water to people. To mitigate for scenarios where pollution spreads to a great extent through distribution system, understanding hydraulic paths and hydraulic limits of critical units in the distribution system such as treatment plants, storage tanks and pumping stations can be helpful to make better judgment in the possible cases of outbreaks. By knowing the hydraulic paths and hydraulic limits in case of contamination from e.g. a storage tank like the case in Askøy, utilities can decide which areas that are most likely affected. This in turn can help utilities to form more educated decisions on which valves to close to contain the contamination and which part of the city to issue boil warning.

To contribute for better understanding of interconnectivity of Trondheim DWDS, this thesis has attempted to demonstrate how to perform a type of water quality analysis called source trace analysis. The objective was to determine hydraulic limits, as well as areas in Trondheim DWDS that experiences mixing of water from two treatment plants, VIVA and Benna DWTP. The idea was that, by performing source trace analysis to determine hydraulic limits for the two treatment plants in Trondheim, future source trace analysis can use the same principles used in this thesis to investigate hydraulic limits of other infrastructural units such as storage tanks and pumping station. Performing source trace analysis has required establishment of constituents found in the drinking water in distribution network that are suitable for source trace analysis. This was done by collecting water samples from in total 29 sampling locations through field work, in addition to collecting samples from the two treatment plants. Areas of mixing was initially planned to be identified by using results from the field work. However, in the period of this project, Benna DWTP was out of operation and this plan became unfeasible. Therefore, source trace analysis with water distribution model (WDM) of Trondheim using the software EPANET had to be performed instead. EPANET allowed simulation of situation where both VIVA and Benna DWTP are in operation, making it possible to identify hydraulic limits of the two treatment plant as well as areas of mixing.

Besides from cases of contamination, general water quality is also subject to deterioration during distribution. There are many reasons, but one general indicator for water quality is hydraulic residence time, also known as water age. This is because as water becomes older, it allows for growth of microbial activities, as well as chemical reactions in the water that can cause negative impact for the quality [16]. As the final part this thesis, feasibility of utilizing bacteria cell count as a parameter for source trace analysis was investigated using automated flow cytometry (FCM) where comparison of cell counts measured at VIVA and cell counts in two pumping stations located in the proximity of VIVA were made. This experiment was performed in conjunction with a tracer study adding NaCl in the outflow at VIVA to determine hydraulic residence time of water from VIVA to one of the pumping stations. The purpose

of the tracer study was to observe how the cell count changes from VIVA with regards to time in the distribution system. By combining the results from FCM and the tracer study, an attempt was made to observe if hydraulic residence time can be determined by observing cell counts in DWDS.

2 Objectives and Research Questions

The main objective of this thesis has been to investigate hydraulic limits of the two DWTP that are in Trondheim DWDS. This objective raised following research questions:

- Which part of Trondheim DWDS are primarily supplied by VIVA?
- Which part of Trondheim DWDS are primarily supplied by Benna DWTP?
- Which part of Trondheim DWDS experiences mixing of water from VIVA and Benna DWTP?
- Where is the hydraulic limit of VIVA and Benna DWTP in Trondheim DWDS?

To prove that source trace analysis is feasible in Trondheim DWDS, it has required investigation of constituent in the drinking water in Trondheim that are suitable to be used as parameter for source trace analysis. The main criteria for suitable parameter were that they should be conservative in distribution system and the concentration of the constituent/parameter between VIVA and Benna DWTP are noticeably distinguishable from each other. Therefore, additional research questions were raised and were as follows:

- What constituents/parameter in drinking water at VIVA and Benna DWTP have noticeable difference in concentration/value?
- How suitable are these parameters for source trace analysis?

As supplementary research, feasibility of using bacterial cell count in drinking water as a tracer to determine hydraulic residence time as well as a parameter for source trace analysis was investigated, employing automated FCM to measure bacterial cell count at VIVA and two nearby pumping stations.

- How suitable is bacterial cell count as parameter for source trace analysis?
- What is the growth rate of bacterial cell count in treated water from VIVA during distribution?
- Can bacterial cell count be used to determine hydraulic residence time of water in Trondheim DWDS?

3 Study Area

This thesis has involved gathering samples and conducting experiments directly on Trondheim DWDS. To assess how the experiments can be best conducted has required a clear understanding of Trondheim DWDS. Therefore, this chapter aims to give better understanding of Trondheim DWDS and the elements within, to give clear context to the research that were performed. General information of the neighboring municipality Melhus and Malvik municipality are also presented for the same purpose. This is because Trondheim DWDS extends beyond the borders of Trondheim municipality and are connected to the DWDS that are in Melhus and Malvik municipality. The experiments of this MSc thesis have taken place primarily within the border of Trondheim municipality but has also to some lesser degree involved gathering samples from Melhus municipality.

3.1 Trondheim

Located in central Norway, Trondheim is one of the major city and municipality in Norway. As of 3rd quarter of 2021, it was registered that Trondheim municipality have 209 802 inhabitants, making it the third most populous municipality and forth largest urban settlements in Norway [17-19] . It is also the home to NTNU in which this MSc thesis is written for [20]. Total area of Trondheim municipality is estimated to be 528.61 km^2 and density of the population 414 people/km^2. Overwhelming majority with 96% of the population lives in what is defined as the urban area [21]. Administratively, the district of Trondheim is divided into four main parts: Midtbyen, Østbyen, Heimdal and Lerkendal [22].

Trondheim municipality borders Melhus municipality to the south and Malvik municipality to the east. Relative location to each other can be seen in *Figure 1*. In 2020 the former neighboring Klæbu municipality merged with Trondheim, becoming a part of Trondheim municipality whilst adding additional 6076 inhabitants under Trondheim municipality's administration [23, 24].

According to the Köppen-Geiger climate classification system, climate of Trondheim can be classified into the group ''Dfc'' meaning, D = cold, f = without dry season and c = cold summer [25]. This falls into the climate type *continental subarctic climate*, characterized by long period of cold winter and short cool summer [26]. The average annual precipitation and temperature in Trondheim for the period 1986 – 2015 was 1191 ± 184mm and 5.3 ± 1.1°C respectively [27].

3.2 Melhus and Malvik

Located south of Trondheim municipality, Melhus is smaller a municipality in terms of population size but bigger in terms of land area. The total size of Melhus is 694.41 km^2 and there were in total 17 060

inhabitants in 3rd quarter of 2021 [28]. The city center of Melhus is only 20 km away from the city center of Trondheim, with good road connections between the two centers. The same applies for Malvik municipality where its city center is 15.7 km away from Trondheim. Malvik municipality is a smaller municipality in terms of both population size and land area than Trondheim. Population size was 14 320 as of 3rd quarter 2021 and its land area is 168.44 km^2 [29].

The climate of Melhus and Malvik are similar to that of Trondheim municipality characterized by *continental subarctic climate* according to the Köppen-Geiger climate classification system [25].

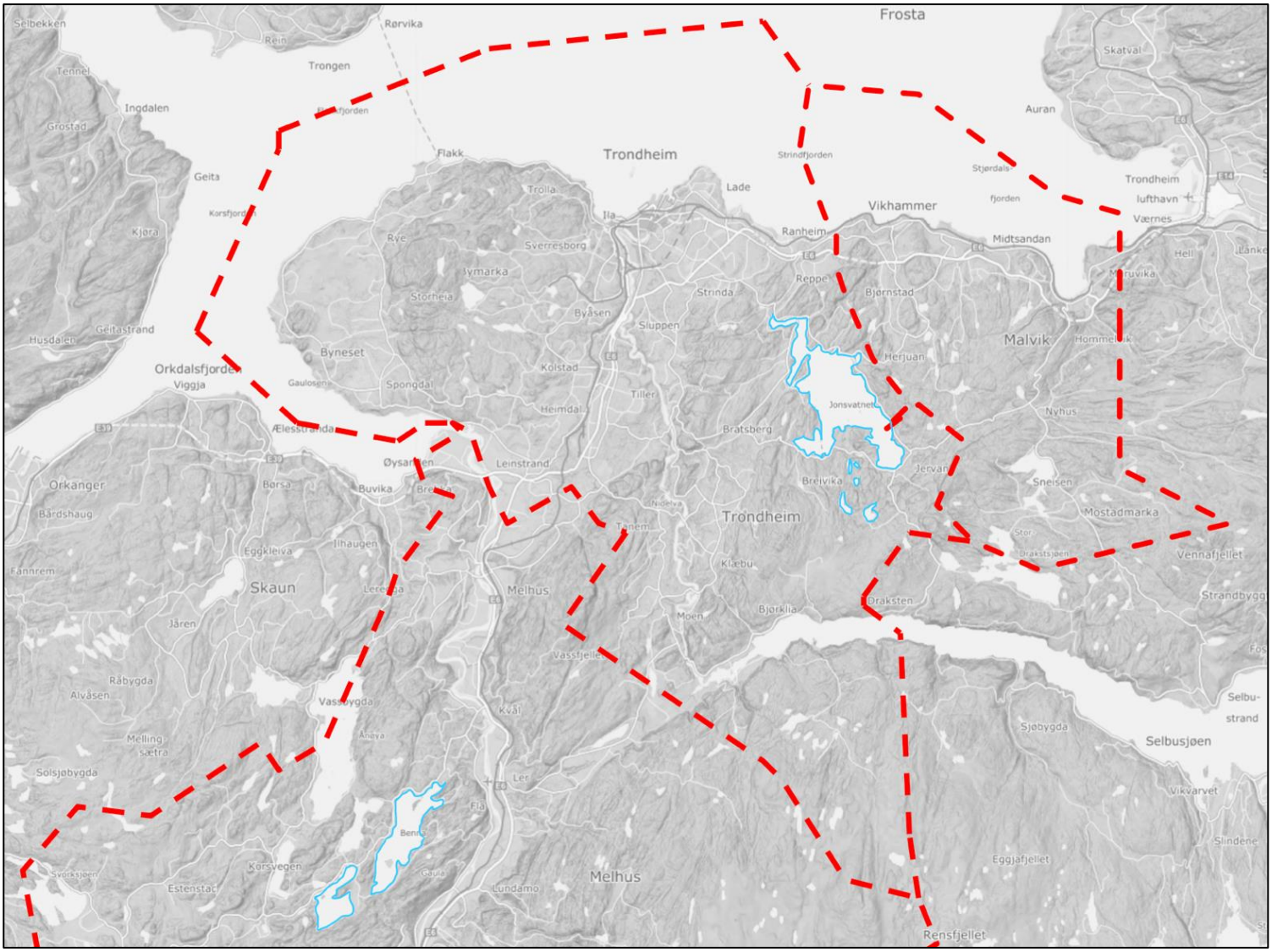

Figure 1. Overview of the borders of Trondheim municipality and neighboring Melhus and Malvik Municipality. The two water sources for Trondheim and Melhus municipality, Jonsvatnet and Benna Lake are highlighted with blue lines. The map was made based on maps from Kartverket (2022) [5] and GEONORGE (2022) [9].

3.3 Drinking Water Distribution System in Trondheim

Trondheim waterworks is the entity that operates drinking water treatment and drinking water distribution for Trondheim, Melhus and Malvik municipality. In the hierarchical order, Trondheim waterworks operates under Trondheim municipality [7]. There are two primary water sources that supplies these municipalities: Jonsvatnet Lake in Trondheim and Benna Lake in Melhus. The locations of these water sources are illustrated in *Figure 1* and *Figure 2*. Jonsvatnet is the primary water source for Trondheim and Malvik municipality whilst Benna is the primary water source for Melhus municipality. Up until 2016, the DWDS in Trondheim and Melhus were separated but through the MeTroVann project between Trondheim and Melhus municipality, the two DWDS were connected with the intention to increase redundancy [7, 30]. In the present time under normal operation, Trondheim is primarily supplied by water from Jonsvatnet but also to some lesser degree by Benna. This involves mainly the southern and eastern part of Trondheim, which it supplies approx. 150 L/s [30]. Under normal operation, Melhus municipality is supplied solely by water from Benna of which it consumes about 50 L/s [7]. The former Klæbu municipality has their own, separated DWDS which is supplied from the ground water source Fremo that lies in Melhus municipality.

In 2015, out of 184 960 inhabitants in Trondheim, 100% of inhabitants were connected to DWDS managed by Trondheim waterworks. Out of 240 000 inhabitants in Trondheim, Melhus and Malvik municipality, more than 97% of the population is connected to DWDS operated by Trondheim waterworks, according to figures from 2015 [7].

In 2015, the average water consumption was 285 liter per person in Trondheim, 404 liter per person in Melhus and 365 liter per person in Malvik. This includes water loss due to leakage and water consumption by businesses, schools, hospitals etc. In total, Trondheim consumed about 609 L/s, Melhus 47 L/s and Malvik 57 L/s [7]. It is estimated these municipalities, and especially Trondheim, consumes more now in 2022 due to population increase.

Alike water in other Norwegian municipalities, water quality in Trondheim is deemed superb [31]. The temperature of water supplied is typically cold, ranging from 5.2 – 8.5 °C [32].

3.3.1 Infrastructure

There are one DWTP for each of the two lakes that supplies Trondheim. Water from Jonsvatnet lake is transported through rock blasted tunnel to the nearby treatment plant VIVA. The same applies to Benna where the water is transported from Benna Lake to Benna DWTP through rock blasted tunnel [7]. Location of these two DWTPs are shown in *Figure 2*. After treatment, about 80-90% of the water from

VIVA is transported through 1.1 km of rock blasted tunnel, called Vikåsen Tunnel before it is transported to the rest of DWDS. The treated water from VIVA, that supplies majority of Trondheim and Malvik, is

Figure 2. Drinking Water Distribution System in Trondheim. The blue lines illustrate main water lines, checkered area equals drainage basins, and the striped lines illustrate water tunnel from the water sources to the treatment plants. The red arrows points to the approximate location of the drinking water treatment plants. Screenshot from report *Kommunedelplan for vannforsyning 2017 - 2028* [7].

distributed through extensive infrastructure. In Trondheim, this includes estimated total sum of 1700 km of pipes, 7 km tunnels, 20 pumping stations and 12 storage tanks. Of the 1700 km of pipes that exist, 800 km are managed by the municipality while the rest are privately managed [7]. The 12 tanks vary in style from some being placed above the grounds whilst some are rock blasted underground tunnel pools. To have sufficient capacity to meet maximum daily demands, fire demands and other emergency demands, they have total volume of 89 000 m^3 and safety reserve of 69 300 m^3. In addition, there are 5 000 m^3 reservoir in the Vikåsen Tunnel.

The water main that connects Benna DWTP with DWDS in Trondheim is 24 km long, has dimensions between 600-1000 mm and has connection point in Kolstad pumping station located in the south of Trondheim [30]. In parallel with water main, there are also wastewater pipe that transport wastewater from Melhus to Høvringen wastewater treatment plant [33]. The location of Kolstad pumping station can be identified in *Figure 3*. Through the MeTroVann project, Kolstad pumping station was remodeled to have the capacity to pass on drinking water from Benna to entire Trondheim and Malvik municipality [30]. Under normal operation, Kolstad pumps 200 L/s of water of which 150 L/s is consumed by Trondheim. Max capacity of Kolstad pumpstations is 800 L/s by current design and the capacity is good enough to satisfy combined water consumption for Trondheim, Melhus and Malvik, which was estimated to be 750 L/s in 2015 [7, 30].

In general, DWDS in Norway have a relatively high water loss due to leakages, where it is estimated that almost a third of the produced water gets lost during transportation [34]. This is also true for Trondheim DWDS, as the water loss due to leakages is estimated 30% [7]. Leaks also increase the risk for contamination in water pipes in case of low or loss of pressure, as drinking water pipes in Norway often share the same ditch as urban drainage and sewage pipes [34]. Primary reasons for the leakages are because of corrosions on grey and cast-iron pipes. In Trondheim, it was a common practice to place iron pipes underground without any forms of protections up until 1975 [7]. Because of this, leakages due to corrosions on these pipes has been the main challenge regarding water loss. The fact that the pipes that have most leakages are also without any form of protection adds to the vulnerability of contamination. Minimum required renewal rate of old pipes in Trondheim are estimated 7 km per year meaning 0.9% renewal of all existing pipes per year. This is the goal for renewal for Trondheim municipality as well as reducing water loss to 20% [7]. The most common pipe materials in Trondheim are ductile cast iron, grey cast iron, polyvinyl chloride (PVC), polyethylene (PE) and glass fiber reinforced plastic (GRP) [7]. The use of plastic pipes did not start until 1970s but has since then been increasing and in present time, over half of newly laid and renewed pipes are made of plastic materials. The average age of pipes is 36 years in Trondheim DWDS [7].

For the period 2017 - 2028, Trondheim municipality have set aside 2125 MNOK to spend on maintenance, repair and renewal of Trondheim DWDS. This includes the sum used for renewal of old pipes, repairs and renovations of existing storage tanks and pump stations, and expansion of VIVA to name a few [7]. It has also been expressed an ambition to connect Fremo DWDS to Trondheim to increase redundancy even further. Fremo groundwater is reported to have among the best drinking water quality in Norway, as well as being the second largest ground water reserve in Norway [7, 35, 36].

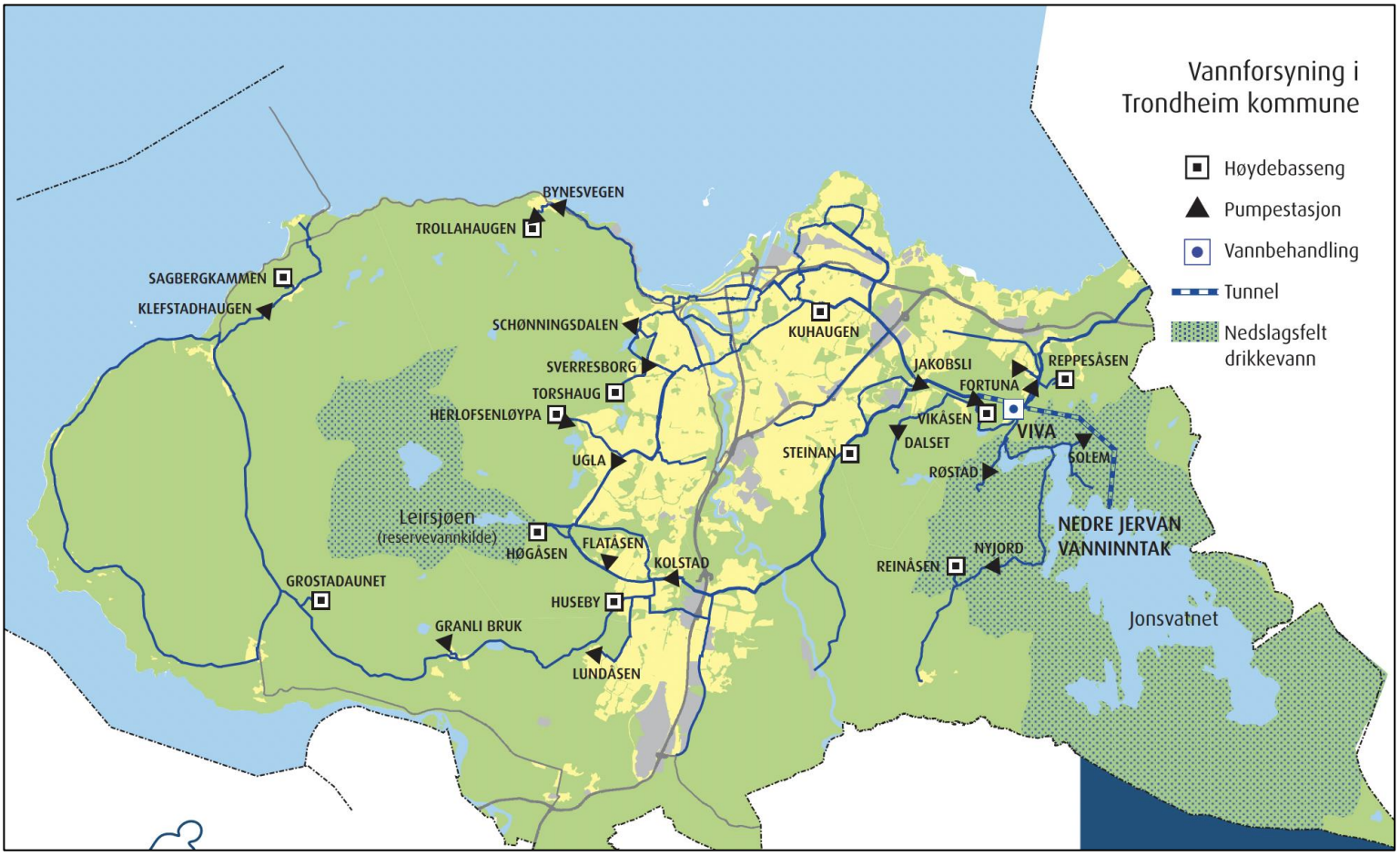

Figure 3. Overview of Trondheim DWDS and its various infrastructure. Screenshotted from brochure *Drikkevann – en livsviktig ressurs. Om vannforsyningen i Trondheim kommune* [4].

3.3.2 VIVA Drinking Water Treatment Plant

Originally constructed in 1998, VIVA was designed for treatment of water from Jonsvatnet to provide clean and safe drinking water to Trondheim and Malvik municipality [7, 33]. Today it is also backup water supply for Melhus municipality. This materialized during the summer of 2017, when it was found that there were Copepods and Pallasea in parts of distribution system that was supplied from Benna [31, 37]. This issue forced Trondheim waterworks to shut down operation in Benna DWTP until October

2019. During that time, VIVA was the sole DWTP that provided water for Trondheim, Melhus and Malvik [31, 38].

During the period of source trace analysis for this thesis 15. March.22 – 25. March.22, it was unexpectedly revealed that Benna DWTP had been shut down again due to Copepods and Pallasea. Trondheim DWDS is therefore currently (March. 2022), solely supplied by VIVA once again.

The treatment process at VIVA starts by raw water intake 4 km away from VIVA, at depth of 50 m by one of two parallel water intake pipes. Each of these pipes possess sufficient capacity to supply Trondheim, Melhus and Malvik [7]. Before the water is transported by gravity through 4 km of rock blasted tunnel to VIVA, the water goes through rotating belt sieve with mesh size of 0.5 mm at the sieving chamber located at Jonsvatnet. As the water of Jonsvatnet are described as corrosive, primarily due to low alkalinity and calcium content, the initial step of the treatment process starts by CO_2 injection and filtration through crushed limestone [4, 7, 33, 39]. This process raises the pH from 7.4 to 8, alkalinity from 0.3 to 1 mmol/l and calcium from 7 to 20 mg/l. This step is followed by disinfection process with chlorination using sodium hypochlorite (NaOCl) resulting in free chlorine OCl^- and HOCl in the water. As the final step, UV light is used for additional disinfection before the produced water is supplied to Trondheim DWDS. The average rate of water produced from VIVA is estimated 750 L/s, but the maximum capacity is estimated 1400 L/s [7, 33, 39].

Sodium hypochlorite (NaOCl) is produced onsite at VIVA by performing electrolysis of brine solution. The brine solution is also created onsite and storage tank with sodium chloride (NaCl) exist within VIVA [7, 33]. The chlorination disinfection step followed with limestone filtration is considered unfortunate as high pH reduces the effectiveness. After filtration with limestone the pH of water is raised to pH 8, and it has been observed that at this pH, there are only 20% of free chlorine HOCL, which is the compound that gives the best disinfection [7]. As such, current disinfection process are able to neutralize bacteria but are vulnerable against certain viruses such as Adenovirus, which also does not get neutralized by the UV lights [7]. Risk assessment done by Trondheim municipality predicts that future climate change will result in more flooding and intense rainfalls. Combined with temperature increase, natural organic matter (NOM) content in water is likely to be higher, thus raising color value of water of Jonsvatnet and reducing effectiveness of the existing disinfection steps. Expansion of VIVA might therefore be necessary in the future. For these reasons, coagulation and/or contact filtration are recommended to be added [7].

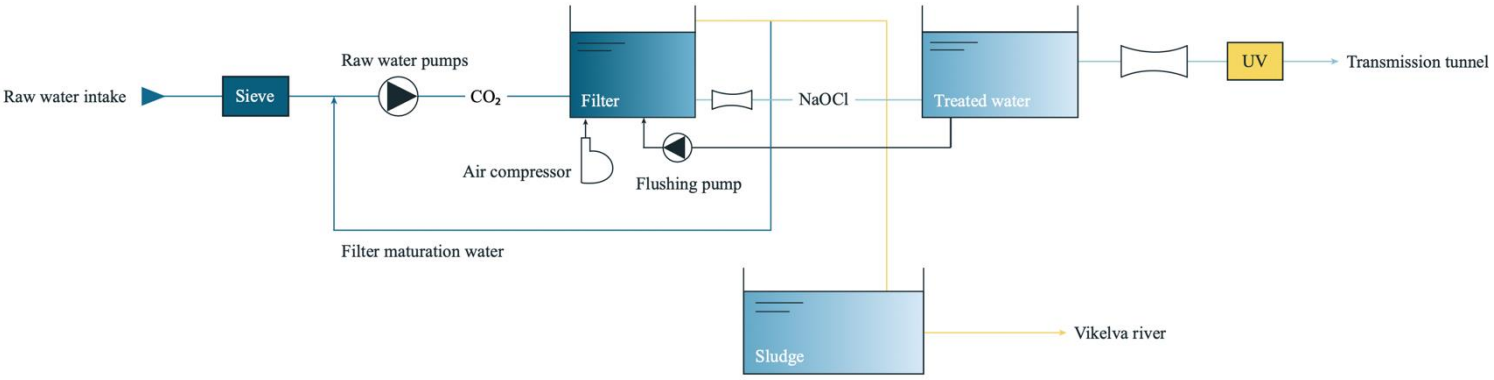

Figure 4. Treatment process at VIVA. Illustration based on figure 4.6 from report *Kommunedelplan for vannforsyning 2017 - 2028* [7] and figure 5 from MSc thesis by Jon.K Rakstang [38].

3.3.3 BENNA DWTP

The current Benna DWTP was opened in spring 2016 and was constructed in relation to the MeTroVann project [7, 30]. The treatment is similar but simpler to the one at VIVA. The process starts with raw water intake 32 m depth which is led to sieving chamber that uses rotating belt sieve with mesh size 0.25mm. Like VIVA, there are two water intake pipes for redundancy. After sieving, the water is transported through 1.5 km rock blasted tunnel until it reaches Benna DWTP. The raw water then passes through UV light chambers before it goes through disinfection by chlorination with sodium hypochlorite (NaOCl) [7, 30]. Unlike VIVA, offsite produced sodium hypochlorite (NaOCl) is used. The water from Benna is not corrosive as from Jonsvatnet. The DWTP was constructed in a manner that allows addition of treatment methods if the future circumstances necessitate for change [7, 30]. Under normal operation, the treatment plant produces estimated 200 L/s, where 50 L/s is consumed by Melhus municipality and 150 L/s is sent to Trondheim municipality. Maximum capacity is 800 L/s but the treatment plant is able to increase capacity to 1200 L/s should the need arise [7, 30].

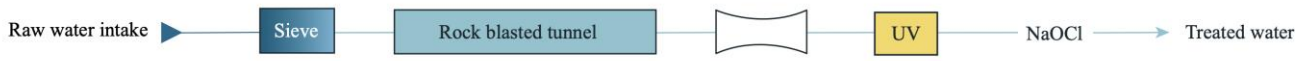

Figure 5. Treatment process at Benna DWTP. Illustration based on figure 4.8 from report *Kommunedelplan for vannforsyning 2017 - 2028* [7]

3.3.4 Regulations

The main regulation that regard drinking water quality and DWDS in Norway are set by Norwegian Food Safety Authority *(Mattilsynet) [40]*. The regulation is called *Forskrift om vannforsyning og drikke vann*

or *Drikkevannsforskriften [41]*. The regulation states what function the DWDS must fulfill, documentations that are required by waterworks, thresholds of compounds in water and approved chemicals for treatment among many other things. The purpose is to secure satisfactory quality and quantity of water to inhabitants in Norway [40, 41]. In addition to the *Drikkevannsforskriften*, municipalities have their own requirements that primarily concern functional requirement of the components in the DWDS, approved construction method as well as requirements for documentations and permits. For instance, in Trondheim municipality, the recommended water pressure in the DWDS is 3.0 – 7.0 bar, but minimum and maximum required pressure is 2.0 and 10.0 bar respectively [42]. Trondheim municipality also require that there is sufficient capacity for firefighting both in terms of water quantity and available hydrants. Guideline value for capacity is 20 L/s for residential areas and 50 L/s for business or industrial areas [42].

4 Literature Review and Background

This chapter aims to provide information, background, and context to the research questions of this thesis, as well as give knowledge and background to the experiments and methodologies that have been performed to achieve the objectives.

4.1 Source Trace Analysis in Drinking Water Distribution Systems

Source trace analysis in the context of DWDS is a type of water quality investigation method that aims to identify the origin of water that are present in the location of interest within a DWDS [1]. Source trace analysis is best understood as water quality characterization study and it is a form of tracer study/constituent analysis that involves measuring features of preferably non-reactive constituents that are found in water at the location of interest [1, 43]. By comparing for instance, the concentration of the chosen constituents at the location of interest to potential origins, origin of the water is determined by connecting to the origin with the most similar concentration levels [8, 10, 43]. Depending on the results, it may be found that there are one or several origins for the water analyzed at the sampling location. Locations with water from several origins can be concluded to have mixing of water [1, 43, 44].

There are several reasons to perform source trace analyses. Water quality differences in natural raw water sources can be significant. Combined with different treatment methods that are present in the DWTPs, produced water from different DWTPs can have significant differences [1, 43]. This can create mixing zones in the DWDS where the mixed water have reduced aesthetic such as cloudiness and solid precipitate as well as taste and odor issues, and problems with maintaining disinfectant residuals [1, 44]. Identifying mixing zones can be useful to be aware where water quality issues are or can become present. The influence and the degree that each DWTPs serves a DWDS is useful information that can be beneficial to make better plans for risks management or general service for utilities. Identifying interconnections can be used to separate water from several DWTP from each other if the need should arise. Knowing which junctions, storage tanks, pumping stations or areas within a DWDS is served by which DWTPs is useful for situations such as tracking water quality problems that are in a location [1]. Other application is to become aware of how far a contamination can spread from for example a storage tank and make use of knowledge of travel path of water from the storage tank to shut down correct valves to contain the contamination and issue public warning to correct areas [1]. Flow paths that induce severe water quality deterioration can be identified so that initiatives such as flushing can be done in correct areas and ensure that satisfactory water quality requirements are met [1, 45].

One important criterion in order to perform source trace analyses is that it must be attainable to distinguish water in the relevant origins from each other [1, 43]. For a distribution system with two water sources, such as Trondheim DWDS, the water quality that are in the two water sources are likely to have natural differences [1, 7]. These natural differences can be used to distinguish the water from each source to determine which areas in the DWDS are influenced by what water source [16]. This approach is similar to fingerprint study where the natural characteristic of the water quality in each water source is understood as the ‘’fingerprint’’ of the water source. To give an example, source trace analysis by *Delisle et al.* [8] involved measuring hardness and conductivity of water in Quebec City DWDS to determine which DWTPs that had been supplying a set of locations. The study area, the distribution system of Quebec City, is described to be adjacent and interconnected to the neighboring DWDS of Sainte-Foy. The two DWDSs have their own DWTP with their own raw water source and water characteristics. Hardness of water in Quebec City DWTP was observed to vary between 30-50 mg/L $CaCO_3$, whilst 70-90 mg/L $CaCO_3$ in Sainte-Foy DWTP [8]. The conductivity was observed to vary in the range 130-160 μS/cm for Quebec and 225-240 μS/cm for Sainte-Foy. Therefore, sampling sites that was measured to have hardness and conductivity in the range of characteristics for either of the two DWTPs, was classified accordingly. For sampling sites with hardness between 50-70 mg/L $CaCO_3$ and/or conductivity between 160-225 μS/cm was suggested to have mix of water from each DWTPs [8].

Application of fingerprint study approach can also be in situations where for instance cases of water quality altercations when it passes through for example, a storage tank. The distinction of water that have passed and not passed the storage tank makes it feasible to determine if water analyzed in the location of interest has the traveled through the storage tank by identifying the ‘’fingerprint’’ of the storage tank in the water [1]. The term ‘’origin’’ in the context of source trace analysis in DWDS depends on the goal of the analysis. It can mean any unit or areas that exist within the DWDS that water passes through and may originate from, such as: raw water source, water treatment plant, tunnels, storage tanks, pumping stations, pipes, manholes, pressure zones and so on.

In situations where there is lack of clear distinction between water from relevant origins, addition of tracer compounds may be necessary to temporarily create artificial differences [43, 46, 47]. This may be relevant for most source trace studies in DWDSs with only one water source. Given that the water found in this type of setting does not experience significant altercations anywhere in the DWDS, the water quality observed throughout the DWDS will lack variation. If the objective of a study is to for example determine the range of potential spread of contamination in water from a storage tank in such DWDS, tracer compound can be added in the water in the storage tank that can best mimic the contamination substance. The extent of propagation of the tracer can then be determined by field measurements by

detecting contents of the tracer in locations tracer compound are suspected to arrive [43, 46, 47]. The usual step is to simulate the propagation of tracer in water distribution model (WDM) beforehand to estimate best sampling locations and times [1].

Produced water from treatment plants is subject to both chemical and physical processes during transportation in the hydraulic network [1, 48]. Therefore, reactions that occur for constituents in the water or tracers that are added in the hydraulic network have to be considered in source trace analysis for accurate concentration assessment. Due to reactions under transport that have resulted in either decay or formation of constituents, concentration level that are observed in the location of interest may have become different than found in the origin. Which substances in the water that are prone to undergo decay or formation will depend on the water chemistry that are at present in the DWDS, as well as things water may interact with in the hydraulic network such as wall materials of pipes or biofilms [1, 32]. A common substance that undergoes decay in hydraulic networks is chlorine, which can also lead to formation of disinfectant byproducts [32, 49]. Chlorination is a common disinfectant method for drinking water and residual chlorine in the DWDS is often desired. Certain concentration levels for residual chlorine are tried to be maintained to suppress water borne pathogens [32, 49]. However, residual chlorine concentration level in the water can decrease as it travels though networks. Reactions with NOM in the bulk flow, oxidation with biofilms and corrosion reactions with pipe materials reduces concentration of residual chlorine [1, 32, 50]. Reaction with NOM also leads to growth of disinfectant byproducts [1, 32]. The extent in which chlorine decays in hydraulic network would therefore be accounted for purpose of source trace analysis if chlorine were to be used as tracer.

The decay or formation reaction of constituents also varies in the rate they decay or grow, and these reaction rate, that is often time dependent, have to be determined to accurately identify the origin of the constituent [1, 16, 48]. Illustration of how a constituent can decay over time in hydraulic network is shown in *Figure 6*, showing the change in concentration level depending on if it is a conservative chemical or undergoes zero-, first- or second order decay reaction [1]. Illustration of how concentration can change from first order growth formation is displayed in *Figure 7*. Conservative chemicals are non-reactive and concentration level stays constant [2, 6]. Therefore, conservative constituents in hydraulic network are preferable for source trace analyses as it eliminates the need to consider decay or formation calculations [1]. In addition, water quality can vary both spatially and temporally in DWDS, which could mean varying decay or formation of constituent depending on time and space of the study within the same DWDS [44]. Because of decays and formations, reactions that can occur and the effects it will have on the concentration of constituents is a consideration that must be made when choosing constituent or tracer compound for source trace analyses [8].

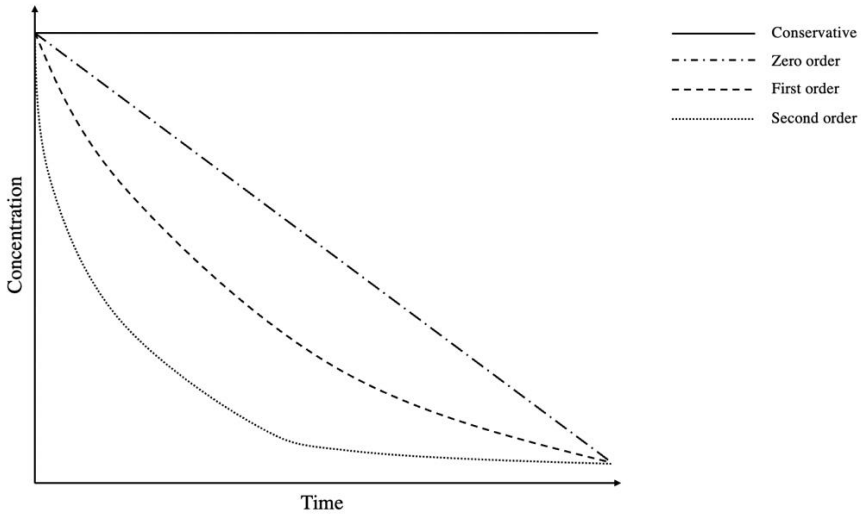

Figure 6. Kinetics of decay reactions. Illustration reproduced from *Haestad et al*. [1].

As there could be many physical, chemical and biological interaction for water in the DWDS, it can be challenging to know exactly how the concentrations of the analyzed constituent or tracer are subject to change [1, 48]. The interactions are also dependent on case specifics of the study area and will differ from one DWDS to another. One way to find concentration changes could therefore be to do it empirically. To examine whether the analyzed constituent or tracer are subject to decay- or formation reactions, and determine the kinetics of those reactions, several concentration measurements of the chosen constituent can be made in various sampling locations with varying hydraulic residence time from point of origin to make a graph that illustrates kinetics, similar to graphs shown in *Figure 6* and *Figure 7* [1]. The result would not reveal what processes the constituent has undergone, but it will reveal whether or not the constituent is conservative or subject to decay- or formation reaction so that correct comparisons can be made when determining origin. Hydraulic residence time would also have to be known to plot the change in the observed concentration to the initial concentration at the origin with regards to time. Therefore, an additional weakness of not having a conservative constituent for source trace analysis is that, in addition to performing source trace analysis, hydraulic residence time would have to be known for the constituents arriving to the sampling locations. Measurements would also have to be done in areas of the DWDS where it is known to be supplied by only one known origin. This is so that the concentrations readings can reflect the change of constituent only from the relevant origin and not be obscured by mixing from other origins. Therefore, choosing tracers that are not conservative naturally entails greatly more effort.

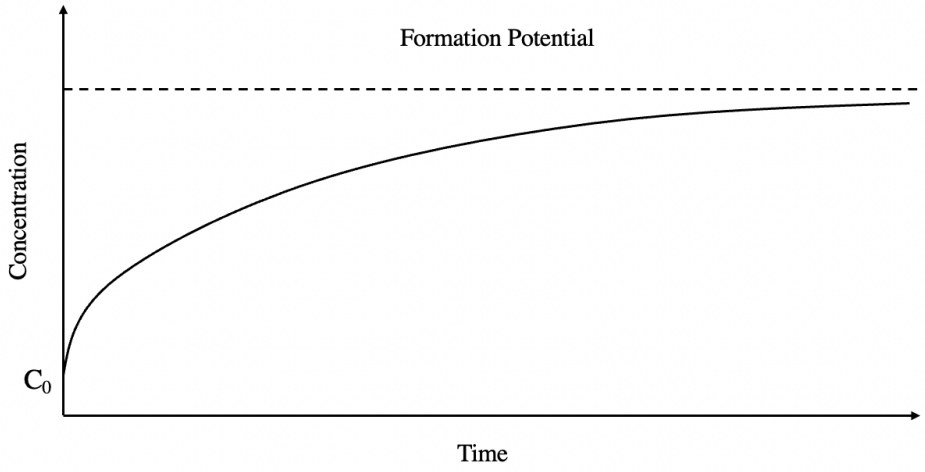

Figure 7. Formation of substance with first order growth rate with a limiting value. Illustration reproduced from *Haestad et al*. [1].

4.2 Tracer Study

The principle of tracer study is to study the concentration of an element and then locate and study the concentration of the element again at a later stage, usually in a different location. Tracer study have many applications, used in many fields. In water engineering, it is more commonly used in reactor analysis to study nonideality of flow behavior [2, 6]. Extreme fluid conditions such as uniform mixing, complete mixing or no mixing in the reactors, and uniform hydraulic conditions, no dispersion and no diffusions are examples of assumptions that are made for ideal reactors [6]. Behaviors of reactors in practice deviates from ideal behaviors, and true behaviors have to be studied and uncovered to properly design and operate the reactors. Non-ideal flow behaviors are especially present in water treatment facilities as it makes use of the largest continuous flow reactors. As the scale increases, the non-ideal flow behavior increases [6]. To study the true flow behavior in reactors, tracer studies are therefore often utilized [1, 2, 6]. Nonideality of flow conditions holds also true for DWDSs where the behavior found in practice deviates from ideal conditions which are often assumed for WDMs [1]. DWDS can be considered large reactor, and the scale of DWDS, especially in larger settlements or cities, makes the real behavior difficult to predict and unknown [1, 43]. By conducting tracer study, information regarding pipe flows, flow pathways and residence time can be obtained. The obtained data can then be used for calibration purposes for WDMs such as water quality models or Extended Period Simulation (EPS) hydraulic models [1]. Additionally, tracer studies may also be used to study storage tanks and reservoirs found in DWDSs and follows the same principles used in tracer studies for chemical reactors. Resulting data may be used to study conditions in the tanks such as residence time of water, mixing conditions and nonideality. The data can further be employed for calibration purposes for WDMs [1].

The basic steps of tracer studies in reactors starts with injection of known amount tracer at the inlet to the influent stream of the reactor, and then measurement of the tracer concentration at the outlet, often as a function of time [1, 2, 6]. Graphical plot of concentration of tracer at the outlet with function to time is known as the C-curve [6]. There are two primarily methods of injection of tracers, pulse input and step input. For pulse input, a desired amount of tracer is injected all at once, whilst for step input, tracer is injected at a steady rate until the concentration at the effluent is equal to influent [2, 6]. Additionally, further observation can be made after injection of steady rate feed of tracer is ceased until absence of tracer response at the effluent. An additional tracer curve can then made for tracer disappearance. This is referred as step-down tracer study [2]. The steps of tracer studies for reactors are also applied for DWDS, where tracer chemical is injected at the locations that are appropriate for study objective. Response of the tracer is then measured in locations where its expected and of interest [1].

Depending on the injection method, the response and the C-curve will vary. This is addition to the type of reactor and the mixing condition that are at hand. For ideal reactors such as Plug Flow Reactor (PFR), which is characterized by having no mixing in the axial direction, will create a different response than Completely Mixed Flow Reactor (CMFR) which have its contents completely mixed and homogenous [2, 6]. Examples of such variations for different type of injection and mixing are displayed in *Figure 8* and *Figure 9*. With regards to the response that are observed from tracer study, characterization and approximation can be made to understand residence time and what flow and mixing conditions water have been through. The compositions of DWDSs are dominated by pipes infrastructures which is more similar to PFRs, but other units can have characteristics to CMFR, such as storage tanks. If water travels through many combinations of units, it may convolute the response in a way that it becomes difficult to interpretate the results.

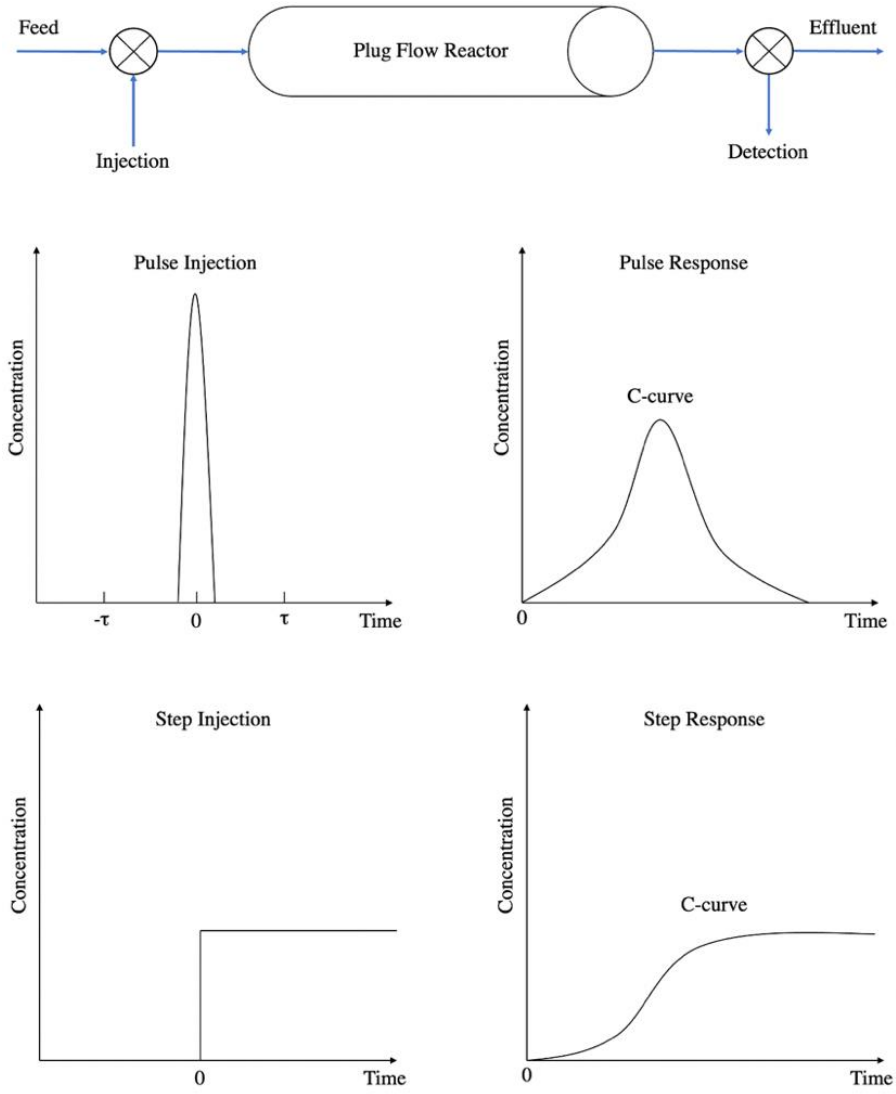

Figure 8. Pulse and step injection in plug flow reactor and its response. Illustration reproduced from Fogler, H.S. [2].

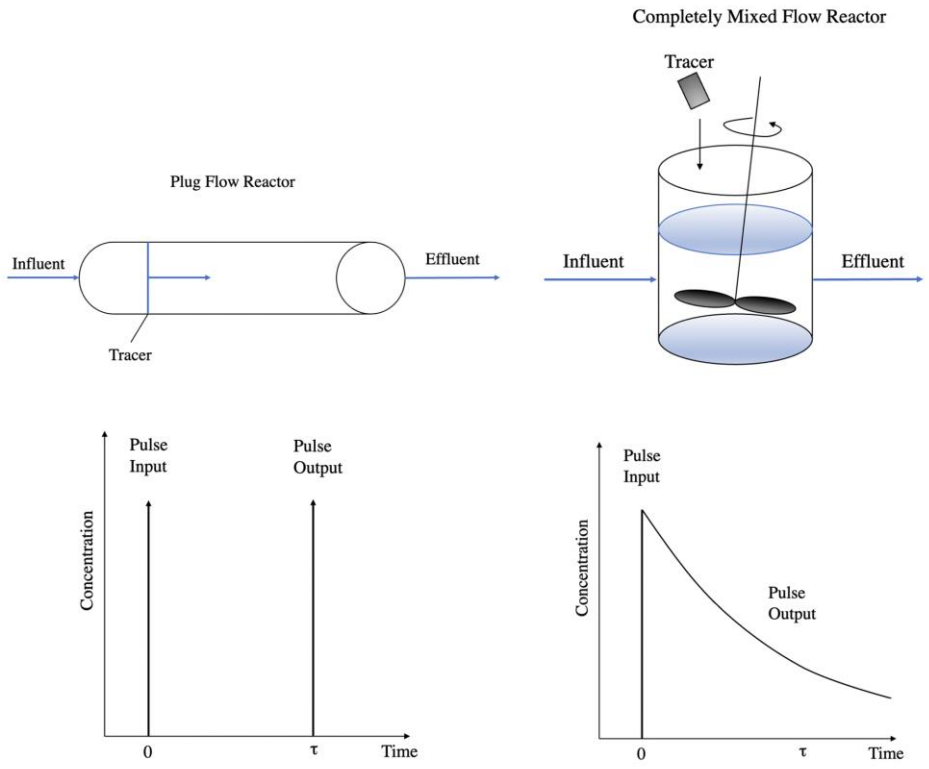

Figure 9. Ideal response of PFR and CMFR from pulse input. Illustration inspired and replicated from *Crittenden et al.* [6].

Although the steps followed for tracer study in DWDS are similar to tracer study in chemical reactors, there are few key things that are different and things that have to be considered beforehand. In general, tracers that are employed for both tracer study in reactors and DWDSs, have to be conservative. Optimally it should also have properties that are similar to the existing constituents in water of the reactor or DWDS, be fully soluble and does not adsorb on the walls or surfaces in the reactors or pipes in DWDS [2]. This is to gain data that reflects the true behavior of the constituents and the water that flows through reactor and DWDS. In addition, for DWDS, the chemical that are used as tracers have to be safe for human consumption, are permitted by existing regulations and perceptions of water by recipients are not negatively altered during the experiment [1, 16]. Whilst tracer studies in chemical reactors commonly use inert gases, colored and radioactive materials, tracer studies in DWDSs utilizes compounds that are commonly used in treatment process. Natural varying water quality characteristics, like fingerprint studies for source trace analyses are also used as tracers [2, 16]. Fluoride, sodium chloride, calcium chloride, lithium chloride, coagulants and chlorine are examples of tracers that are documented to have been used for tracer studies in DWDS [16, 43, 46, 47]. Fluoride and coagulants are commonly used in DWTPs and tracer studies with these chemicals are examples of utilizing pre-existing chemicals in DWTP that are used in normal treatment operation to conduct tracer studies. By temporarily shutting off

fluoride feed in the treatment plant or switching coagulants, subsequent responses in concentration of these compounds can be measured in chosen sampling locations to determine origin, flow path and hydraulic residence time [1, 16]. Fluoride however can experience wall uptake in systems where use of fluoride is not common and can therefore behave as non-conservative, and coagulation is an important step of water treatment process and utilities may therefore be reluctant for alterations [16]. Tracers such as sodium chloride requires that it is added. The amounts that are added depends on the regulatory concentration thresholds for the relevant tracer and the detection level of available measurement method for concentration [1]. Sodium chloride has been used as tracer compounds for various tracers studies in DWDSs, including the tracer study performed in Trondheim DWDS in 2020 [16, 51]. From the examined tracer studies that have utilized sodium chloride as tracer, it has been common step make to first make brine solution that are then injected to the effluent stream at DWTPs. Propagation and arrival of brine solution are then determined by detecting increase in water conductivity at the sampling locations [46, 47, 51]. While sodium chloride is conservative and easy to get regulatory approval, a drawback is that it requires large amounts to make significant enough response that can be measured [2, 16]. Since sodium chloride often needs to be added, it is also difficult to create step response as continuous injection for a prolonged time would require huge amount of sodium chloride.

From scrutiny of existing academic literature regarding tracer study in DWDS, it has been observed that it is easier to make use of existing water treatment method to create response to concentration of tracers. This was concluded in the preparatory work for this thesis, presented in *Appendix D: Preparatory Work*. Cases where utilizing for instance fluoride as tracer, which implies shutting off fluoride feed for a given time, is logistically easier than to introduce a new substance as injection to create response [1, 8, 16]. Main reasons is that, it is harder to control concentration of tracers, it requires more work to get regulatory approval to introduce a chemical that are not already in the network and large amounts of tracers are normally required [2, 16]. To illustrate, tracer study by *Boccelli et al.* [46] which involved injection of brine solution (350g/L NaCl) for duration of 24 hours, was stated to use approximately 10 000 liters of brine. Continuous sampling must also be done well ahead of time before, as well as after tracer injection to obtain and correctly assess initial and final concentration of the constituents. This step is especially important to calculate residence time [8].

4.2.1 Tracer Study for Source Trace Analysis

Of the explored literatures that have conducted tracer study in DWDS, usual aims have been to investigate flow path, hydraulic residence time, hydraulic limits, mixing conditions and residence time in storage tank and gathering data of DWDS for calibration purposes for WDMs [1, 8, 10, 16, 46, 52]. As already

mentioned in chapter 4.1, tracers can also be employed to create distinction of water for DWDS that are supplied from water sources with lack of variance in the water quality. Even in DWDS with variance in water quality between sources, addition of tracer may be preferable due to reasons of creating a stronger contrast between the sources for easier detection and classification. Available measuring method that are more suited to detect the constituent other than natural varying water quality characteristics can also be a contributing factor to preferring use of tracer chemical. In parallel with creating distinction of water quality with tracer chemicals, C-curves obtained at sampling locations can be used to determine hydraulic residence time of the tracer [1]. Since data from a tracer study can be used for investigation of both source trace analysis and hydraulic residence time in DWDS, it has been observed in the explore literatures that source trace analyses are often performed with tracer studies. Some of the explored source trace analysis studies and their approach are explored in the following sections.

In relation to the tracer study performed by *Delisle et al.* [8], data from tracer study with main goal of investigating hydraulic residence time of water in Quebec City, Canada was also utilized to determine hydraulic limits for Quebec DWTP and Sainte-Foy DWTP. The study area, briefly presented in chapter 4.1, is the distribution system of Quebec City which is adjacent and interconnected to the neighboring DWDS of Sainte-Foy. Tracer study with step injection of fluorosilicic acid solution at the DWTP in Quebec City was conducted for the duration of 26 hours. The acid solution dissociating into tetrafluorosilance, and hydrogen fluoride made it feasible to measure increase in fluoride concentration throughout the DWDS. Sampling in various sampling locations within the DWDS was conducted for 36-40 hours. To interpret the data to make assessment of residence time and origin of water at the sampling locations, three main categories for fluoride curves were made. Illustration of this is shown in *Figure 10.* Category 1 suggested that if the C-curve at the sampling location is observed to be flat, meaning no significant change of fluoride is observed before and after injection of tracer injection, then it is possible that the location of sampling location is supplied by neighboring Sainte-Foy DWTP. Alternatively, it could be supplied by Plains of Abraham Reservoir, a reservoir within the Quebec City that have estimated residence time of 3-5 days. A flat C-curve at the sampling location was also hypothesized to have hydraulic residence time greater than the duration of sampling period (36-40 hours). Category 2, C-curves with a slow progression of response was hypothesized to have mixing of water with no tracer, meaning water from neighboring Sainte-Foy DWDS or old water from the Plains of Abraham Reservoir. Otherwise, it could be a sign of low water consumption at the sampling locations, leading to higher hydraulic residence time and thus creating a slower response. Category 3, which has C-curve characteristics similar to step injection response seen in *Figure 8,* with fluoride concentration reaching maximum during sampling, was presumed to be primarily and directly supplied by Quebec DWTP with low hydraulic residence time.

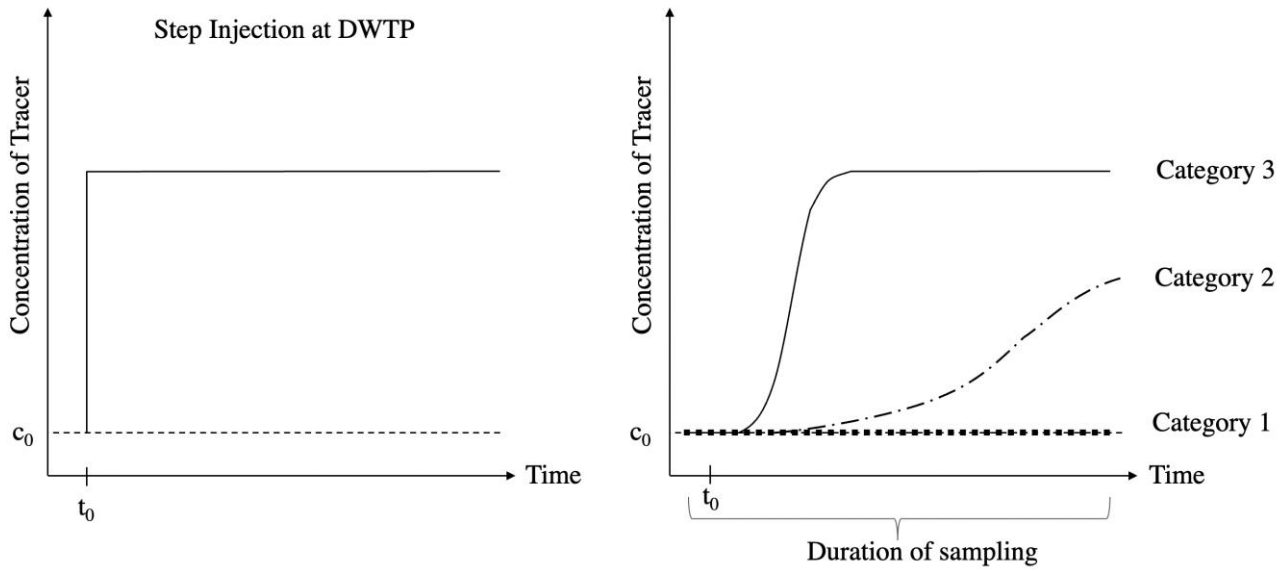

Figure 10. C-curves for three different responses depending on influence from the DWTP with tracer injection. c_0 and t_0 denotes the background concentration of tracer in DWDS and starting time of tracer injection, respectively. The illustration is inspired by Figure 2 from *Delisle et al.* [8] and Figure 6 from *Simard and Rodriguez* [10].

A different approach for source trace analysis using three different tracer chemicals was conducted in the study by *DiGiano et al.* [43]. The study area, DWDS of Durham, North Carolina, was described to have two DWTP, Brown Water Plant and Williams Water Plant. Brown Water Plant was stated to use ferric chloride ($FeCl_3$) as coagulant for water treatment whilst Williams Water Plant was stated to use aluminum sulfate $Al_2(SO_4)_3$. The produced water from each station could therefore be distinguished by comparing the concentrations of chloride (Cl^-) and sulfate (SO^{-2}); chloride being higher in the produced water from Browns, approximately 28 mg/l, whilst 9 mg/l for Williams, and sulfate being higher in Williams, approximately 30 mg/l, whilst 7 mg/l for Browns. In addition, fluoride (F^-) feed at Brown Water Plant had been turned off several weeks prior to the study, inducing low concentration of fluoride at Browns to approximately 0.1 mg/l, whilst fluoride concentration of approximately 1.7 mg/l was maintained at Williams [43]. To find origins of supplied water at 10 sampling sites throughout DWDS, concentration for the three chemicals was measured at each site. Thereafter, by using *Eq. 1* for fluoride and equivalent equations for chloride and sulfate, percentage contribution of water from Browns and Williams were made [43].

$$\%\,Williams\ WTP = \frac{[F^-]_{station} - [F^-]_{Finished\ Brown\ WTP}}{[F^-]_{Finished\ Williams\ WTP} - [F^-]_{Finished\ Brown\ WTP}} \times 100 \qquad \textit{Eq. 1}$$

Given from *Eq. 1*, if the fluoride concentration at the measured station is equal to fluoride concentration at Williams, the percentage contribution from Williams would be hundred percent whilst zero percent from Browns. The results showed that sampling sites had increasingly higher percentage contribution from Browns or Williams, the closer the sampling site was to either of the DWTPs. The results for each tracer chemicals were also recorded to have good agreement, meaning the results were consistent with each other. Since the fluoride feed was turned off several weeks prior, the uncertainty of whether slow or no response from induced concentration change were due to high hydraulic residence time, that were discussed for category 1 and 2 in *Figure 10*, was avoided.

Hydraulic residence time of tracers are not constant but varies in large part due to variations in water demand. In some cases, the variations have been recorded where hydraulic residence time have been up. to 30% longer than other [53]. For peripheral areas, the combination of less demand and longer flow path leads to greater hydraulic residence time. The conductivity measurements that were conducted in Quebec City in relation to *Delisle et al.* [8] were performed for three different time periods, with approximately one month between each period. This temporal variation of the sampling periods uncovered that there are also spatiotemporal variation of the hydraulic limits [8]. Therefore, to obtain the best results, sampling for source trace analysis in DWDS may have to be performed during a short period. Differences between water demand and other influencing factors can then be minimized so that obtained data from sampling locations are from same demand situation with the same hydraulic limits.

4.2.2 Tracer Study in Trondheim

The case of using existing chemical in the treatment method as tracer was also applied for tracer study in Trondheim DWDS in 2020, when sodium chloride (NaCl) was used as the tracer chemical [47, 51]. As already mentioned, due to existing on-site sodium tank that is used to create brine solution and subsequently sodium hypochlorite (NaOCl) at VIVA, large amount of sodium chloride, as well as equipment that are used to create brine solution, that would have been otherwise required to be brought to the treatment plant was already in place. In the study, the brine solution that are normally used to create sodium hypochlorite, was step injected to increase sodium chloride concentration and hence the conductivity in the water. [47, 51]. Because of the on-site sodium tank, sodium chloride is deemed as the best option for tracer chemical for tracer study from VIVA. At Benna DWTP, there are limited options of on-site treatment chemicals that can be used for tracer study. This issue was briefly explored in *Appendix D: Preparatory Work*, recognizing that disinfection at Benna DWTP is done with offsite produced sodium hypochlorite. No other chemicals are used in the treatment process as Benna Lake have

naturally good water quality and consequently have relatively simple treatment steps [7]. Suggestion to create tracer by briefly ceasing to use sodium hypochlorite to induce a reduction of free chlorine OCL^- and HOCL in the water was made in the preparatory work. However, this leaves Benna DWTP with only one disinfection step in during the period of experiment where UV-light is the sole disinfection step. Up until the 01.01.2017, the regulation for drinking water in Norway *Drikkevannsforskriften* stated that number of hygienic barriers should be at least two. The current regulation states that there should be sufficient amount of barriers, depending on the context and underlying risk assessments, without clear requirement on number of barriers [7, 41]. Due to this reason, it remains uncertain if briefly ceasing to use sodium hypochlorite is feasible with regards to the regulation, in addition to the likely lack of willingness from managers in Trondheim waterworks due to vulnerability of Benna DWTP during study period. This leaves with the option of adding a tracer compound as the better approach where the tracer compound is brought from offsite. Since there is experience of utilizing sodium chloride as tracer in Trondheim DWDS, the most logistical and simplest method may therefore be to use sodium chloride as tracer from Benna DWTP. The disadvantage here is that the required sodium chloride would have to be brought to Benna DWTP and equipment that are used to create brine solution and dosage of brine solution as step or pulse injection have to be created and installed into place.

Tracer study by *Delisle et al.* [8] demonstrated that DWDS with two DWTPs can perform source trace analysis with use of tracer injection from only one of the DWTPs. The distinction of the source at the sampling sites are made by separating sites that have and have not recorded change in concentration of tracers and categorizing the sites by comparing to C-curve responses as presented in *Figure 10*. As already discussed, for Trondheim DWDS, the most feasible way would be to inject sodium chloride, thereby inducing increase in conductivity in the produced water from VIVA. The subsequent increase could be used to differentiate between sampling sites that experiences and not experiences increase in conductivity to estimate the origin, while simultaneously gathering data to calculate hydraulic residence time. The benefit of this approach is that it leaves out the challenge of performing tracer study from Benna DWTP. However, the con would be that knowledge of hydraulic residence time for water from Benna DWTP in Trondheim DWDS would not be gained. Therefore, if the objective was also to study hydraulic residence from both DWTPs, tracer study from Benna DWTP would have to be performed. In addition to the use of tracers for source trace analysis in Trondheim DWDS, additional supporting data using fingerprint method can be gained to verify and validate the results. This approach would be the same as performed in study by *Delisle et al.* [8], where after tracer study from Quebec City DWTP, fingerprint study throughout Quebec City DWDS was done by measuring hardness and conductivity of water at the sampling sites to check the correspondence between the conclusion of origins that were made from tracer study and data from hardness and conductivity [8].

4.2.3 Calculating Residence Time

Residence Time Distribution (RTD), also known as exit-age distribution, which is defined as the probability function that describes the total time fluid elements have spent in a reactor, can be derived from C-curves [2, 6]. RTD is a dimensionless function which is often denoted as ***E(t)*** and is expressed differently for pulse and step inputs. RTD is more naturally derived from pulse inputs and is given as

Eq. 2 or *Eq. 3* [2, 3]. *Eq. 3* is beneficial when the total amount of injected tracer is unknown or only C-curve data are obtained [2, 3].

$$E(t) = \frac{v\,C(t)}{N_0} \qquad \textit{Eq. 2}$$

Where:

$v = Effluent\ volumetric\ flow\ rate$
$C(t) =$ Concentration curve
$N_0 =$ Total amount of injected tracer

$$E(t) = \frac{C(t)}{\int_0^\infty C(t)\,dt} \qquad \textit{Eq. 3}$$

Where:

$C(t) =$ Concentration curve

RTD function is normalized so that the area under the curve ***E(t)*** equals 1 [2, 3]. This is so that sum of all fractions of tracer material leaving the reactor equals 1. This entails that all tracer material injected leaves the reactor eventually [2]. This is expressed in *Eq. 4* [2]. Purpose for this is that the distribution function can be used to determine fractions of tracers residing in the reactor for a given time [2, 3, 6]. Deriving RTD from C-curve of tracers at sampling sites in DWDS can therefore be used to determine

hydraulic residence time to assess fractions of total tracer amount injected and calculate how much different fractions spends in the network between injection point to detection point for a given timeframe.

$$\int_0^\infty E(t)dt = 1 \qquad \textit{Eq. 4}$$

For step injection, it is more natural to determine cumulative RTD function, often denoted as ***F(t)*** [2]. The function is derived by C-curve for step injection and normalized to the constant concentration of tracers at the injection, C_0. Like ***E(t)***, ***F(t)*** is a dimensionless curve. The fraction of tracer that are recorded at the effluent is expressed through cumulative curve that rises from 0 to 1 [2, 3, 6]. The cumulative RTD function is defined as *Eq. 5* [2, 3]. From cumulative distribution function *Eq. 5*, RTD can be derived as shown in *Eq. 6* [2, 3].

$$F(t) = \frac{C(t)}{C_{max}} \qquad \textit{Eq. 5}$$

Where:

$C(t) =$ Concentration curve

$C_{max} =$ Constant concentration of tracer injected as step input at influent

$$E(t) = \frac{d}{dt}F(t) \qquad \textit{Eq. 6}$$

The integral relationship between ***E(t)*** and ***F(t)*** are demonstrated below. *Eq. 7* calculates the fraction of tracers that spends time in the reactor less than time (t). *Eq. 8* calculates the fraction of tracers that are in the reactor greater than time (t).

$$\int_0^t E(t)dt = F(t) \qquad \textit{Eq. 7}$$

$$\int_t^\infty E(t)dt = 1 - F(t) \qquad \textit{Eq. 8}$$

Finally, RTD and cumulative RTD can be employed to calculate mean residence time (MRT), which tells the average time the tracer spends in the reactor [2, 3, 6]. Alternatively, in the context of DWDS, it can be used to calculate, for instance the average time water travels from DWTP to a storage tank. MRT have been observed to be employed among the explored tracer studies to assess the average time tracer molecules spends from injection time to detection at the sampling sites. The studies that have used MRT includes *DiGiano et al.* [43] and *Delisle et al*.[8], which have been presented in the earlier chapters. MRT is also defined as the area above the ***F(t)*** curve and are illustrated in *Figure 11*. Mathematically it can be given as *Eq. 9* or *Eq. 10* [2, 3].

$$MRT = \int_0^\infty tE(t)dt \qquad \textit{Eq. 9}$$

Where:

$t = time\ since\ injection\ start\ at\ the\ influent$
$E(t) = Residence\ time\ distribution$ function

$$MRT = \frac{\int_0^\infty tC\ dt}{\int_0^\infty C\ dt} = \frac{\sum_{i=0}^\infty t_i C_i \Delta t_i}{\sum_{i=0}^\infty C_i \Delta t_i} \qquad \textit{Eq. 10}$$

Where:

$t = time\ since\ injection\ start\ at\ the\ influent$
$t_i = time\ at\ measurement\ i$
$C(t) = Concentration\ curve$

To summarize, the relationships between C-curve, RTD, cumulative RTD and MRT are illustrated in *Figure 11*, *Figure 12* and *Figure 13*. Instead of smooth response that are illustrated in the figures, for DWDS, the pattern of C-curves can be jagged and irregular. This is because travel path of tracers in the vast hydraulic network are influenced by changing factors such as water demand, mixing at junctions and varying residence time in storage tanks [43].

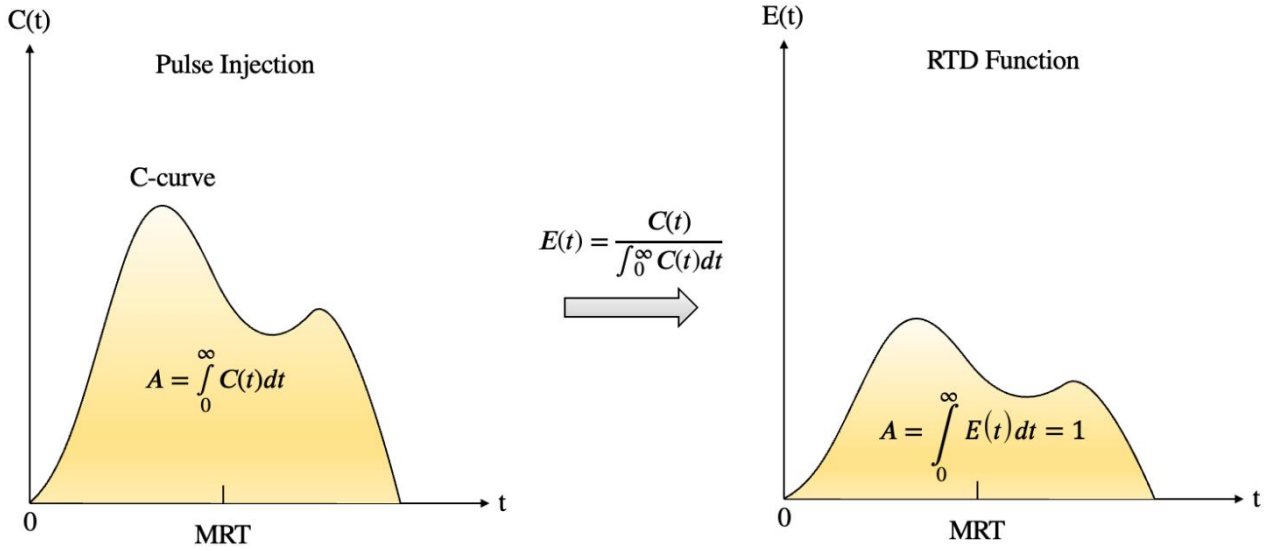

Figure 11. Converting C-curve from detection point after pulse injection to RTD function. Illustration inspired from *Levenspiel* [3] and *Fogler* [2].

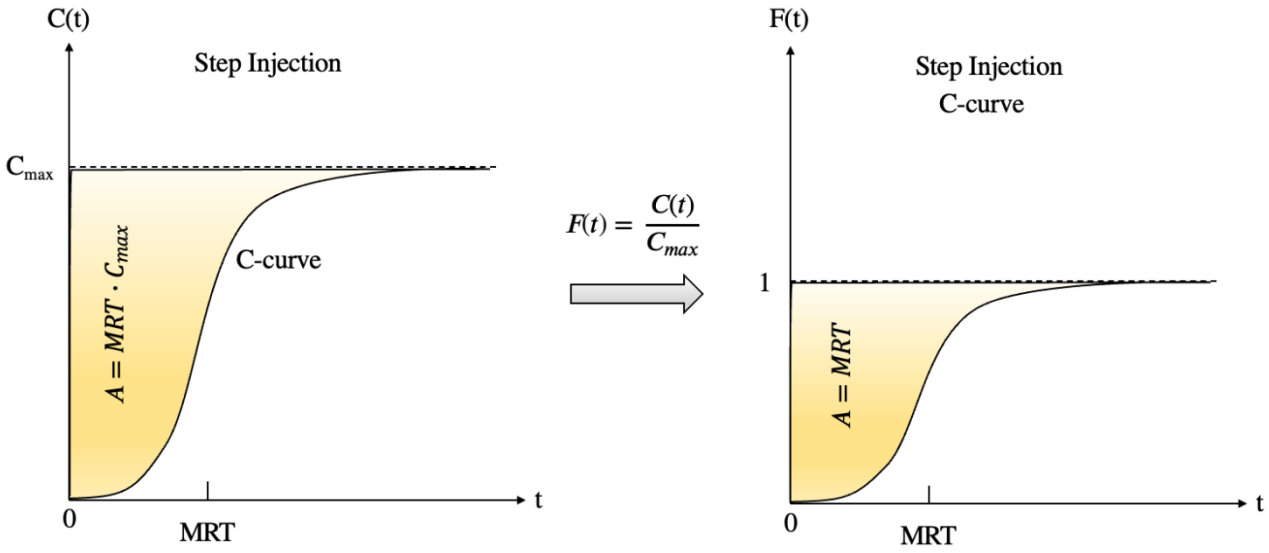

Figure 12. Converting C-curve from detection point after step injection to cumulative RTD function. Illustration inspired from *Levenspiel* [3] and *Fogler* [2].

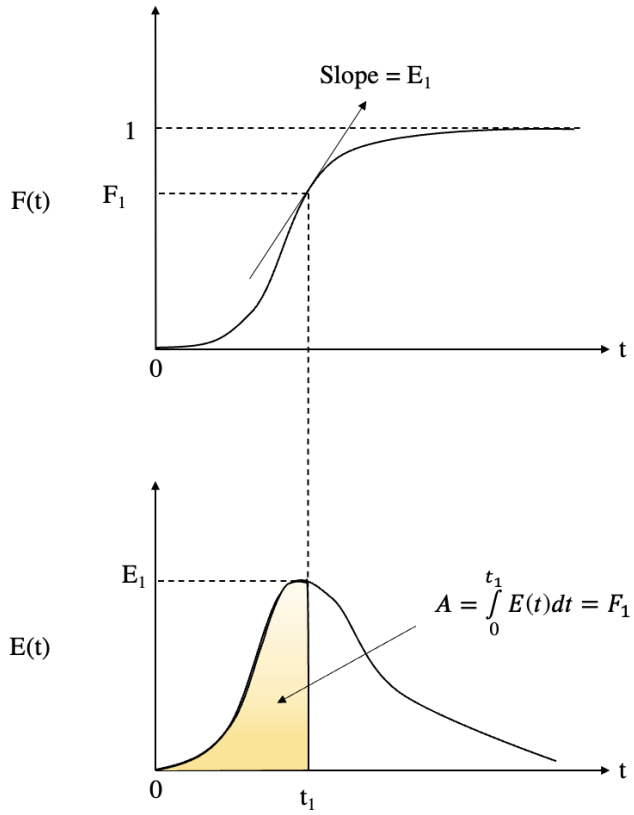

Figure 13. Relationship between RTD and cumulative RTD seen as curves. Illustration replicated from *Levenspiel* [3].

As demonstrated, to assess residence time, MRT can be obtained from either pulse injection or step injection. Primarily challenge of pulse injection is related to the injection, where the injection has to happen during a very short moment [2]. Dispersion between point of injection and the entrance to the reactor must also be negligible so that obtained C-curve corresponds with the amount of tracer injected [2]. Long tail of the C-curve can also lead to higher inaccuracies when calculating the area of the C-curve, potentially leading to inaccurate MRT. Due to this reason, step injection is described to be easier to perform. However, as already mentioned in the earlier chapter, challenges related to maintaining constant concentration and requiring large amount of tracers are some drawbacks. Therefore, in cases where the tracers are expensive, pulse injection are preferred [2]. Alternatively, shutting off tracer feed such as fluoride at DWTP, can be inexpensive way as external tracers are not required to be bought.

For DWDS with several water sources, mix of water can occur, and water from each source at the mixing locations can have varying MRT. To account for this, weighted MRT approach by *DiGiano et al.* [43] where the percentage contribution of water at each sampling location were accounted for by using *Eq. 11*. Percentage contribution was established in advance of weighted MRT calculations, obtained from source trace analysis. The equation calculates weighted MRT from two different sources, as the research dealt with two DWTPs. Additional concern for DWDS where mixing occurs is that if same tracer

chemical is used from each source, C-curve at the mixing points will become distorted, unfeasible to distinguish contribution from each source. Therefore, tracer study from each source therefore have to be spaced out temporally or use different tracer chemicals to be able to distinguish contributions of water from each source [43].

$$Weighted\ MRT = MRT_A \times \%Contribution_A + MRT_B \times \%Contribution_B \qquad Eq.\ 11$$

Where:

$MRT_A = Mean\ Residence\ Time\ from\ Source\ A$
$MRT_B = Mean\ Residence\ Time\ from\ Source\ B$
$\%Contribution_A = Percentage\ Contribution\ form\ Soruce\ A$
$\%Contribution_B = Percentage\ Contribution\ form\ Soruce\ B$

4.2.4 Hydraulic Residence Time and Water Quality Deterioration

As it has been presented in this chapter, tracer study is a method that can be used to determine hydraulic residence time in DWDS. This is of relevance to water quality investigations as high hydraulic residence time in the distribution system, are related to reduced water quality [1, 16]. The topic of water quality deterioration in conjunction with increasing hydraulic residence time in the distribution system has been already explored in *Appendix D: Preparatory Work.* The main cause for the deterioration of water quality with increasing water age, is thought to be because of the chemical reactions in the water that affects water quality are time dependent reactions. Example of this can be growth of microbial regrowth, disinfectant decay, or disinfection by-product formation [1, 16]. Since there are several reactions and water quality parameters in the water that are affected by hydraulic residence time, water age is a great general parameter to use for assessing overall water quality in distribution system.

4.3 Water Distribution Model

Hydraulic model is a mathematical model of fluid systems that is used to analyze hydraulic behaviors [1]. Models in this context is understood as digital models. Therefore, water distribution model is a type of hydraulic model that is a digital representation of real-world DWDS and is created by inputs of data from the real world [1]. DWDS is understood as the aggregate of all elements that have functioning role

to deliver water from a water source to recipients. Distribution systems typically comprises of raw water source, DWTP, transmission and distribution mains, storage tanks, pumping stations, fire hydrants and valves. Consequently, to build an accurate model that represent the real water distribution system, data of existing aforementioned elements from the real system have to be used as inputs in the digital model [1].

Water distribution models are used to run simulations. By running simulations, behaviors from the real system can be imitated and system response can be predicted for various settings and scenarios without disrupting the real system [1, 16]. This can be useful towards developing strategies for improvements and maintenance and assess risks and exposure of the system. Simulations are either steady state or extended period simulation. The difference is that while steady state simulation represents a snapshot of behavior of a system, extended period simulations are used to simulate the behaviors of the system over time [1].

It is not necessary to have all the inputs from the real world in the model as not all elements are relevant, and the degree of inclusion of the elements depends on the purpose of the model. The process of simplifying the model is often referred as skeletonization [1]. Skeletonization allows the modeler to save time and resources as the insignificant elements are neglected and only significant parts are included. Distribution models that are used for broader aspects of the system such as for master planning, regional water studies or energy operation studies, require less details and higher degree of skeletonization are accepted [1]. However, studies such as water quality studies, entails more details to achieve the same degree of accuracy. To ensure that a model has the desired accuracy, calibration is necessary. Aim of calibration is to adjust a model so that there are good agreements between results from simulation and real system behavior. This is typically done by adjusting the inputs in the model until the results from simulation agree with measured value from the real system [1, 16]. After calibration step, validation should be done to validate legitimacy of the result. Validation is typically done by comparing output of the model with observation from the real system. The model's capability to accurately predict the behaviors of the system are then revealed [1].

For water quality models, more details such as wall reaction coefficient, as well as bulk reaction coefficient, may have to be known [1]. Source concentrations and initial conditions can also be necessary as inputs. Transport, mixing, and decay are central aspect that are simulated in water quality models [1]. As source trace analysis is a type of water quality study that examines propagation and distribution of certain constituents in water, models that are used for source trace analysis should in general have high degree of detail for accurate results. Same applies for water age analysis. The quality of water quality models relies on several factors. High degree of skeletonization may decrease the accuracy of the model

[16]. Typically, when smaller distribution pipes are not included, water age is underestimated as water age tends to be higher areas with lower demand or in dead-ends. Inputs of settings on water storage tanks can also have impact on water age [16]. For instance, estimation to completely mixed reactors for storage tanks leads to underestimation of water age. Moreover, insufficient calibration can contribute to inaccuracies and inaccurate demand allocation can result in false hydraulic limits and water age [16]. Demand allocations are therefore especially important for source trace analysis and water age analysis.

4.4 Bacteria in Drinking Water Distribution System as Potential Tracer

Even after treatment, water in DWDS generally contains microbes that have either entered through the source or detached itself from biofilms that usually exist on the surface layers of pipes [54, 55]. Nearly all of the biomass that exist in DWDS exist in biofilms, and although these are not necessary harmful, it can acts as habitat for harmful microbes such as *Legionella ssp*. which can be a major health risk for humans [32, 54]. Harmful pathogens can form and multiply in biofilms where biofilms act as shelter that protects these pathogens against disinfectants and the harsh environment in the bulk flow [32, 55]. Additionally, biofilms can be a source for reduced aesthetic such as color and malodors, and cause corrosions [54, 55]. High concentration of bacterial cells is undesired as it can lead to several issues. Monitoring microbial count can therefore be of interest to ensure that safe drinking water is assured in DWDS [56]. Heterotrophic plate count is one of commonly used methods that are used to estimate heterotrophic bacteria in water, which sudden changes can indicate growth of biofilms, and are used as a general indicator for microbial activity [48]. However, the method involves sampling of water with analysis often ex situ and requires several days of incubation period of bacteria before the results are ready. Automated online FCM which is more novelty than conventional method like heterotrophic plate count, offers a more accurate, rapid, and holistic picture of bacteria in water sample. With higher temporal resolution with the ability for in situ monitoring with online update of cell count measured, it can also give more detailed concentration of bacterial community [56, 57].

The number of bacteria in DWDS is not constant but constantly changing depending on several factors. Seasonal change that affects temperature have been observed to increase bacteria when temperature rises [32, 47, 56]. Availability to nutrients affects the growth of biofilms and microbes, and high water age have been observed to correlate with high heterotrophic plate count [47, 54]. Even so, study by *Besmer et al.* have observed that baseline of bacteria cell count can be established for water in DWDS [57]. The study was conducted in Dübendorf, Switzerland where the water in the DWDS was non-chlorinated, much like typical water in Norwegian DWDS. Cell count was measured with automated FCM for water

sample drawn at a sampling point within the DWDS every 15 min for in total 14 days, totaling in more than 1000 data points. The researchers observed daily reproducible fluctuations and saw cell count correspond with hydraulic conditions caused by daily pattern of demand, allowing for establishment of baseline of total cell count [57]. The results may therefore suggest that cell count in locations in distribution system that are supplied by a specific water source, have a more or less stable cell count that fluctuates with daily demand pattern within the confines of baseline cell counts. Moreover, cell count in DWDS seems to be more affected by bacteria from water source even though studies have estimated that majority of biomass that exist in DWDS are in biofilms [55]. This was observed in study by *Chan et al.* [58], where FCM were used to measure cell count at several sampling locations in the DWDS of Varberg, Sweden. The DWTP in Varberg had recently undergone an installment of ultrafiltration. Comparison of the cell count in the DWDS before and after the installation showed that 99.5% of bacteria were removed as a result of ultrafiltration [58]. The sampling locations were chosen in sites with short hydraulic residence time to make sure that the cell counts were not affected by bacteria from regrowth. The drastic reduction of observed cell count in the DWDS after installment of ultrafiltration seems to signify that water source is the primary driver of bacteria in flowing water of DWDS that have DWTPs with no corresponding treatment process like ultrafiltration. This conclusion combined with observation of reproducible fluctuations of cell count from *Besmer et al.* sets a basis for a new research question of whether cell counts in Trondheim DWDS are stable enough, so that it can be used as a tracer compound, and distinguishable enough between Jonsvatnet and Benna, so that cell counts can be used as a parameter for source trace analysis. Study by *Chan et al.* [58] showcased that cell count in water from biofilms were negligible compared to cell count from the water source, prior to installment of ultrafiltration. As VIVA and Benna DWTP do not have ultrafiltration or comparable treatment process, it might be the case that also in Trondheim DWDS, cell counts are primarily influenced by the water sources, and that Jonsvatnet and Benna have their own unique characteristic cell count.

5 Parameter Study for Source Trace Analysis in Trondheim through Field Work

Sampling campaign for parameter study for source trace analysis in Trondheim DWDS was performed during period 15. March. 2022 – 25. March. 2022. Water samples from 29 sampling locations within Trondheim DWDS, in addition to water samples from VIVA and Benna DWTP were obtained. Water samples were then analyzed for copper concentration, pH, conductivity, and color levels. The initial goal of the field work was to attempt source trace analysis with field data, determining hydraulic limits of VIVA and Benna DWTP, and identify areas where mixing of water from the two DWTPs occurs. Given that the chosen parameters act conservative during distribution, the strategy was to use the ‘’fingerprint’’ approach by measuring concentration of copper, pH, conductivity, and color value found at the sampling locations and compare the values with value found at the two DWTPs. By comparing how similar these water characteristics at the sampling locations are to the water characteristics to either of the two DWTPs, how much contribution each of the two DWTPs had given to the sampling locations was to be determined. However, during the period of sampling campaign, it was revealed through meeting with personnel at VIVA that Benna DWTP had been shut down for some time due to Copepods and Pallasea. As a consequence, Trondheim DWDS had been and was supplied solely by water from VIVA. This meant that the initial goal of field work became unfeasible because there was only one water source in Trondheim DWDS. Areas that would have normally been supplied by Benna DWTP were supplied VIVA and since there were no water from Benna DWTP present in Trondheim DWDS, mixing zones could not be determined by analyzing water samples obtained from the field.

Copepods and Pallasea has been a reoccurring issue for Benna DWTP since its inception [31, 37]. As a result, a contingency plan that was made specifically made for this scenario, where Benna DWTP are shut off due to Copepods and Pallasea, prepared in *Appendix D: Preparatory Work*, was followed instead. Following the contingency plan, the goal of the source trace analysis shifted to assess how suitable the four chosen parameters, copper, pH, conductivity, and color, are for source trace analysis in Trondheim DWDS. It is generally desired that tracers used for source trace analysis are conservative. The focus became therefore to investigate if the parameters copper, pH, conductivity, and color are conservative during distribution. In this way, suitable parameters for future source trace analysis were investigated.

5.1 Parameters

From *Appendix D: Preparatory Work*, it was presented that the constituents in the water that had the greatest difference in terms of percentage, between water from VIVA and Benna DWTP are copper, aluminum and nickel, respectively. Therefore, it was stated that these three metals are good candidate

constituents for source trace analysis in Trondheim DWDS. From these three, only copper was chosen due to viability, decided based on the difficulty of the method of measurement and availability of equipment needed to measure concentration of these metals. In addition, color, pH, and conductivity was analyzed. Based on water quality data from 2020, these three additional parameters also had some distinct differences between water from VIVA and Benna DWTP. The average levels from 2020 for the four chosen parameters are shown in Table 1. Although not having as great difference between the two DWTPs as copper concentration levels, the three additional parameters were chosen mainly on the basis that they are typical water quality parameters that are easy to measure and the necessary equipment for measurement were available. Having parameters other than just copper was also thought to help to verify any conclusion made off on only one parameter, as the results from each parameter can be used to observe if the results correspond with each other.

Table 1. Average value of copper, pH, conductivity, and color found in treated water at VIVA and Benna DWTP from 2020 [59].

Parameter	VIVA	Benna DWTP
Copper [µg/L Cu]	44.7	0.8
pH	8.1	7.7
Conductivity [µS/cm, 20 °C]	128	98.5
Color [mg/L pt]	15.2	3.4

5.2 Hypothesis

It was initially hypothesized that samples from nearby areas of these two treatment plants would have approximately identical water characteristics to the closest treatment plant. For instance, it was expected that a sample from Melhus city center would have very similar water characteristics to water from Benna DWTP due its proximity to the treatment plant. As it was later discovered that Benna DWTP had been shut down and VIVA was the only DWTP that were supplying Trondheim DWDS, it was hypothesized that water from any locations within the DWDS would have approximately same water characteristics as produced water from VIVA. Water sample from Melhus city center were therefore expected to have very similar water characterizes as water from VIVA. Given that there are no errors or process leading to variance during lab work, any observation of great discrepancy would mean that the parameters analyzed are susceptible to change during distribution, either due to chemical instability or unknown factors within distribution system that forces the parameters to be altered.

5.3 Sampling Locations

Water samples were obtained from in total 29 sampling locations within Trondheim DWDS. Majority of the sampling locations consisted of grocery stores and shopping malls, primarily because of convivence of finding a location with available facility to take drinking water samples. The sampling was typically done in bathroom for customers or in breakrooms for employees. Permission to take water samples was acquired beforehand. The sampling locations were chosen on the basis to obtain water quality data from each of the districts in Trondheim, in addition to follow the main water line that are in Trondheim and Melhus municipality (see *Figure 2*). Distance between each sampling locations were also considered to cover as much of Trondheim DWDS with evenly spacing. Combined with other logistical concern in the lab, amount of sampling locations per day was limited depending on the distance needed to travel for sampling and the time needed to complete the analyses. Overview of the sampling locations, as well as the date and time of sampling, and temperature of fully flushed water during sampling, are presented in *Appendix A: Sampling Locations.*

5.4 General Procedure

European Standards for water analysis of pH, conductivity and color recommends that the samples are analyzed as soon as possible [60-62]. For copper analysis, using porphyrin method by Hach Company, adjustment of the sample to the range of pH 2-6 are required, unless the sample are analyzed within 24 hours from the sampling time [63]. Due to these reasons, sampling was normally performed during morning to early afternoon. The samples were then brought back to water analysis lab at NTNU, and copper and pH analyses were performed immediately. Color and conductivity analyses were sometimes performed the next day, but usually on the same day as well. Following the standards, the samples that were planned for analyses the next day were stored refrigerated (≈ 4°C) and kept dark [60, 62].

5.5 Equipment

Numerous equipment was utilized for the purpose to conduct source trace analysis. List of equipment used for measurement and analyses of copper, pH, conductivity, and color, as well as equipment used for sampling, are displayed in *Appendix B: Equipment.*

5.6 Sampling Method

As already mentioned, water samples were collected from ordinary faucets found in bathrooms, kitchen, etc. at the sampling locations. To make sure that the water collected was from the network and not water that had been stagnant in the pipes in the building, water was turned on for at least five minutes to allow

for flushing. In the past, temperature of water in water mains in Trondheim DWDS have been measured to be in the range 5.2 – 8.5 °C [32]. Therefore, temperature of water was measured right before sampling to verify that temperature was at least in this range to verify that the water was not stagnant water. From each of the sampling locations, water was obtained in two different types of containers:15 mL metal-free tube for copper analysis and 500 mL plastic bottle for pH, conductivity, and color analysis. Same procedure was followed for all the sampling locations. Only one plastic bottle was needed for each sampling locations whilst the number of metal-free tubes used varied. For some sampling locations, first drawn water samples were also collected for copper analysis to check if there are significant differences of copper concentration between first drawn and fully flushed water. Additionally, for some sampling locations, two samples of fully flushed water for copper analysis were collected to check if the results of copper concentration could be reproduced. This was done to check precision of the copper analysis.

In total there were ten plastic bottles that were used for containing water for pH, conductivity, and color analysis. Since there were 29 sampling locations, each plastic bottle had to be reused 2-3 times. Before reusing the bottles, they were rinsed thoroughly in the lab by filling the bottles half-full of ultrapure water and shaking the bottles vigorously. This was done several times. The water bottles were then let to dry off overnight. During sampling, the bottles were rinsed again with water from the sampling location. The rinsing procedure at the sampling locations were done couple of times before collecting water for analysis in the lab.

Sampling Procedure

A. Turn on the faucet for cold water

B. (Optional) Fill metal-free tube from the faucet to collect first drawn water

C. Let the faucet run for five minutes.

D. Measure temperature of the running water.

E. Rinse the plastic bottle by filling it half full of water from the faucet. Close the lid and shake the bottle. Repeat the process one more time.

F. Fill the plastic bottle and the necessary amount of metal-free tubes from the faucet.

5.7 Copper Analysis

Porphyrin method developed by Hach company was used to measure copper concentration in the water samples that were obtained at the sampling locations. Porphyrin method are most suited to determine copper concentration in the range 1 - 210 μg/L Cu and the expected precision under ideal test conditions are within 95% confidence interval [63]. The method involves adding set of reagents in the obtained samples, creating a mixture in which the copper concentration can be determined by absorbance readings with spectrophotometer [63, 64].

The decision to use Porphyrin method was made on the basis that it is a relatively simple method to perform, it can determine range of copper concentration that are expected in Trondheim DWDS, and the required instruments to perform this method was available at the department of civil and environmental engineering in NTNU.

5.7.1 Porphyrin Method - Procedure

At the start of each session, the spectrophotometer was switched on and left to warm up for at least 30 minutes before use. To account for reagent blanks, meaning portion of absorbance by spectrophotometer that are contributed by the reagents, a blank solution was prepared by using ultrapure water. The blank solution was then used to zero the spectrophotometer. Thereafter, samples from the field were measured. The procedure was followed in accordance with user guide for Porphyrin method [63] and *Water Analysis Guide* by Hach company [65].

Measuring Blank

A. Pour ultrapure water from ELGA PURELAB into the sample cell up to the 10mL fill line.

B. Add one Copper Masking Reagent powder pillow to the sample cell. Swirl till the reagent is dissolved.

C. Add one Porphyrin 1 Reagent Powder Pillow to the sample cell. Swirl till the reagent is dissolved.

D. Add one Porphyrin 2 Reagent Powder Pillow to sample cell. Swirl till the reagent is dissolved.

E. Set timer countdown to 3 minutes and wait.

F. While waiting, clean the sample cell with paper tissue and then with lens tissue paper, wiping of any water or substances that is on the sample cell that may interfere with readings.

G. After 3 minutes, insert the sample cell into the cell holder in the spectrophotometer, facing the fill line towards the user.

H. Press ZERO on the screen menu on the spectrophotometer.

Measuring Samples

A. Rinse and saturate the sample cell with sample water by pouring water from metal-free tube to the sample cell.

B. Swirl the sample cell to thoroughly saturate the sample cell

C. Empty the sample cell and then fill the sample cell again with sample water from metal free tube. Fill the sample up to the 10mL fill line.

D. Repeat the steps C – G in **Measuring Blank** .

E. Press READ in the menu on the spectrophotometer.

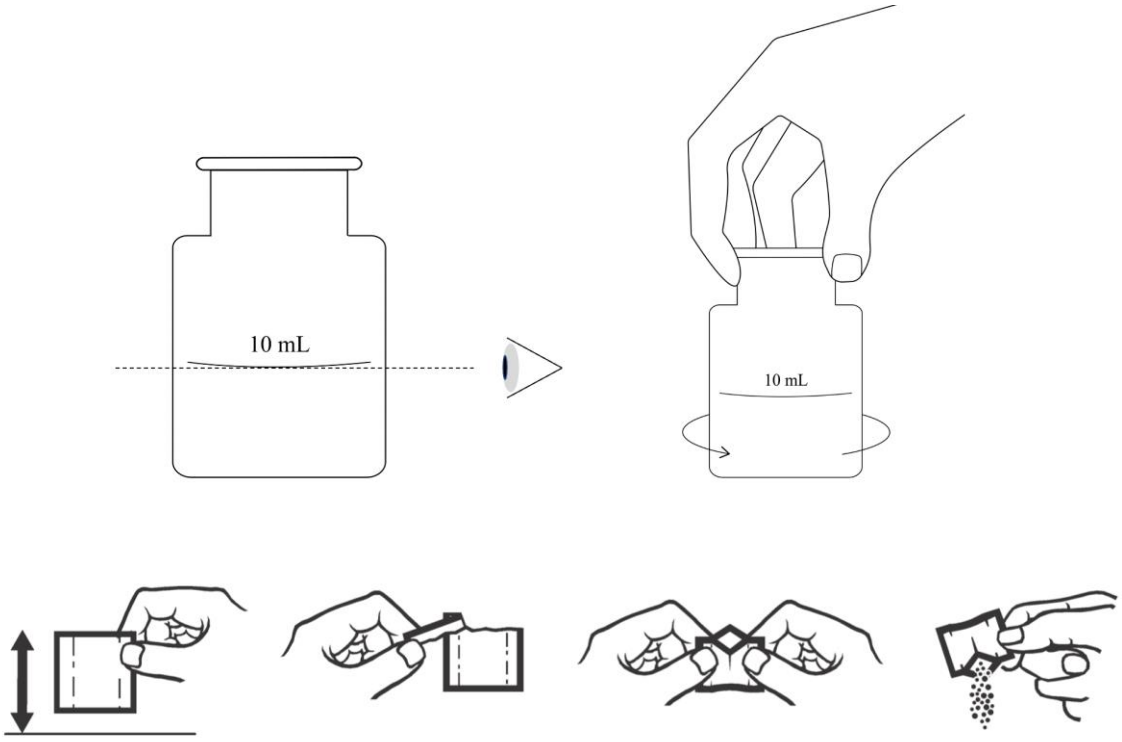

Figure 14. **Upper left:** Filling the sample up to 10mL fill line by observing meniscus was done. **Upper right:** Swirling the sample cell to saturate the sample cell with sample water or mix sample with added reagents. **Bottom:** Method of opening powder pillows of reagents - illustration screenshotted from *Water Analysis Guide, 09/13 Edition 1* by Hach Company [65].

5.7.2 Calibration, Validation and Verification

Several precautions and measure were taken for equipment to reduce errors during copper analysis.

Sample Cells

In total, four 1-inch, square glass 10 mL sample cells were used. Identical type of sample cells was deliberately used to eliminate bias in the readings due to different path lengths caused by different shape of the sample cells [65]. To check for variance between the sample cells caused by e.g. micro-scratches on the sample cells, sample cells were filled with blanks using ultrapure water and general procedure of measuring copper concentration using porphyrin method was applied. The results showed that there is negligible variance between the sample cells, with variance in the range 0 – 2 μg/L Cu.

After end of each day of analysis, sample cells were rinsed with ultrapure water several times and then filled with 1M nitric acid (HNO_3). This was in order to remove any deposits that can lead to higher results on the next analysis. Instructions by Hach Company advises to use hydrochloric acid (HCl) with concentration 6N for cleaning the sample cells to remove any remains of copper from the analyzed samples [63, 65]. Since nitric acid was used instead, sample cells were left with nitric acid overnight to make up for using a weaker acid.

Metal Free Tube

All metal free tube used for sampling were brand new for each sample and never reused. Despite this, verification of metal free tube was done to check whether the metal free tube used to collect water samples for copper analysis could lead to higher copper concentration readings. In general, the water for copper analysis was contained in the tube for approximately 2-3 hours from being sampled to being analyzed. To replicate this scenario, four new metal free tubes were filled with ultrapure water and then left to sit for 3 hours. Thereafter, the water in the tubes were analyzed by following the porphyrin method. Any signs of the metal free tubes leading to higher copper concentration could not be observed.

Pipettes

Manual single channel pipette 40 - 200 μL and 0.5 - 5 mL were used for diluting copper standard solution for the purpose of making calibration curve for spectrophotometer and performing standard addition method to investigate matrix effect in the samples. Therefore, the accuracy of the pipettes was important to accurately validate spectrophotometry and investigate the matrix effect. To validate the pipettes, calibration curves for the two pipettes were made. A 150mL beaker was filled with ultrapure water and

then put on top of a digital scale. The weight of the beaker with its content was then tared. With the pipette 40 - 200 μL, ultrapure water was pipetted out from the beaker, starting from 40 μL to 200 μL with 20 μL increase each step. Each step was repeated three times. Average weight reduction in the beaker from pipetting for each step was then plotted against the amount that was set to be pipetted. Same process was followed for the pipette 0.5 mL – 5 mL, starting from 0.5 mL to 5 mL with 0.5 mL increase each step. The results are shown in *Appendix C: Calculations and Calibration Curves.*

Assuming that the density of water is equal 1 g/mL, coupled with stated inaccuracy of the weight scale ± 0.01g, the results shows that the pipette 40 - 200 μL had inaccuracies which can be explained by the inaccuracy of the scale. For the pipette 0.5 – 5 mL, inaccuracies started to appear in the pipette range 2 – 5 mL. However, the inaccuracies were < 0.1g which is negligible. For both calibration curves, $R^2 \approx 1$, meaning pipettes had no notable error.

Spectrophotometer

The spectrophotometer that was used for copper analysis, *DR3900 Spectrophotometer for water analysis by Hach Company*, comes with factory calibration that relates to absorbance and percent transmittance [66]. Every time the spectrophotometry is powered up, the instrument performs a self-check which includes a wavelength calibration [64]. Therefore, it is stated that the instrument does not need calibration unless it is desired to make own calibration curve with standard solution.

Despite these claims, five standard solutions were prepared and measured to verify that the spectrophotometry could determine concentration of samples with reasonable accuracy. Standard solution is a solution with a known concentration of the relevant analyte [66]. In this study, copper standard solution 100 mg/L Cu was used. Following the *Water Analysis Guide* by Hach company [65], five standard solutions with concentration 10, 20, 50, 100 and 200 μg/L Cu were prepared. However, since the available standard solution had the concentration of 100 mg/L Cu, the solution had to be diluted twice, first from 100 mg/L to 1 mg/ L and then to 10, 20, 50, 100 and 200 μg/L. The first diluted solution was prepared in a 50 mL volumetric flask. This was done by pipetting 0.5 mL of 100 mg/L Cu solution to the volumetric flask and filling the remaining 49.5 mL with ultrapure water by using pipette. A stopper was then put on top of the volumetric flask and the flask was inverted several times to allow for mixing. The five solutions with 10, 20, 50, 100 and 200 μg/L Cu was prepared directly on the sample cells by pipetting 0.1, 0.2, 0.5, 1.0, and 2.0 mL of 1 mg/L Cu, respectively onto the sample cells. The remaining volume in the sample cells were filled with ultrapure water by the use of pipette. A new pipette tip was used for each time pipette was used. After preparing the solutions, the copper content was measured by following the porphyrin method as described in *5.7.1 Porphyrin Method - Procedure.* Calculations of the

volume of the standard required for dilution are showed in *Appendix C: Calculations and Calibration Curves*, along with the results of measurement of the standards.

The results shows that the spectrophotometer determined the concentration for the 50, 100 and 200 µg/L Cu standard as expected. For 10 and 20 µg/L Cu standards, the measurement was slightly off. Overall, the calibration curve gives $R^2 \approx 1$, suggesting that the spectrophotometer is reasonably accurate. The variance that was observed for 10 and 20 µg/L Cu standards could have either been due to inaccuracy on the spectrophotometer, but also from inaccuracies during preparation of the standards. Since the original 100 mg/L standard had to be diluted and switch vessel twice to become the final five standards, inaccuracies for each step could have accumulated to give the variance that was observed. This uncertainty could have been avoided if a copper standard with lower concentration were available. Calibration curve presented in *Appendix C: Calculations and Calibration Curves* are shown with prepared sample concentration in relation to measured concentration. Calibration curves are usually made by giving measured concentration in relation to absorbance. However, data of absorbance was not attained due to researcher of this paper failing to remember to record this data.

5.7.3 Interference, Matrix Effect and Standards Addition Method

Matrix refers to components in the sample other than the analyte, that can interfere and give false results. This interference is called matrix effect [64]. According to user guide for porphyrin method by Hach Company, certain substances are stated to be interfering with the method if the concentration are above a certain threshold value [63]. The list of interfering substances and related interference level are shown in Table 2. By using the publicly available water quality data from VIVA and Benna DWTP from 2020 [59], the concentration of these substances was checked to see if some exceeds the interference level. It was found that most of the interfering substances have values far lower than interference level. However, data could not be found for all interfering substances. Since the data also was from 2020, standard addition method was performed with samples from sampling location 1, shown in *Appendix A: Sampling Locations.*

Table 2. Interfering substances and levels for porphyrin method in water from VIVA and Benna DWTP 2020.

Interfering Substance [mg/l]	VIVA 2020 [average mg/l]	Benna DWTP 2020 [average mg/l]	Interference Level [mg/l]
Aluminium, Al^{3+}	0,082	0,0051	60
Cadmium, Cd^{2+}	0,000002	0,000003	10
Calcium, Ca^{2+}	20,1	14	1 500
Chloride, Cl^{-}	6,96	5,75	90 000
Chromium, Cr^{6+}	0,0001	0,0001	110
Cobalt, Co^{2+}	-	-	100
Fluoride, F^{-}	0,013	0,013	30 000
Iron, Fe^{2+}	0,0071	0,0017	6
Lead, Pb^{2+}	0,00017	0,00005	3
Magnesium	0,9	0,88	10 000
Manganese	0,0004	0,0005	140
Mercury, Hg^{2+}	0,000005	0,000005	3
Molybdenum	-	-	11
Nickel, Ni^{2+}	0,0007	0,0001	60
Potassium, K^{+}	-	-	60 000
Sodium, Na^{+}	4,34	3,73	90 000
Zinc, Zn^{2+}	-	-	9
Chelating agents	-	-	Interfere at all levels unless either the Dgesdahl or vigorous digestion is completed
Highly buffered samples or extreme sample pH	-	-	Can prevent the correct pH adjustment of the sample by the reagents. Sample pre-treatment may be necessary

The purpose of standard addition method is ‘’verifying the combability of an analysis method with a particular sample and determining if there are any substances in the sample that will interfere with the analysis method’’ [66]. Standard addition was performed by following the method that are described in the user guide for porphyrin method [63]. In total, there were 4 metal free tubes with samples from location 1 that were obtained for standard addition. Copper concentration of the first sample was measured following the *Porphyrin Method - Procedure*. Then, copper standard solution 100 mg/L Cu was diluted to 4 mg/L Cu by pipetting 2 mL of the standard onto 50 mL volumetric flask and then filling the remaining volume with ultrapure water. A stopper was put on top and the flaks was inverted several times for mixing. Each of the remaining three samples were poured onto a sample cell up to 10 mL fill line. Then 0.1, 0.2 and 0.3 mL of the diluted 4 mg/L standard solution was pipetted respectively onto the sample cells to spike the samples. The sample cells were then swirled to mix the sample with the added standard. After mixing, the spiked samples were analyzed for copper concentration using *Porphyrin*

Method - Procedure. Calculations that were done in relation to standard addition method and the results are presented in *Appendix C: Calculations and Calibration Curves.*

The results showed that the spiked samples increased in concentration, close to expected concentration. Recovery rate less than 90% or greater than 110% of spiked concentration may indicate that there is matrix that interfere with the method. However, recovery rate for the three spiked samples were between 101-102%, signifying that there is no matrix that interfere with the samples, at least in a significant way.

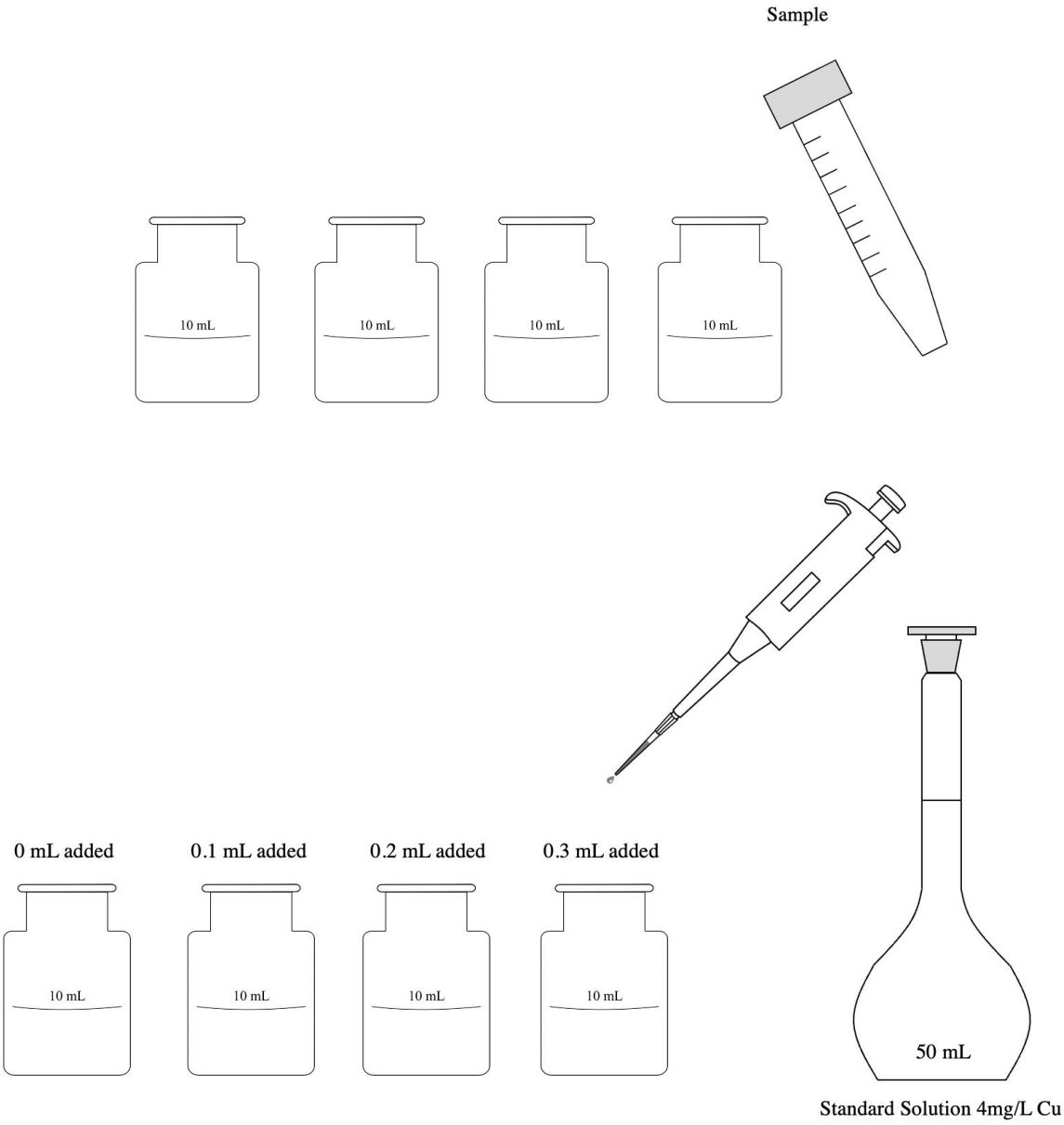

Figure 15. Illustration of steps in standard addition method. **Top:** sample from metal free tubes were added to fill line in the sample cells. **Bottom:** Standard solution were pipetted into the sample cells 0, 0.1, 0.2 and 0.3 mL respectively. Illustration inspired by Figure 4 from *An Introduction to Standards and Quality Control for the Laboratory* [66]. Drawing of pipette downloaded from www.labicons.net [67]

5.7.4 Additional Copper Analysis

Through water analysis during source trace analysis, it became quickly apparent that copper concentrations are higher than expected, and there is high variance of copper concentrations between the sampling locations. This raised the question if the flushing period of 5 min was not sufficiently long to properly flush out stagnant water in the pipe that could have been affected copper concentrations in the samples. To find out if longer period of flushing has an effect on decreasing copper concentration, additional sampling campaign for copper analysis was done 06. April.22. Additional samples from location, 9, 14 and 23 shown in *Appendix A: Sampling Locations*, were gathered. This time, samples were collected at each passed time of flushing in interval of five minutes, starting from 0 to 30 minutes. This totaled 7 samples from each sampling location. Corresponding temperature of the samples were also taken to see if temperature of water had any relation to copper concentration. Collected samples were brought to the lab and copper concentration were measured with porphyrin method on the same day. Results showed that flushing for more than 5 minutes did not any effect.

5.8 pH Analysis

The European standards states that pH measurements should preferably be done at the sampling locations because pH of the sample can change rapidly due to physical, chemical, and biological processes during transportation [61]. However, portable pH meter was not at one's disposal, and pH of the samples from sampling locations were measured by using stationary pH meter at water analysis lab at NTNU. To achieve the best results, pH measurement was done as soon as possible. As already mentioned, pH analysis along with copper analysis, were always performed on the same day of sampling.

The standard also states that buffer solutions and samples should have same temperature to gain the best results [61]. Buffer solutions of pH 4, pH 7 and pH 10 were used to calibrate the pH meter. The solutions were contained in small plastic bottle containers, which had magnetic stir bar inside, and were kept dark in room temperature. To have samples at room temperature, at the start of each session of pH analysis, samples were transferred from the general water sampling bottle 500mL, to glass test tubes with flat bottoms. Then, magnetic stir bars were added to the glass tube with the sample. The samples were then left to rest on the work bench while performing copper analysis - porphyrin method. Resting time roughly equaled roughly 1-2 hours. This amount of time was observed to be adequate to allow the samples to reach room temperature. This step was always followed except on the first day. Before starting on measuring pH of the samples, calibration was always done with the buffer solutions. After each measurement, the probe of the pH meter was rinsed by squirting laboratory wash bottle filled with ultrapure water on the probe.

5.8.1 pH Analysis – Procedure

Calibrating with Buffer Solutions

A. Put plastic bottle container with buffer solution pH 4 on top of magnetic stirrer of the pH meter.
B. Make sure magnetic stir bar is rotating.
C. Lower the probe into buffer solution.
D. Measure pH and temperature.
E. Repeat for buffer solution pH 7 and buffer solution pH 10.

Measuring pH of the Samples

F. Put the glass test tube with sample on top of magnetic stirrer of the pH meter.
G. Make sure magnetic stir bar is rotating.
H. Lower the probe into sample solution.
I. Measure pH and temperature.

5.9 Conductivity Analysis

Conductivity in water is temperature dependent. It is therefore common to measure conductivity of samples at a reference temperature, which is usually 25.0 °C [60]. Hence, samples with temperature not equal to the reference temperature have to be converted to the conductivity it would have had at the reference temperature. The conductivity meter that was used for this analysis are equipped with automatic temperature compensation, meaning it automatically makes correction of conductivity for samples with temperature that are not equal to reference temperature 25.0 °C. Nonetheless, samples for conductivity were first transferred from general water sampling bottles 500 mL to glass test tubes with flat bottom and then put in a test tube rack. The samples were then put in water bath set at temperature 25.0 °C. After the samples had reached the desired temperature, measuring of conductivity began. Before measuring, the probe of the conductivity meter was rinsed with ultrapure water by dipping the probe into a glass test tube with ultrapure water several times. This step was also followed in between measurement of each sample to rinse the probe.

5.9.1 Conductivity Analysis – Procedure

Measuring Conductivity

A. Dip the probe of the conductivity meter into the glass test tube with sample.

B. Let it rest for 30 seconds for the measurement to equalize.

C. Read and note the conductivity of the sample that are displayed on conductivity meter.

5.10 Color Analysis

True color of the samples was determined by utilizing UV/VIS spectroscopy spectrophotometer by PerkinElmer for determination of absorbance at wavelength λ = 410 nm. True color is defined as the color as a result of dissolved substances with absence of undissolved suspended matter. To remove undissolved suspended matter, the samples were filtered through cellulose filter paper using membrane holder and chemistry syringe. This step was done in accordance with European standards for water analysis to determine color [62]. After filtration, the filtered samples were transferred to glass cuvette designed for spectrophotometer for color measurement. Between filtration of each sample, all parts of syringe and membrane holder were rinsed with ultrapure water using laboratory wash bottle. A new cellulose filter paper was used for each sample.

The spectrophotometer was connected to a windows PC to make use of the interface program *UV WinLab Software for Uv/Vis by* PerkinElmer. It was through this software the desired setting could be made and the measurement could be read. Calibration curve that was already stored in the software, made by 1000 mg/L Pt platinum standard solution was used as a reference. Spectrophotometer were turned on at least 30 minutes before measuring color of the samples to warm up the equipment. The spectrophotometer has two slots for cuvettes, one for sample and one for reference solution. Before measuring color of the samples, the spectrophotometer was zeroed with ultrapure water. This was done by placing cuvette containing ultrapure water in the reference slot and the sample slot. Thereby, the samples were zeroed through the interface of the PerkinElmer software. The cuvette containing ultrapure water in the reference slot remained in the spectrophotometer, whilst the cuvette in the sample slot were taken out and replaced with filtered samples to measure true color of the samples. The cuvettes were inserted into the spectrophotometer facing the same direction for all blanks and samples. Each filtered samples were measured three times and the average of the three were used as the result.

5.10.1 Color Analysis – Procedure

Filtration of the Samples

A. Place a cellulose filter paper on top of membrane holder and lock the lid.

B. Join the membrane holder to the chemistry syringe.

C. Insert and fill 50 mL sample water from the sampling bottle 500mL to the barrel of the syringe.

D. Insert and press down on the plunger of the syringe to squeeze sample water through the filter onto a glass test tube.

Measuring Blank

A. Fill two cuvettes with ultrapure water almost up to the top.

B. Wipe any excess water on the outside surface of the cuvettes with paper tissue.

C. Wipe outside surface of the cuvettes with lens paper tissue to remove any substances.

D. Insert the cuvettes in the spectrophotometer, one in the reference slot and one in the sample slot.

E. Zero the instrument through PerkinElmer software for UV/VIS spectroscopy set at wavelength $\lambda = 410$ nm.

Measuring Samples

A. Rinse the cuvette with ultrapure water by filling the cuvette almost to the top. Place the lock on top and shake.

B. Pour out the content and fill the cuvette with filtered sample. Place the lock on top and shake.

C. Pour out the content and fill the cuvette again with filtered sample.

D. Wipe any excess water on the outside surface of the cuvettes with paper tissue.

E. Wipe outside surface of the cuvettes with lens paper tissue to remove any substances.

F. Insert the cuvette in the spectrophotometer in the vacant sample slot.

F. Measure color of the filtered sample by pressing ‘’read’’ on the interface in the PerkinElmer software for UV/VIS spectroscopy set at wavelength $\lambda = 410$ nm. Measure three times.

6 Source Trace Analysis with Water Distribution Model

As already mentioned, source trace analysis was initially planned to be done by using results from the field work but could not be accomplished as Benna DWTP was out of operation. The aim was to gain knowledge of areas in Trondheim DWDS that experience mixing, as well as identifying areas that are predominately influenced by VIVA and Benna DWTP. To compensate for this non-success, a brief attempt was made to simulate the results instead by using WDM of Trondheim DWDS. The utilized WDM is a confidential model used by Trondheim municipality and due to its sensitive information concerning layout of Trondheim DWDS, any work with the WDM had to be done with NTNU's computer, in cooperation with supervisor Marius M. Rokstad who had access to the model. The WDM is a MIKE+ model, which is a proprietary software for water modelling developed by DHI Group, Inc [68]. After getting hand of the MIKE+ model, it was exported and formatted as an EPANET file (.inp). Source trace analysis using WDM was then performed using EPANET version 2.2.0, a public domain software for water distribution modelling developed by United States Environmental Protection Agency [69]. The EPANET simulation was run on 64bit-Windows 10, Dell 7410 laptop with Intel 2.30 GHz i7 processor, 32GB RAM and SSD Storage.

6.1 Modelling

EPANET is a software for water distribution modelling with capability of simulating the movement of reactive and non-reactive tracer material in distribution system over time [69]. EPANET are able to perform EPS, and this was utilized to conduct source trace analysis. In the model, both of the two DWTP in Trondheim were set as operational. The node for VIVA was set as the source for an unlimited amount of non-reactive tracer material which propagated through Trondheim DWDS. The simulation time was set to 28 days (672 hours) with 10-minute time steps. This amount of simulation days allowed the spread of the tracer material to stabilize. After the simulation had completed, observation of which areas in Trondheim DWDS are influenced by VIVA could be made as every node in the model had a tracer content value ranging from 0 – 100%, where the percentages represent the degree of water from VIVA. Node with 100% therefore indicate that it is consuming water only from VIVA, whilst node with 0% indicate it is consuming water only from Benna DWTP. Consequently, nodes that are subject to mixing of water have tracer content value between 0 and 100. Due to fluctuations of influence, likely due to hourly demand pattern, an average influence percentage for the last 48 hours, with time step of 1 hour, was calculated.

7 Flow Cytometry and Tracer Study in Trondheim

As explored in the literature review *4.4 Bacteria in Drinking Water Distribution System as Potential Tracer*, study by *Chan et al.* [58] showed that the DWDS in Varberg, Sweden had majority of bacterial cell count originating from the raw water source when the DWTP in Varberg did not have ultrafiltration treatment process. Since neither VIVA or Benna DWTP does not have filtration step of eliminating cell counts in the treatment process, this raised the question of whether cell counts in water from VIVA and Benna DWTP could be distinguishable from each other since they have each different water source, Jonsvatnet and Benna Lake. The results from *Besmer et al.* [57] also showed that cell counts for areas in DWDS might be stable with variations mostly related to hydraulic conditions in the network and not due to growth. Founding from these studies raised the question if bacterial cell count can be used as a parameter for source trace analysis. The reasoning is that if the treated water from VIVA and Benna DWTP have their own unique cell count and the cell counts are more or less stable for various locations in Trondheim, origin of water can then be established based on cell count signature.

During literature review, it was also presented that hydraulic residence time, also known as water age, have a close relation to water quality, where high water age is related to reduced water quality. To determine water age, the usual method is to perform a tracer study, where injection or removal of tracer compound from a desired origin is implemented. However, this method can require a lot of effort with regards to setting up the equipment needed for injection of tracers. In addition, this method has the weakness of being dependent on the willingness of the managers of the utilities. This is because to perform tracer study, the usual step is to induce a concentration change of tracer compound at the DWTP, which bears the consequence of altering water quality characteristics for drinking water, as well as treatment process in the treatment plant during the study period. Reluctance due to potential negative impact on public health resulting from tracer study can therefore become roadblocks. As an alternative method to investigate water age, attempt was made to develop a novel method to determine water age by studying cell counts in water. The basis for this objective is that if the growth rate of cell counts in distribution system are known from an established point, then water age can be determined by observing cell counts in another location and calculating the time it would have required for the cells to reach the observed cell counts from the established point.

During 24. May.2022 – 07. June.2022, bacterial cell counts in Trondheim DWDS was measured using automated flow cytometer in three different locations: VIVA, Fortuna pumping station and Jakobsli pumping station, shown in *Figure 16.* The aim was to establish baseline of bacterial cell count at the three locations and then observe whether there is growth or decline of bacterial cell count in the water from VIVA to the two pumping station during distribution. To determine the growth rate of the bacterial

cell counts from VIVA to distribution system, hydraulic residence time had to be determined. This was done by performing tracer study with injection of NaCl solution at VIVA to induce a temporary increase in salt concentration, and thus increase of conductivity in treated water from VIVA. The increase was then measured at Jakobsli pumping station and the time difference between injection at VIVA and observance of conductivity increase at Jakobsli was used to calculate hydraulic residence time. List of equipment used for flow cytometry and tracer study are listed in *Appendix B: Equipment.*

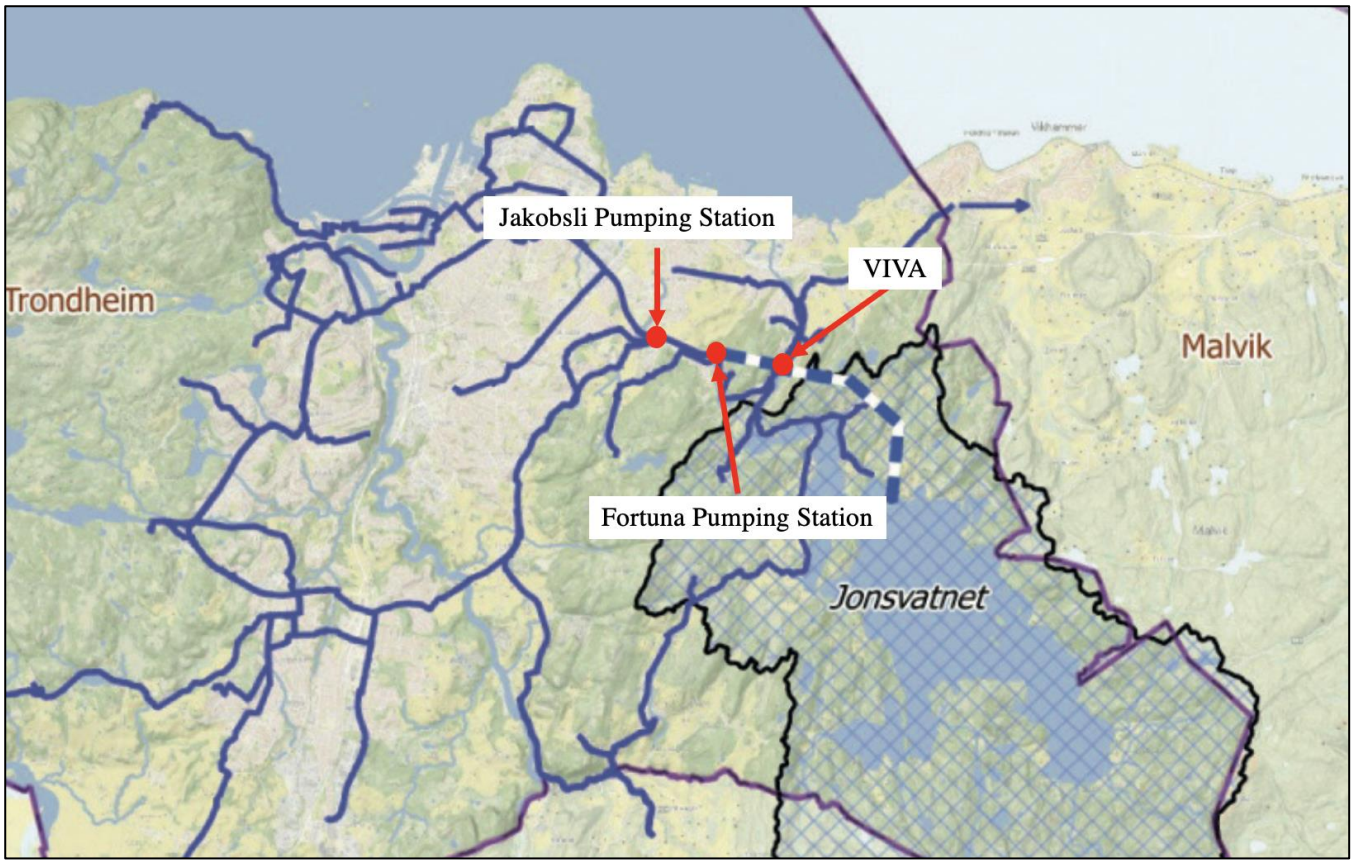

Figure 16. Location of three stations relative to each other. Specification of the stations were made in PowerPoint with screenshot from report *Kommunedelplan for vannforsyning 2017 - 2028* [7]. The hydraulic distance between VIVA and Fortuna pumping station is roughly 1.1 km and the distance between Fortuna pumping station and Jakobsli pumping station is roughly 1.3 km [7].

7.1 Method – Automated Flow Cytometry

To measure the bacterial cell count, bNovate BactoSense - an automated online FCM was connected to a branch pipeline that was connected to the water main that transfers treated water at VIVA. Same was applied at Jakobsli pumping station. The measurement of cell count in treated water at VIVA lasted from Tuesday 24. May.2022 to Friday 27. May.2022. Afterwards, the FCM was moved from VIVA to Jakobsli pumping station and was set to measure cell counts from Tuesday 31. May.2022 – Friday 07. June.2022.

Measurements were taken every 1 hour. Data of bacterial cell count at Fortuna pumping station was provided by Trondheim waterworks, as BactoSense FCM was something that were already being utilized by Trondheim waterworks at Fortuna pumping station. FCM at Fortuna had been in use by Trondheim waterworks since December 2021 to monitor abrupt bacterial cell count changes due to possible pollution. Reason for this is because the treated water from VIVA travels through a rock blasted tunnel to Fortuna pumping station, where during the 1.1 km distance, there is a risk of contamination by leaks through the cracks.

Before starting the measurement of cell counts with BactoSense, the insertion point of inflow on the FCM was wiped with Cutisoft Wipes. Then the instrument was rinsed with decontaminating and rinsing fluid from cleaning kit for BactoSense, see *Appendix B: Equipment.*

Figure 17. Set up of BactoSense FCM at VIVA. The inflow to BactoSense was connected to the faucet using adapters. The flow in and out of the BactoSense was constant.

7.2 Method – Tracer Study with NaCl

For the tracer study which had the objective of determining hydraulic residence time from VIVA to Jakobsli pumping station, same steps of tracer study performed in Trondheim DWDS in 2020 by Rakstang.J.K [38] was followed. Tracer study was performed at the same period of automated flow cytometry at Jakobsli pumping station, 31. May.2022 – 07. June.2022.

A 70L plastic box with separation wall and outlet pipe was constructed for this experiment, see *Figure 19*. Conductivity probe with Campbell Scientific CR200 data logger attached was placed in the plastic box at Jakobsli pumping station 31. May.2022, taking measurement of water conductivity every 10 minutes. The box was utilized to create a stable environment for the probe to measure conductivity and the separation wall in the box was created to release air bubbles. The box was created following the design of similar box utilized in the tracer study in Trondheim DWDS 2020 by Rakstang.J.K [38]. Prior to the installment of the logger at Jakobsli, the data logger and the probe were tested with standard solution of NaCl to verify it was functional.

Injection of NaCl began at VIVA on 09:53am, 01. June.2022. After injection of salt, first sign of increase in conductivity on the outflow from VIVA was registered at time 10:18am, 01. June.2022. Conductivity of outflow at VIVA was measured using a handheld conductivity meter. Injection of the brine solution ceased around 11:00 am, 01. June.2022, resulting in approximately 1 hour of injection.

Figure 18. Set up for tracer study at Jakobsli pumping station. **1.** Protection case that contains data logger. **2.** 70L plastic box where the measurement of conductivity takes place. **3.** Extension cord for power supply.

Figure 19. 70L plastic box at Jakobsli pumping station. **1.** Inflow from faucet connected to a hose. **2.** Separation wall. **3.** Conductivity probe. **4.** Plastic outlet pipe. Red arrow points to the opening in the bottom of the box that connects the inflow chamber to the measuring chamber.

7.2.1 Injection of NaCl Brine at VIVA

Sodium hypochlorite (NaOCl) which is used as disinfectant at VIVA is produced onsite. This is produced by firstly creating saturated salt brine, pouring food grade salt into a plastic tank filled with water. The brine is then pumped to the electrolysis units, where the sodium hypochlorite (NaOCl) is produced. For the tracer study, a portion of the saturated salt brine in the plastic tank was pumped directly to contact pool where in normal setting, water and chlorine resides for approx. 30 minutes before moving onwards to UV lights and then to the distribution system. The brine was pumped with a membrane pump, connected with a flexible plastic tube, see *Figure 20.* The brine was pumped with a constant flow of approximately 2.31 L/min.

The saturated NaCl solution at VIVA had temperature roughly in the range of 10 – 15 °C. At 15 °C, NaCl has solubility of 358.7g NaCl in 1L water [70], which corresponds to 26.4% w/w. During the injection of brine, the outflow from VIVA was roughly in the range of 750 – 800 L/s. With an average outflow of 775 L/s of treated water, and constant flow of 2.31 L/min of brine, this meant an increase of Δ13.1 mg/L of NaCl in the treated water from VIVA. Theoretical increase of conductivity as a result of increase in NaCl concentration was calculated to be Δ26.2 µS/cm. This calculation was done by using the *Eq. 12*, that were found from *N.R.G Walton* [71]. Correction factor K = 0.5 was chosen and used for calculations as it was the best value suited for the condition present at VIVA. Calculations are presented in *Appendix C: Calculations and Calibration Curves.*

$$EC = \frac{TDS}{K} \qquad \textit{Eq. 12}$$

Where:

$EC = Electrical\ conductivity\ at\ 25°C\ [\frac{\mu S}{cm}]$

$TDS = Total\ dissolved\ solids\ [\frac{mg}{L}]$

$K = Correction\ factor\ [\frac{mg \cdot cm}{\mu S \cdot L}]$

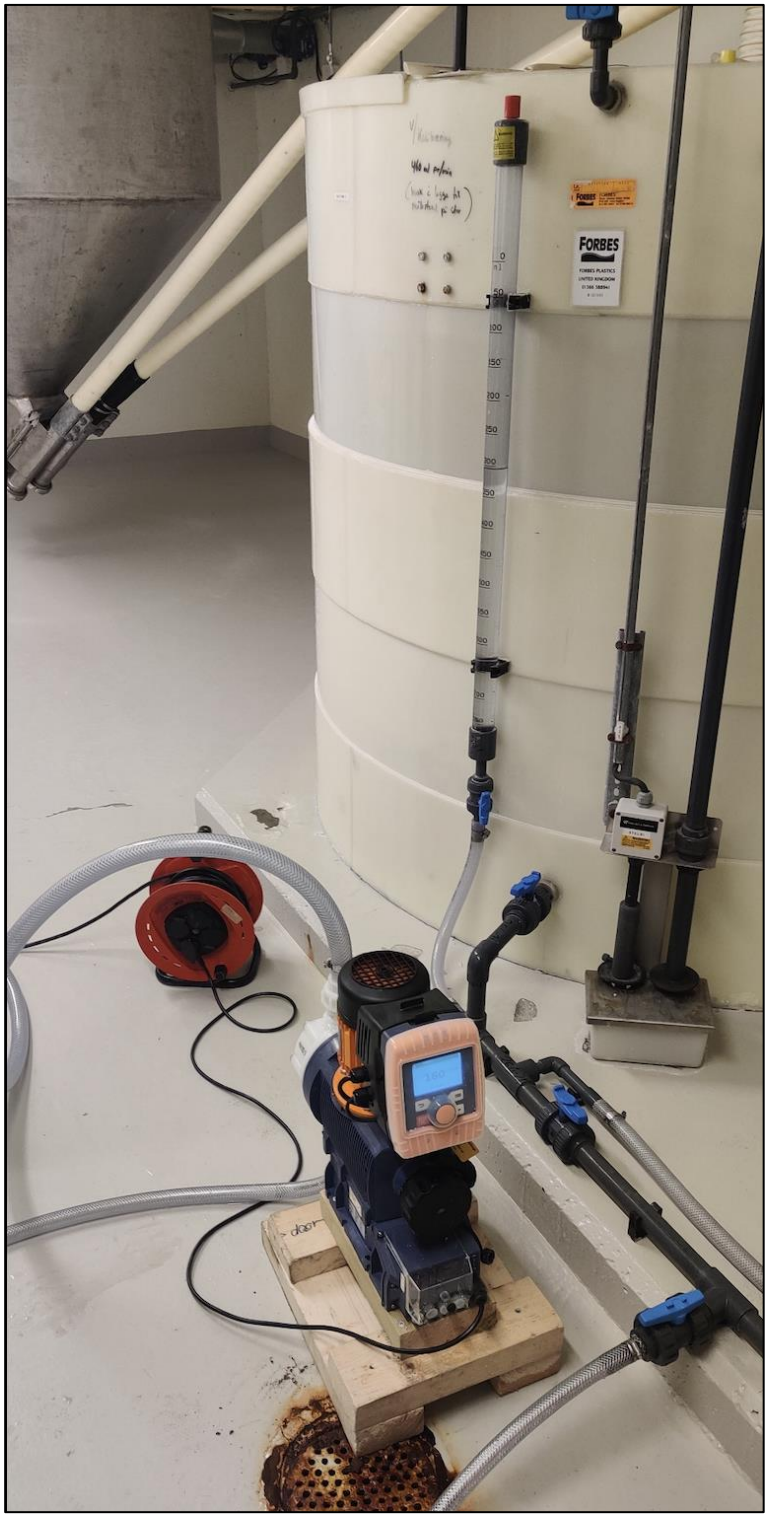

Figure 20. Membrane pump for pumping salt brine from the brine tank to mainline at VIVA

8 Results

The results of the main analyses that were done in relation to the thesis are presented in this chapter. First, the result of source trace analysis through field work is presented. Thereafter, result of source trace analysis with water distribution model is presented. This is followed by results from the automated flow cytometry and tracer study with NaCl solution.

8.1 Results of Parameter Study for Source Trace Analysis in Trondheim through Field Work

Table 3 shows concentration of copper, pH, conductivity and color values that were measured for treated water from VIVA, and raw water from VIVA and Benna raw water. By VIVA raw water, it refers to the untreated water that are from Jonsvatnet Lake, whilst Benna raw water refers to the untreated water from Benna Lake. As Benna DWTP was not operational during source trace analysis through field work, sample of treated water from Benna could not be obtained and analyzed. For each of the three types of water, four samples were obtained for copper analysis to calculate the average concentration.

Table 3. Fingerprint of VIVA and Benna

Sampling Location	Copper Concentration [µg/L Cu]					pH		Conductivity [µS/cm, 25 ˚C]	Color [mg/L Pt]
	Sample nr.1	Sample nr.2	Sample nr.3	Sample nr.4	Average	pH	Temperature [˚C]		
VIVA Treated Water	2	0	2	0	1	8.2	18.8	141	16.9
VIVA Raw Water	2	3	2	0	2	7.7	17.6	63.5	17.1
Benna Raw Water	1	1	1	2	1	7.5	19.6	101	5.1

Table 4 presents the results of copper, pH, conductivity, and color analyses that were done for samples obtained from the 29 sampling locations. As already mentioned in *5.6 Sampling Method*, first flush sample and additional sample for copper analysis were obtained in some chosen sampling locations. The results of these extra samples are also presented in Table 4. Temperature of water that was measured at the sampling location after flushing for 5 minutes are also presented in Table 4. Temperature of sample water that were used to measure pH are presented under pH. Range, average and median values for the parameters are presented in the bottom three rows.

Full overview of the locations of the sampling locations, as well as date and time of sampling are presented in *Appendix A: Sampling Locations.*

Table 4. Copper, pH, conductivity, and color values present at the 29 sampling locations during 15. March. 2022 – 25. March.2022.

Sampling Location	Temperature of sampling water [˚C]	Copper Concentration [µg/L Cu]			pH		Conductivity [µS/cm, 25 ˚C]	Color [mg/L Pt]
		First Flush	Flush 5 min (nr.1)	Flush 5 min (nr.2)	pH	Temperature [˚C]		
1	3.5	-	32	-	8.1	11.1	135	17.6
2	5	-	43	-	8.1	10.0	133	17.4
3	3	-	12	-	8.3	10.2	131	17.2
4	5	-	8	-	7.6	9.7	131	17.3
5	4	-	16	-	8.3	8.8	131	17.5
6	3.5	-	6	-	8.3	9.4	130	17.6
7	5.5	-	27	-	8.2	18.7	129	18.2
8	5.5	-	25	-	8.2	18.5	128	17.9
9	7	-	75	-	8.2	18.5	130	17.8
10	4	-	17	-	8.3	18.6	129	17.6
11	5	-	48	-	8.2	18.6	129	18.0
12	9	-	35	-	8.2	18.8	129	17.7
13	4	-	9	5	8.1	18.1	128	17.0
14	4	-	16	13	8.1	18.6	129	17.4
15	4	-	1	-	8.2	18.7	129	17.1
16	6	-	10	-	8.1	18.9	129	17.2
17	5	-	17	-	7.9	19.5	129	17.4
18	7	283	83	-	8.2	16.8	129	16.4
19	4	-	22	21	8.3	16.5	129	13.3
20	7	39	31	32	8.0	16.7	130	13.3
21	4	49	4	2	8.2	21.0	128	17.3
22	7	239	45	44	8.3	20.9	129	17.5
23	4.5	150	5	8	8.2	21.1	129	17.5
24	7	-	52	50	8.8	24.8	129	17.4
25	5	67	32	30	8.5	24.9	129	17.5
26	4	14	6	5	8.8	24.7	129	17.2
27	4	-	7	6	8.9	24.7	130	16.9
28	6.5	107	17	14	8.6	21.7	130	17.1
29	3.5	1	0	2	8.8	21.4	131	16.6
Range	[3.5 - 9]		[0 - 83]		[7.6 - 8.9]	[9.4 - 24.9]	[128 - 135]	[13.3 - 18.2]
Average	5.1		25		8.3	17.9	130	17.1
Median	5		17		8.2	18.6	129	17.4

8.1.1 Results – Additional Copper Analysis

Results of additional copper analysis that were performed in 06. April.22 at the three sampling locations, 9,14 and 23, to investigate copper concentration in relation to duration of flushing are presented in Table 5. Corresponding temperature of water that were measured for the obtained samples are also presented.

Table 5. Additional copper analysis - copper concentration in relation to duration of flushing.

Flush Duration	Sampling Location 9		Sampling Location 14		Sampling Location 23	
	Copper Concentration [µg/L Cu]	Temperature [˚C]	Copper Concentration [µg/L Cu]	Temperature [˚C]	Copper Concentration [µg/L Cu]	Temperature [˚C]
First Flush	67	-	336	-	362	-
Flush 5 min	68	6	13	4	41	5
Flush 10 min	62	6	13	3.5	36	5
Flush 15 min	60	5.5	11	3.5	32	4
Flush 20 min	58	5.25	11	3.5	31	4
Flush 25 min	66	5.25	14	3.5	32	4
Flush 30 min	61	5.25	11	3.5	30	4

8.2 Results of Source Trace Analysis with Water Distribution Model

The map was produced using QGIS 3.22.7 LTR, where the map of Trondheim was imported from OpenStreetMap plugin. The coordinates of the nodes from WDM were imported as .csv file. To obscure the level of detail of Trondheim DWDS, the coordinates of nodes were randomized by ±10m from the original coordinates. *Figure 21* and *Figure 22* shows the results from the simulation.

In *Figure 21*, the percentage of water that are from VIVA are color graded where the red color represents nodes that have 100% of water from VIVA, whilst blue color represents nodes that have 0% of water from VIVA. Orange and teal represent nodes that have on average 90-100% and 0-10% of water from VIVA respectively. These two ranges were added to show nodes that experiences mixing but still predominantly have water from one DWTP. Yellow and green represents nodes that experiences mixing, where yellow nodes are more influenced by VIVA and green nodes are more influenced by Benna DWTP. In the WDM, the distribution system of Klæbu was connected to Trondheim DWDS. This caused the area of Klæbu (right bottom) to be areas of blue nodes. This is because, as mentioned in chapter *3.1 Study Area*, Klæbu have water from their own ground water source, Fremo. Therefore, the blue nodes in Klæbu area should not be mistaken as nodes that are supplied from Benna DWTP.

Figure 22 shows standard deviations from the average percentages of contribution from VIVA. This reveals nodes that are subject to fluctuations of contribution from the two DWTPs. Consequently, nodes with heavier red color indicates nodes that have higher degree of fluctuations.

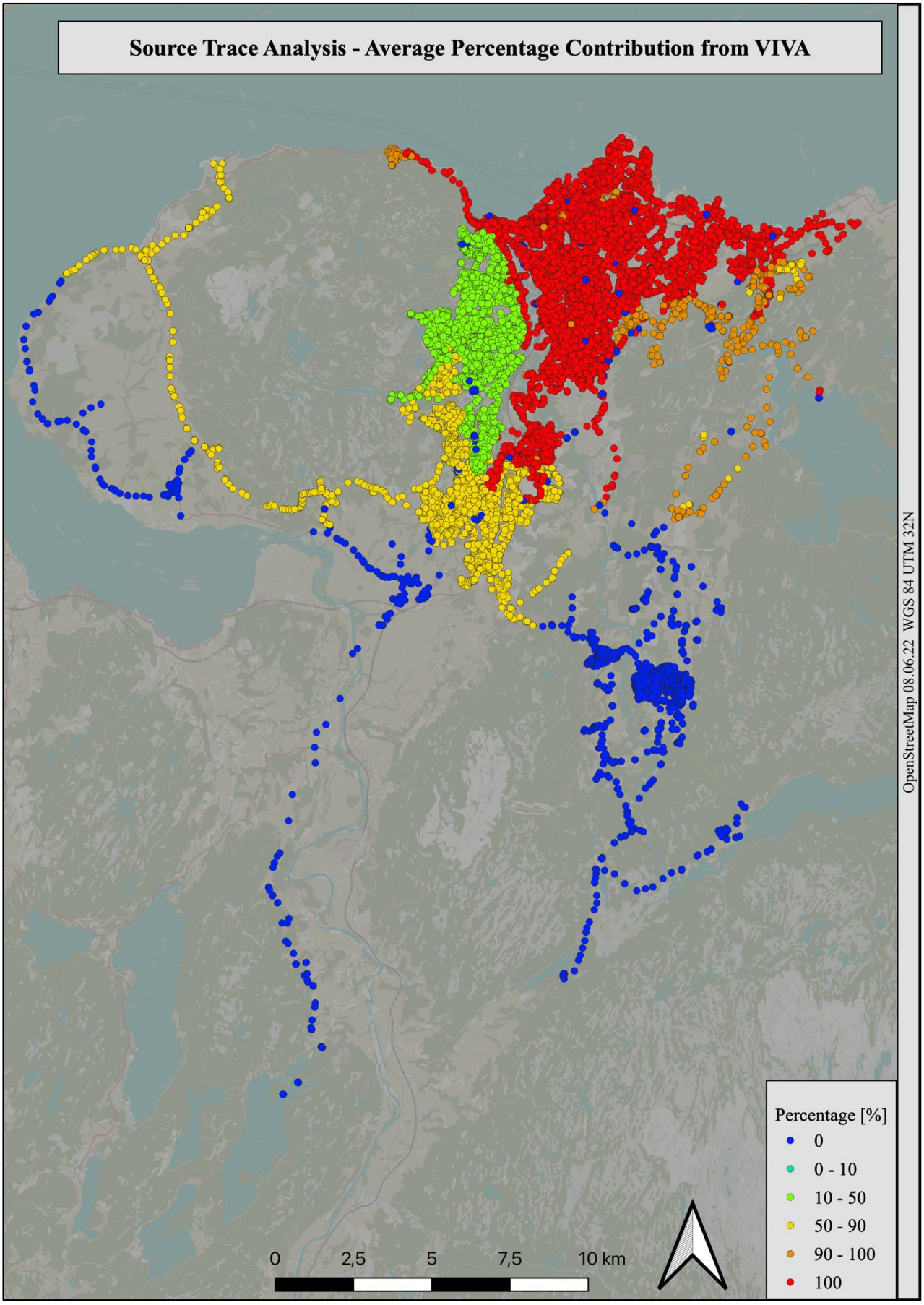

Figure 21. Average percentage of water that are from VIVA in Trondheim DWDS. Average was calculated for the last 48 hours of the simulation.

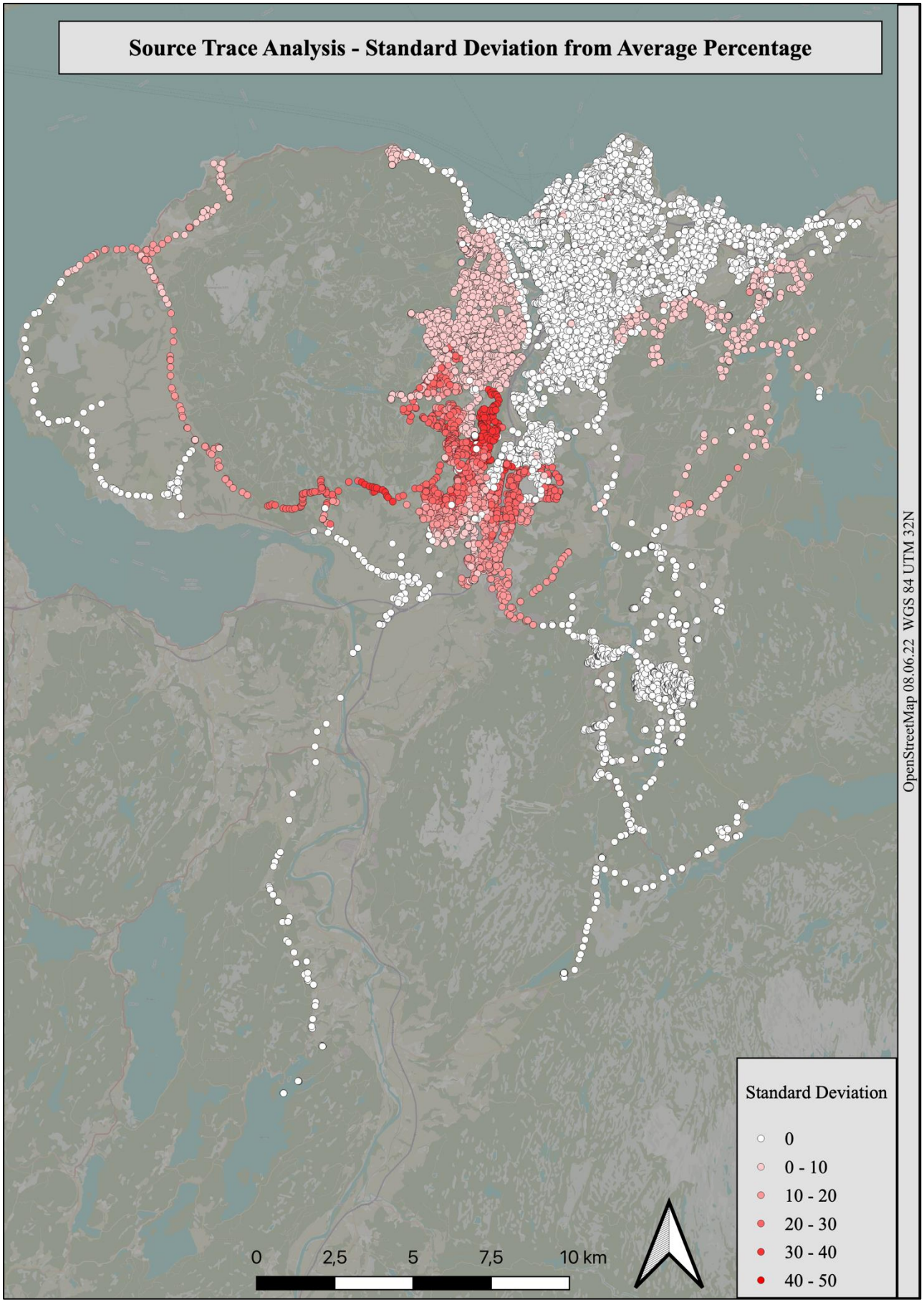

Figure 22. Standard deviation from average percentage of water from VIVA for the last 48 hours of the simulation.

8.3 Result from Flow Cytometry

Measurement of bacterial cell counts in drinking water were performed with automated FCM – BactoSense and were done at VIVA (24. May.22 – 27. May.22) and Jakobsli pumping station (31. May.22 – 07. June.22) with timesteps of 1 hour. Due to technical issues with the BactoSense at Jakobsli pumping station, measurement from between 31. May.22 – 02. June.22 are omitted from the presented results. FCM measurement from Fortuna pumping station were provided by Trondheim municipality and are measurement from 23. May.22 – 07. June.22, with time steps of 6 hours.

Automated FCM at VIVA and Jakobsli measured Total Cell Count (TCC), Damaged Cell Count (DCC), Intact Cell Count (ICC), High Nucleic Acid Count (HNAC) and Low Nucleic Acid Count (LNAC). The provided data from Fortuna pumping station contained only ICC, HNAC and LNAC. The relationship between the different cell counts is that TCC is the sum of DCC and ICC, and ICC is the sum of HNAC and LNAC. The results are presented below in *Figure 23* and *Figure 24*.

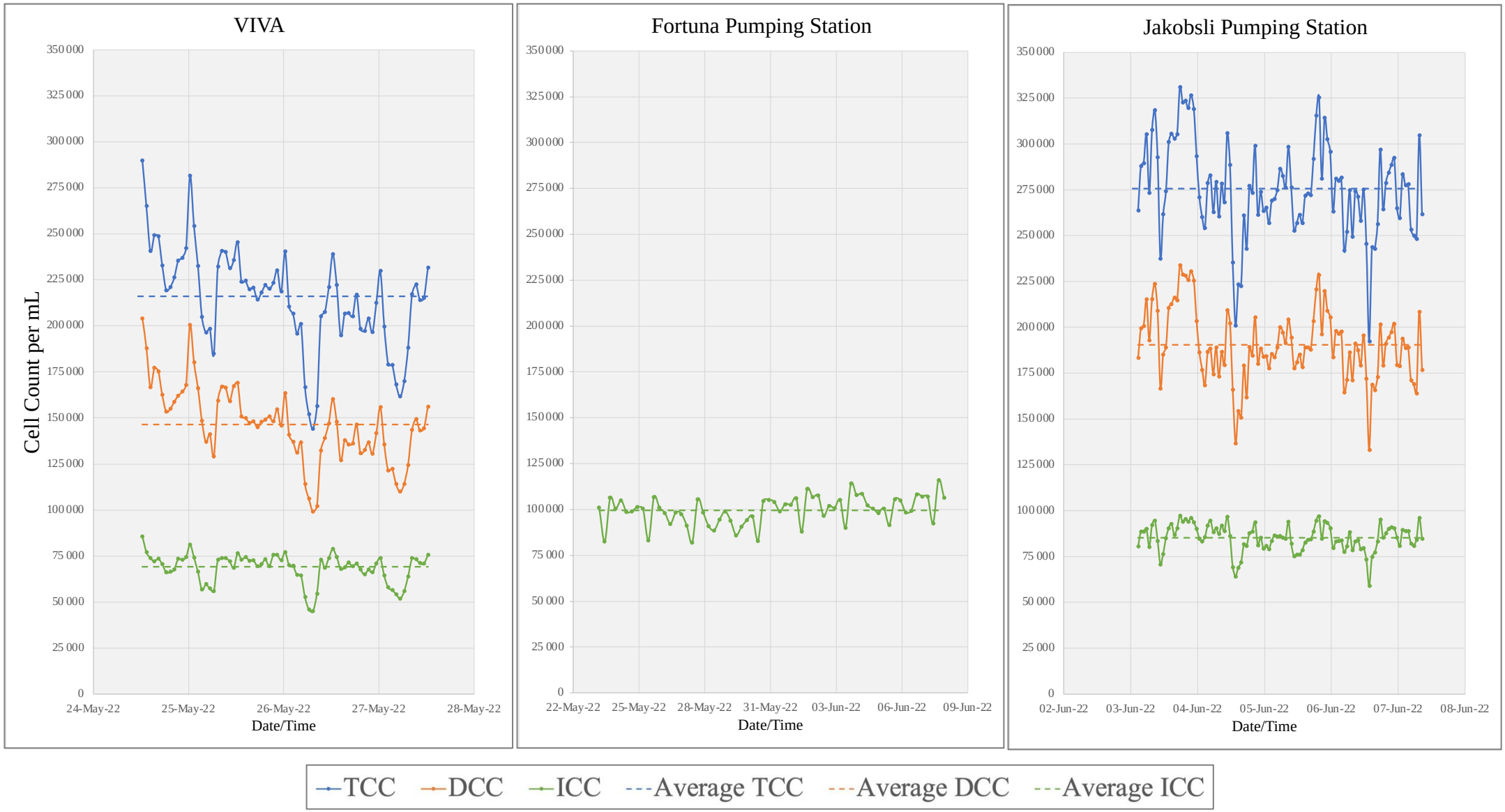

Figure 23. Result of TCC, DCC and ICC from automated flow cytometry. TCC and DCC from Fortuna pumping station were not available.

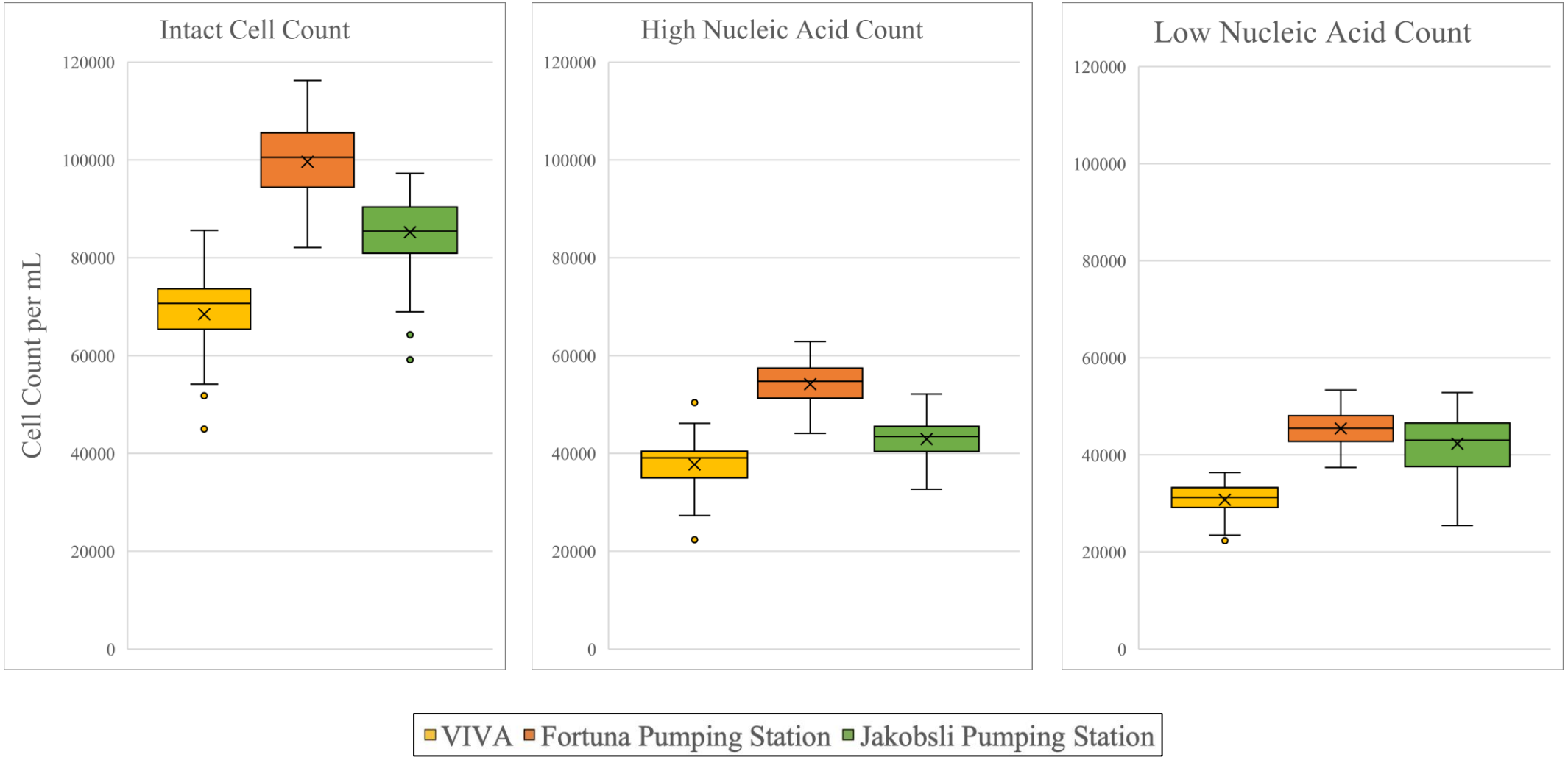

Figure 24. Results of ICC, HNAC and LNAC from automated flow cytometry at VIVA, Fortuna and Jakobsli pumping station.

8.4 Result from Tracer Study in Trondheim

Injection of saturated NaCl brine started at 09:58 am on 01. June.2022. After 20 minutes, first increase in conductivity was observed in the outflow at VIVA. The increased conductivity stabilized to roughly 160 µS/cm, resulting in increase of ≈Δ30 µS/cm, see *Figure 25.*

Data logger at Jakobsli pumping station registered first increase in conductivity roughly 5.5 hours after start of tracer injection. The increase lasted for roughly 3 hours, see *Figure 26* and *Figure 27.* Average conductivity at Jakobsli pumping station in period 01. June.22 – 07. June.22, was measured to be 114.4 µS/cm. As a result of tracer injection, the highest conductivity measured at Jakobsli pumping station was 137.4 µS/cm, meaning an increase of maximum Δ23 µS/cm from average.

Tracer's mean residence time (MRT) from start of tracer injection to detection at Jakobsli pumping station was calculated to be 6.9 hours. Since it took 20 minutes before tracer started leaving VIVA after injection, MRT from outflow at VIVA to Jakobsli pumping station is 6.6 hours. This means that water on average used 6.6 hours in the distribution system to travel from outflow at VIVA before arriving at Jakobsli pumping station. Calculations of the MRT are shown in *Appendix C: Calculations and Calibration Curves.*

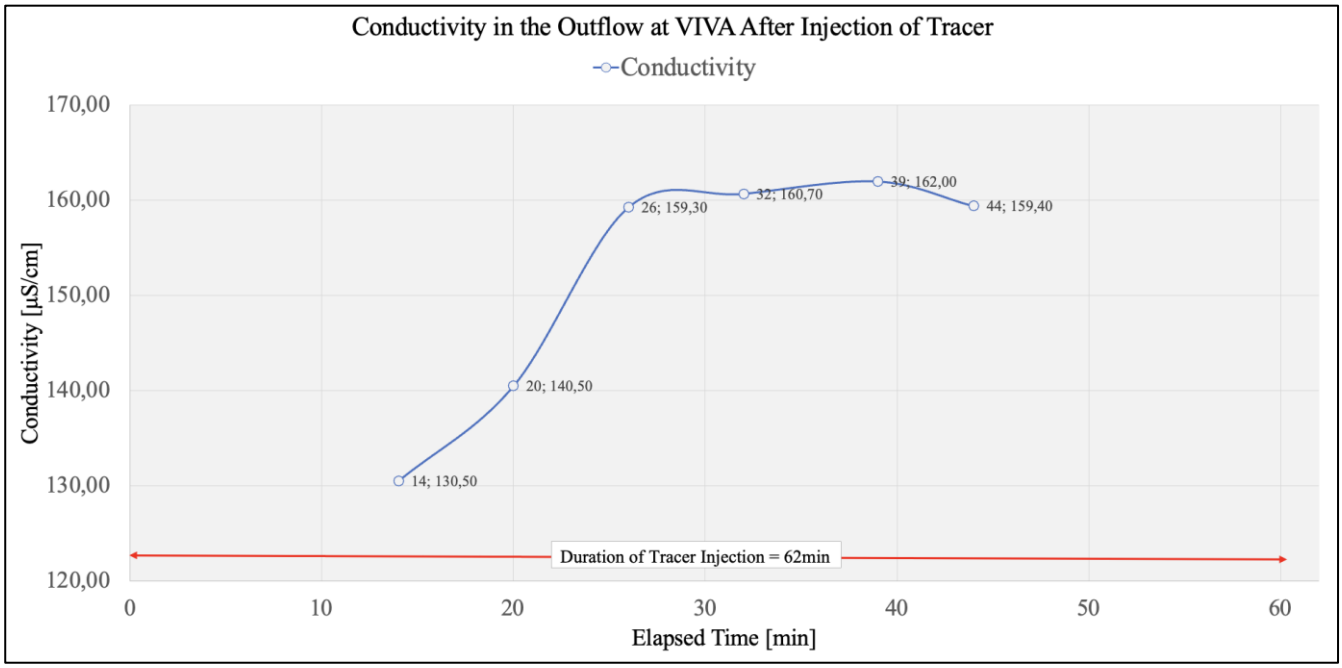

Figure 25 Increase in conductivity in treated water at VIVA in the outflow after injection of NaCl. First increase in conductivity in the outflow was registered 20 minutes after start of tracer injection.

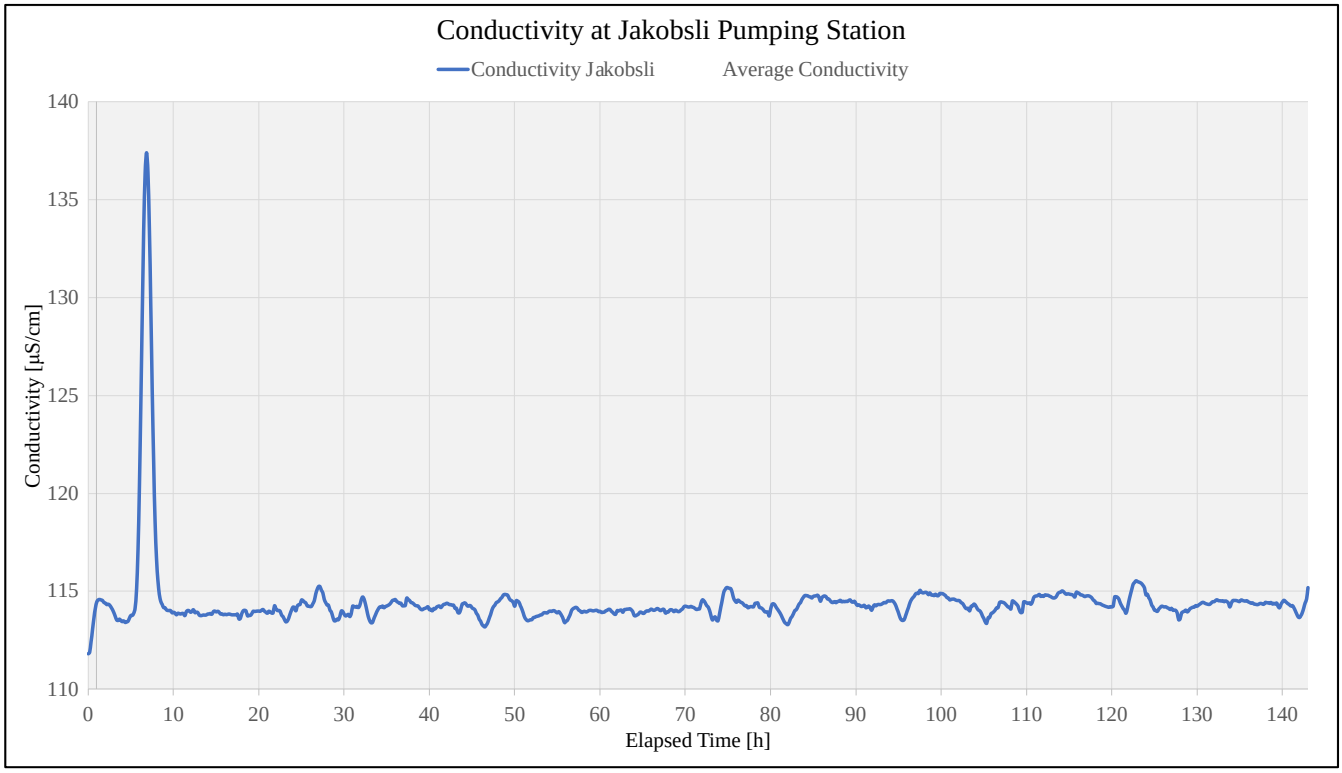

Figure 26. Water conductivity at Jakobsli pumping station from 01. June.22 - 07. June.22.

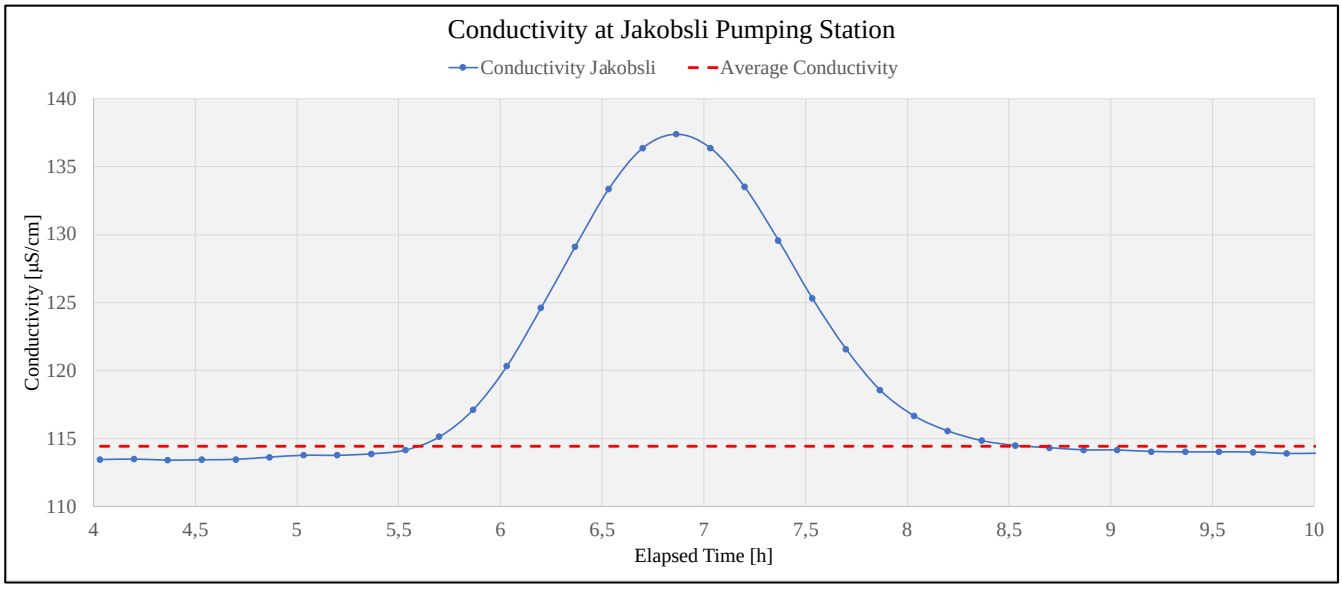

Figure 27. In depth look at water conductivity increase in Jakobsli pumping station 01. June.22.

9 Discussion

Discussion of the results are done in this chapter. It aims to discuss whether the experiments and the simulation in this thesis achieved to answer the established research questions and presents possible interpretations of data and result from the experiments.

9.1 Parameter Study for Source Trace Analysis in Trondheim through Field Work

The initial goal of field work was to determine zones of areas in Trondheim DWDS where water from VIVA and Benna DWTP mixes with each other. However, during the field work it was uncovered that Benna DWTP had been shut down and VIVA was the only DWTP that were supplying Trondheim DWDS. As such, this meant that every location in Trondheim DWDS had water originating at VIVA, making it unfeasible to determine mixing zones through field work data. Thus, the objective of source trace analysis through field work changed from investigating locations of mixing zones to investigate conservativeness of the four parameters copper, pH, conductivity, and color in Trondheim DWDS. As explored in literature review, conservativeness is desired for tracers so that concentration level of tracer at origin and where it is detected are the same. This makes it easier to determine that the tracers have arrived and establish its origin more confidently.

Prior to the field work it was assumed that the four parameters behaved conservative in Trondheim DWDS. As such, the water characteristics of the samples that were obtained at the sampling locations were expected to be similar, if not identical, to water characteristics of treated water at VIVA. However, results from field work revealed that this is not the case. Copper concentration varied greatly between water at VIVA and water at the sampling locations. pH values were more consistent than copper, suggesting to be more conservative, but nonetheless, non-negligible variances could be observed. Conductivity and color values between VIVA and sampling locations had less variances, suggesting that the two parameters are conservative during distribution as initially assumed. As for field data from March 2022 compared to data from 2020, changes in copper concentration at VIVA were observed whilst same observation but with smaller changes for the other three parameters could be made.

Table 6 compares the average value of the four parameters at VIVA and Benna DWTP that were observed in 2020 (which were presented in Table 1) with average value from field work from March 2022. Since sample of treated water at Benna could not be obtained, comparison of treated water at Benna DWTP from 2020 and raw water from Benna DWTP 2022 are made in Table 6. This is thought as non-problematic as the treatment process at Benna DWTP do not affect copper, pH, conductivity, and color from raw water. The conductivity values from 2020 were measured with temperature reference 20 °C.

To be able to compare the values with field work values from March 2022, which were measured with reference temperature 25 °C, conductivity values from 2020 were converted to values at 25 °C with temperature correction factor from *European Standards Water quality – Determination of electrical conductivity [60]*. The calculations are shown in *Appendix C: Calculations and Calibration Curves*

Table 6. Comparison of water characteristics at VIVA and Benna DWTP between 2020 and 2022.

Parameter	VIVA 2020	VIVA 2022	Benna DWTP 2020	Benna DWTP (raw) 2022
Copper [µg/L Cu]	44.7	1	0.8	1
pH	8.1	8.2	7.7	7.5
Conductivity [µS/cm, 25 °C]	143	141	110	101
Color [mg/L pt]	15.2	16.9	3.4	5.1

9.1.1 Copper

When planning for source trace analysis through field work, copper was chosen as the primary parameter to investigate due to concentration level found at VIVA and Benna DWTP greatly differed. However, this decision was made based on water characteristics data from 2020. Results from March 2022 showed that the average concentration of copper is much lower compared to data from 2020. Average copper concentration was also the same for VIVA and Benna. Therefore, it can be concluded that even if Benna DWTP were operational during field work, it would have been unfeasible to perform source trace analysis by investigating copper concentration level because it would have been impossible to distinguish water from VIVA and Benna.

Considering the suitability of copper for source trace analysis in Trondheim DWDS, the results suggests that copper concentration are not stable and makes it difficult to establish if the water is from VIVA. Therefore, copper is not as good candidate for source trace analysis as initially thought. Originally, it was expected that copper acts conservative in distribution network. Hence, copper concentration was expected to be same for VIVA and the 29 sampling locations. Average copper concentration measured at VIVA was 1 µg/L whilst the obtained samples from majority of the sampling locations showed higher concentration. This suggest that copper concentration in water in Trondheim DWDS is subject to growth during distribution. To increase the certainty that the observed higher concentration was not from lab errors, several measures were taken for the utilized lab equipment, in addition to standard addition method to determine if there are any interferences in the samples. Results from these measures showed no defects or abnormality in the equipment and interreferences in the samples.

Where the extra copper concentration could have been originated from in the distribution system is uncertain. However, results from first flush samples and results from the additional copper analysis

showed that copper concentration are significantly higher for first flushed samples. Thereby, the extra copper can have derived from copper pipes in the plumbing of the buildings where the samples were obtained. This seems likely as existing literatures affirms that copper levels in drinking water are highly influenced by interior plumbing with copper pipes, especially if there are corrosion in the plumbing [11, 72]. This might also explain why some locations such as sampling location 15 and 29 did have same copper concentration of 0 – 1 μg/L like measured at VIVA. The level of exposure the water has to copper pipes in the buildings can factor into the copper concentration, and thus if the building where the samples are obtained do not have copper plumbing, the copper concentration are same as the origin. But this potential interpretation does not account for possible copper availability in the network which can increase copper concentration during distribution in the network [11, 72]. To include this, it might be the case that, some hydraulic paths from VIVA to sampling locations have an interfering point where copper is added in the water whilst some hydraulic paths do not. Therefore, potential explanation of why sampling locations 15 and 29 had same low copper concentration as VIVA might be that, in addition to the buildings where the samples were obtained did not contain copper in the plumbing, the hydraulic path from VIVA to the sampling locations 15 and 29 did not have points where extra copper is added. Supporting data for this conclusion, that added copper is not solely from copper plumbing but also from unknown source in the network, is the results from additional copper analysis. The additional copper analysis, which investigated relationship between copper concentration and duration of flushing, showed that flushing for more than five minutes at the sampling locations 9, 14 and 23, had negligible effect to decrease the copper concentration. Although the samples obtained were flushed up to 30 minutes, copper concentration reached baseline after five minutes, which were measured to be higher concentration than at VIVA. This can be interpreted as following: hydraulic paths from VIVA to the sampling locations 9, 14 and 23 have interfering points where extra copper is added in the water and thus makes the copper concentration in the water at the locations constantly higher than at VIVA. A weakness of this interpretation is that it assumes that flushing for 30 minutes were adequate to fully flush out stagnant water in the building and obtain water from the network. Additionally, it assumes that copper is not added when water travels briefly through copper pipes in the building. Without comparing copper concentration in the water main or distribution line and copper concentration in the buildings, it remains uncertain if the extra copper that were observed for majority of the obtained samples are due to copper pipes in plumbing or possible copper availability in the network or combination of both. To investigate this, further copper analysis has to be made with samples directly from the water main or distribution line to eliminate source of copper from plumbing in the buildings and observation of whether the copper concentrations are as low as VIVA in the water main and distribution line have to be made.

The variability of the copper concentration obtained from 29 sampling locations makes it difficult to establish the origin of water by looking at copper. It has been observed that plumbing in the buildings have traces of copper that can add to higher copper concentration and the addition can also have been from unknown sources in the network. But the magnitude of these contributions has been less than 400 μg/L Cu for first flushed samples. After flushing for five minutes, the observed copper concentrations were all less than 100 μg/L, and the average copper concentration was 25 μg/L. As copper concentration in Trondheim DWDS are in the lower range, it is susceptible to change significantly even by small influence. For this reason, copper could have been a better parameter for source trace analysis in Trondheim if the natural copper concentration were much higher, e.g. 1 mg/L. Then the significance of extra copper concentration of 25 μg/L on average from unknown sources, would have been much less. The data would have been much easier to interpret and establishment of origin of water at a sampling location could have been done with more confidence. Unfortunately, this is not the case, and the results from field work allows for conclusion that copper is not suited parameter for source trace analysis in Trondheim DWDS.

9.1.2 pH

The pH values for the obtained samples from the 29 sampling locations had slight variance, but overall showed values that were expected. The average pH value from the 29 sampling locations were pH 8.3 and median value was pH 8.2. The pH value at VIVA were measured to be pH 8.2. Since the observed average pH value from the sampling locations is almost identical with the pH value that were measured at VIVA, it can be an indication that pH is less susceptible to change during distribution and more suitable for source trace analysis than copper. The average pH value at VIVA from 2020 was pH 8.1, meaning that there has been negligible change in pH at VIVA since the last 2 years.

Although the average pH value may indicate that pH is conservative during distribution, pH values between 7.6 – 8.9 have been observed at the sampling locations. The reason for this variation is largely uncertain but it is likely that it may have its origin in the lab work. A great source of error is that pH measurements were not taken at the sampling locations directly. This strongly suggestion by *European Standards for Water quality - Determination of pH* was ignored [61]. Instead, samples were brought to the lab for measurement, which resulted in samples being measured after 2 - 4 hours of sampling. Another source of error could have been inaccurate pH meter, although calibration with buffer solutions were performed each day of analysis. Maybe the biggest source of error for pH analysis was that the temperature of the samples that were used to measure pH were not identical with each other. The buffer solutions that were used for calibration were kept dark in a drawer in room temperature, approx. 20 °C. To achieve the best results, it is suggested that temperature of the buffer solutions and the samples should

have same temperature for pH analysis according to the European Standards [61]. Therefore, prior to measuring pH of the samples, the samples were left to reach room temperature for 1 – 2 hours, as described in *5.8 pH Analysis.* Unfortunately, consideration to bring the samples to room temperature before measuring pH was forgotten on the first day of analysis. This can be seen in the results for pH for sampling locations 1 – 6. For all the other day, this step was followed. However, from observing the results, temperature of the samples greatly varied, especially between different days of analysis. This is because the duration of which the samples were left to reach room temperature were not done systematically but arbitrary decided on how long it took to finish copper analysis of the day before moving on to pH analysis. Since pH of water is dependent on the temperature, with decreasing pH as temperature increases, it might be the reason why there was variance in pH [73]. Still the variations in temperature of the samples are not able to explain the magnitude of variance in the pH. It especially does not explain why there were higher pH than at VIVA for higher temperatures observed in results for sampling locations 24 – 29, and why there were lower pH than at VIVA for lower temperature observed in result for sampling location 4, whilst opposite should have been true.

Results have also shown that pH value at VIVA and Benna are different, with data from 2020 and March 2022 suggesting the same. The difference is however quite minimal, with VIVA having roughly 0.7 higher in pH than Benna, derived with data from 2022. Although it seems that pH is relatively stable in the distribution network, the range pH values that have been measured through field work makes it difficult to declare with confidence that a location is supplied by water from VIVA only by looking at the pH value. For instance, if Benna DWTP were operational during field work and sampling location 4 was supplied solely by VIVA, it would still have been more reasonable to state that sampling location 4 is supplied by Benna DWTP, since the pH value are more similar to pH value found at Benna DWTP than VIVA.

Due to the sources of error that were mentioned and mistakes that were done during pH analysis, it cannot be concluded whether if pH is conservative in DWDS. Repeated pH analysis is required where the pH is measured directly at the sampling locations, and temperature of the samples are greatly more considered. Even if pH is stable in distribution network, the small differentiation of pH value between VIVA and Benna DWTP might make it more preferable to utilize other parameter for source trace analysis which is more distinguishable.

9.1.3 Conductivity

Conductivity was the parameter that was observed to be the most stable of the four parameters. For majority of the sampling locations, conductivity of the samples was measured in the range 128 – 131

μS/cm, while a couple of samples deviated slightly out of this range. Overall, the conductivity between the 29 sampling locations were very consistent with each other. One notable observation is that conductivity for the treated water at VIVA was measured to be 141 μS/cm, meaning that for almost all samples obtained at the sampling locations had roughly 10 μS/cm lower than the origin. Although 10 μS/cm is a relatively small difference, why the conductivity of the samples from sampling locations all had roughly the same conductivity while simultaneously all having 10 μS/cm lower than the origin is uncertain. A possible reason might be that measurement of conductivity for treated water from VIVA contained error or was done improperly, and thus leading to having 10 μS/cm higher than actual value. This would explain why the observed values from the field are so consistent with each other, at the same time having slightly lower conductivity than VIVA. Supporting evidence for this is that, when conductivity was measured at VIVA in relation to the tracer study, conductivity was measured to be around 130 μS/cm before increase of conductivity was observed as a result of added NaCl. Another explanation might be that the conductivity of treated water from VIVA decreases slightly shortly after leaving the treatment plant. Since conductivity at VIVA in 2020 and March 2022 are practically the same, this might support the argument that the measurement of conductivity was done correctly for March 2022. Theory that conductivity decreases slightly, shortly after leaving the treatment plant might explain why there were slightly higher conductivity at the sampling locations 1 and 2 than rest of the sampling locations, since these two sampling locations were the closest to VIVA of all the sampling locations.

Conductivity of treated water at VIVA is much higher than the raw water. Although the reason is uncertain to the author of this thesis, it is hypothesized that it is caused by the filtration step with limestone in the treatment process. This causes the conductivity at VIVA to be higher than conductivity at Benna DWTP, with VIVA having almost 40 μS/cm higher conductivity than Benna. Because of this difference, it is possible to distinguish water from VIVA and Benna. However, the differences in conductivity between raw water from Jonsvatnet and water from Benna DWTP are also approx. 40 μS/cm, where water from Benna DWTP have higher conductivity than raw from Jonsvatnet. Therefore, even if the raw water from Jonsvatnet did not undergo a process which results in higher conductivity after treatment, it would have been feasible to distinguish water from VIVA and Benna DWTP from each other solely by looking at conductivity values.

Observation of conductivity values between the sampling locations suggest that conductivity is very stable and conservative in DWDS with minimal variance (± 2 μS/cm except for a couple of samples). Even for sampling locations located far away from VIVA, such as sampling location 26 and 29, had the same conductivity values as rest of the sampling locations indicating that water is not subject to alteration in relation to conductivity during distribution. Moreover, conductivity analysis was the simplest and

easiest analysis of all the analyses that were performed. Gathering samples and analyzing later in the lab was not considered as a big of an issue as it was for pH, and there were a lot less required contamination control and calibration like for copper analysis. With combination of conservativeness of the parameter, natural differences of conductivity between water at VIVA and Benna DWTP, and easy to perform analysis, it is concluded that conductivity is a favorable parameter for source trace analysis in Trondheim DWDS.

9.1.4 Color

Including all the sampling locations, the color of water was observed in range between 13.3 – 18.2 mg/L Pt. However, excluding the color result from sampling locations 19 and 20, observed color were in range between 16.4 – 18.2 mg/L Pt, making the range much narrower. Average and median value of color were 17.1 and 17.4 mg/L Pt, respectively. Since the color of the sample from VIVA was 16.9 mg/L Pt, the results suggest that, on aggregate, the color values are subject to negligible change and acts conservative. Why the color at sampling location 19 and 20 differed so greatly in comparison to others is a mystery. Since only VIVA was in operation during field, water in sampling location 19 and 20 were for a fact from VIVA. Therefore, assuming that there were no errors during lab work, color of water became clearer somehow on the way from VIVA to sampling locations 19 and 20. If this is the case, it is a problematic, as it could lead to misinterpretation of data in source trace analysis. If Benna DWTP had been in operation, the results from sampling location 19 and 20 could have been interpreted as these locations being mixing zones.

Compared to data from 2020, color value at VIVA and Benna were slightly higher than average. Still the difference is quite small. Color values at VIVA compared to Benna DWTP is noticeable, making it feasible to differentiate water from the two sources from each other. By looking at data from 2020 [59], the lowest value of color that have been measured at VIVA is 8 mg/L Pt, whilst the highest value of color at Benna DWTP is 6 mg/L Pt. Thereby, even in the worst circumstance, differentiation could have been made. In normal circumstances however, the difference is roughly around 12 mg/L Pt between VIVA and Benna DWTP as evidenced from field results and data from 2020. As it has been shown through results from field work March 2022 that color is relatively stable and conservative, with exception for the result from 19 and 20 that had lower concentration than other samples for unknown reasons, color seems to be a good tracer of choice for source trace analysis next to conductivity. For future source trace analysis however, further investigation of why sampling location 19 and 20 had distinguishably lower color values than rest of the distribution system is suggested, to not incorrectly conclude that these areas are mixing zones.

9.2 Source Trace Analysis with Water Distribution Model

The result from simulation confirmed some earlier beliefs of hydraulic limits of VIVA and Benna DWTP but also revealed some new knowledge. As expected, northern-eastern part of Trondheim, including the whole city center area, is predominantly supplied by VIVA. This was foreseen due to these areas being relatively close to VIVA. Likewise, southern part of Trondheim, which is closer to Benna DWTP and Kolstad pumping station, is predominantly supplied by Benna DWTP. The most prominent area of mixing was observed in the middle parts of Trondheim. The same area was also observed to be subject to heavy fluctuations of influence from the two treatment plants. Single blue nodes that are seemingly out of place in areas where it is surrounded by primarily other colors, are results of nodes that did not stabilize due to having extremely low water demand. These nodes can be seen sporadically throughout DWDS.

Hydraulic limit of VIVA extends all the way down to the southern part and western part of Trondheim, as evidenced by border between yellow and blue nodes in the southern and western region. Hydraulic limit of Benna DWTP extends almost to city center and reaches all the way to the middle-northern part of Trondheim. The hydraulic limit can be observed by looking at border between green and red nodes, and yellow and red nodes. The little area of orange nodes in the far north of Trondheim also signifies that small quantity of water from Benna DWTP are able to reach to that area. Overall, the result from simulation show that Trondheim DWDS allows for good interconnection between VIVA and Benna DWTP, resulting in large areas of Trondheim experiencing mixing of water from the two sources.

9.2.1 Western Part of Trondheim - Byneset

Surprisingly, water from VIVA had significant influence in the far western part of Trondheim DWDS in the area of Byneset, as evidenced by yellow nodes in the area. It was initially hypothesized that far western part would predominantly be supplied by Benna DWTP and be full of blue and teal nodes, due to the area being a lot closer to Kolstad pumping station that connects Trondheim DWDS with Benna DWTP. At the same time, isolated area of blue nodes, representing water from Benna DWTP, are observed in Byneset. This looks odd at first glance as isolated nodes that are connected and surrounded by yellow nodes are not yellow themselves. However, this is not an error and is caused by a watermain connection to Byneset in the WDM that cannot be seen in *Figure 21* and *Figure 22*. Whether this connection is in real life is uncertain. However, without this connection, the whole area of Byneset would be yellow, a mix of water with slightly more influence from VIVA.

9.2.2 Effects of Klæbu DWDS

Orange and yellow nodes in the eastern part of Trondheim, close to Jonsvatnet, signify that there are mixing. This is likely caused by mix of water from VIVA and Klæbu, due to Klæbu DWDS being connected to Trondheim DWDS in the provided WDM of Trondheim. It is uncertain if this connection exists in real life, but without this connection, this area would most certainly be red nodes signifying those nodes are exclusively supplied from VIVA.

9.2.3 Accuracy and Fluctuations

The result from simulation should be treated as an estimation of hydraulic limits of the two DWTP as the WDM of Trondheim DWDS is highly skeletonized model where smaller pipes are not included and smaller junctions are clustered to one node, meaning that each node in the model may represent a whole neighborhood [51]. WDM always contains deviations from the real network and calibration is needed to verify the accuracy of the model. However, the scope of this thesis did not include calibration of the provided WDM, which usually is a time and resource intensive work. It is unknown when the last time Trondheim municipality attempted to calibrate their model prior to this project. Thus, the results from the simulation cannot be taken as the truth. Nonetheless, since the provided model is a version that the utility uses in their work, where several people are responsible for maintaining the model, it should be regarded as a fairly good estimation of Trondheim DWDS.

The model uses numerous demand patterns with aims to factor in varying hourly water demand. Daily demand pattern due to hourly water demand variation had influences on the hydraulic limits of VIVA and Benna DWTP in the model. This created nodes where the degree of influence from the DWTPs were not constant but fluctuating as a consequence of the demand variation. Areas of mixing was observed to have varying degree of influence depending on the time of the day. It was for these reasons it became necessary to present the result as an average value of the last 48 hours of the simulation to highlight nodes that had fluctuating influence from VIVA and Benna DWTP. This was also the reason for creating an additional map with standard deviation, that highlights nodes with fluctuations of influence from the treatment plants.

9.3 Flow Cytometry and Tracer Study

The purpose of flow cytometry was to investigate whether bacterial cell counts in drinking water in Trondheim are stable or experiences growth during distribution. In the event where growth is observed, MRT calculated from tracer study was to be used to determine growth rate of bacterial cell count during distribution. This in turn would then be used to relate bacterial cell count to hydraulic residence time, which then hydraulic residence time can be determined by observing bacterial cell counts.

9.3.1 Flow Cytometry – Cell Count Stability

Bacterial cell counts in the three different locations, VIVA, Fortuna and Jakobsli pumping station, are seemingly stable. Cell counts are not widely sporadic and fluctuates within a range that are idiosyncratic for the three locations. This is especially apparent when observing ICC, see *Figure 23*. Data from Fortuna pumping station shows that ICC fluctuates within the range of 82 – 116k per mL with an average 99.59k per mL. Same behavior can be seen in VIVA and Jakobsli pumping station, although TCC and DCC have stronger fluctuations than ICC. Since sampling period was longer at Fortuna pumping station where the data provided from Trondheim municipality are a collection of measurement from 16 days, compared to only 4 days at VIVA and Jakobsli, it provides much better evidence that ICC are in fact stable at Fortuna.

9.3.2 Flow Cytometry – Cell Count Growth in Distribution System

Although cell counts at the three different locations have been observed to stable, the idiosyncratic range in which the cell counts fluctuate within in the three locations, differ from each other. Looking at *Figure 23*, TCC, DCC and ICC at Jakobsli pumping station exist in a higher range of cell counts than VIVA. Same thing applies for Fortuna pumping station, where the range of ICC, HNAC and LNAC at Fortuna are all higher than at VIVA, see *Figure 24*. This suggest that, although each locations have their own unique cell count range, there is growth of cell count after treated water leaves VIVA. However, ICC and the subsequent HNAC and LNAC, are lower in Jakobsli than Fortuna pumping station. This is peculiar because hydraulic path dictates that water from VIVA travels first to Fortuna, and then Fortuna to Jakobsli (VIVA $\rightarrow$ Fortuna $\rightarrow$ Jakobsli), see *Figure 16*. If the results are correct, this means that there are reduction of cell counts along the hydraulic path from Fortuna to Jakobsli.

The results that show reduction of ICC from Fortuna to Jakobsli brings uncertainty of whether there are growth of bacterial cell counts during distribution after Fortuna pumping station. It has been previously mentioned that treated water from VIVA first travels through 1.1 km of rock blasted tunnel before entering Fortuna pumping station, where it is then set under pressure to distribute to the rest of the network. A possible interpretation to the reason of increase in cell counts from VIVA to Fortuna and

reduction from Fortuna to Jakobsli, is that growth of cell count may in fact only take place in the 1.1 km tunnel between VIVA and Fortuna, where the water is not under pressure. It is possible that the environment that exist in the tunnel provides a condition in which the cell counts are allowed to multiply, but once water pressure increases at Fortuna pumping station, the harsh environment in the bulk flow reduces cell counts. This would also open up for possibility that bacterial cell counts experiences growth, not only in the tunnel between VIVA and Fortuna, but also in storage tanks or other locations where there is less harsh environment than under distribution. This interpretation however remains a conjecture and more measurement with flow cytometry are needed in locations in Trondheim DWDS to further assess if the trend of decline in bacterial cell counts are continuous after Fortuna pumping station. If the decline of bacterial cell counts after Fortuna pumping station in the distribution system can be confirmed, then it would give stronger evidence that bacterial growth only takes place in the tunnel or alike environments. One known issue of the tunnel is that, since it is a rock blasted tunnel where the surfaces of the walls are not sealed, treated water that flows through this tunnel is susceptible by unknown particles and substances from outside that have seeped through the cracks into the tunnel. This might also be the reason for the increase of cell counts from VIVA to Fortuna.

9.3.3 Tracer Study

Theoretical water conductivity increase from NaCl injection at VIVA was calculated to be Δ26.2 μS/cm. Measurements from real life showed fairly close to the theoretical increase. In the outflow of VIVA after tracer injection, conductivity increase of Δ30 μS/cm was measured. At Jakobsli pumping station, increase of Δ23 μS/cm was measured.

The conductivity probe and the data logger that was used in Jakobsli pumping station, was tested with NaCl standard solution before the tracer study but was not calibrated. This might explain why the average conductivity at Jakobsli pumping station was 114 μS/cm, while average expected conductivity value was around 130 μS/cm as evidenced from field work March 2022, and conductivity measurement at VIVA on 29. May.2022. The decision to not calibrate the instrument was made on the fact that the purpose for measuring conductivity at Jakobsli was to measure a temporal increase in conductivity and the magnitude. Therefore, calibration to ensure high accuracy of the conductivity probe was not as prioritized. Making sure that conductivity probe was working and was able to detect spike in conductivity from a NaCl solution was of higher importance. Ideally, it should have been calibrated but due to time constraints, this step was neglected.

The tracer, NaCl brine solution, was injected for approximately 1 hour. Even though this classifies as step injection, the C-curve at Jakobsli pumping station looked more like a response from a pulse injection.

It appears that the injected volume and duration were not adequate to trigger a step response. This illustrates that if step response is desired with NaCl in Trondheim DWDS, NaCl needs to be continuously injected for much longer duration.

Overall, the tracer study was a successful experiment. Increase in conductivity could be observed and the increase was almost the same as the expected, calculated increase. From this, MRT from VIVA to Jakobsli pumping station could be calculated, which was 6.6 hours. One thing to note is that hydraulic residence time is not constant but can fluctuate depending on factors such as hourly demand. This might explain why the tracer study with NaCl done in 2020 by Jon.K Rakstang [38], water age from VIVA to Jakobsli pumping station was observed to be 9.25 hours, a difference of 2.65 hours from this year's tracer study.

9.3.4 Relating Bacterial Cell Count Growth to Hydraulic Residence Time

MRT from VIVA to Jakobsli was determined to be 6.6 hours. If data from Fortuna is neglected, the growth rate from VIVA to Jakobsli can be established in a linear fashion, where cell count at VIVA takes 6.6 hours to reach the cell count at Jakobsli, see *Figure 28*. However, these linear relationships is false because the decline of cell count from Fortuna to Jakobsli is omitted.

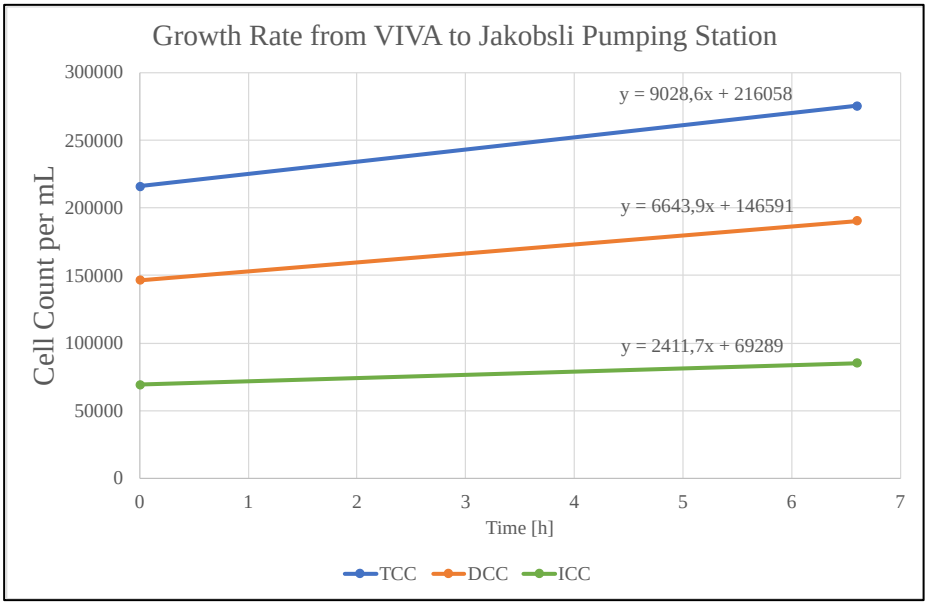

Figure 28. Linear Relationship of Cell Count Growth from VIVA to Jakobsli Pumping Station without including data from Fortuna. Made with average TCC, DCC and ICC from VIVA and Jakobsli.

Including data from Fortuna, cell count growth rate looks different. MRT from VIVA to Fortuna was not measured and are unknown, but assuming that MRT from VIVA and Fortuna is 3.3 hours, half of MRT from VIVA to Jakobsli, illustration of how ICC growth rate can look like is presented in *Figure 29*.

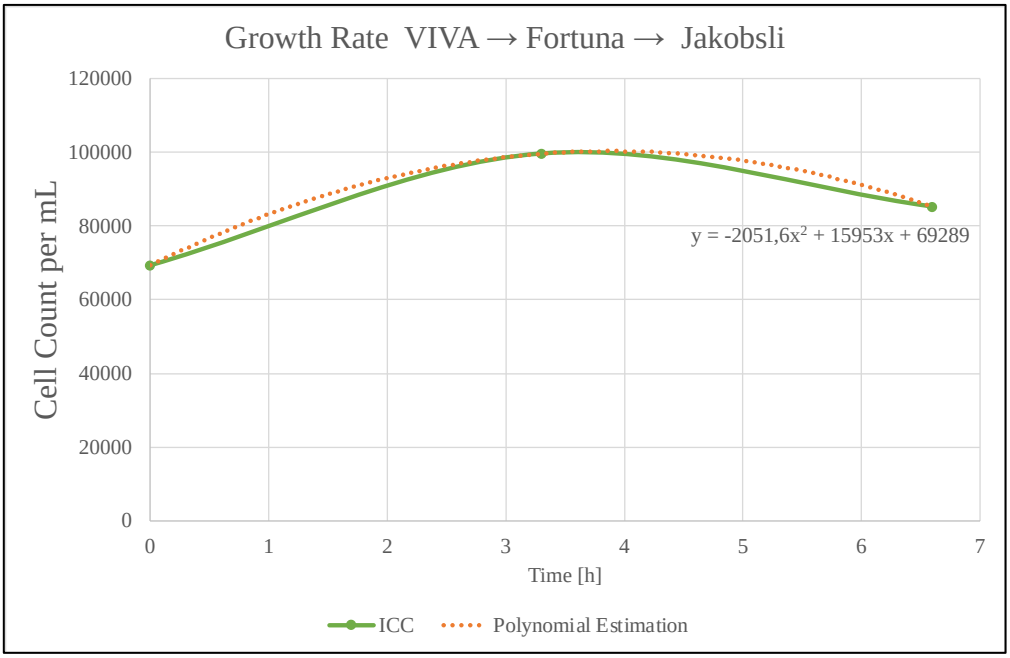

Figure 29. ICC Growth Rate from VIVA → Fortuna → Jakobsli. Made with average ICC.

Problems of the presented cell count growth rate in *Figure 29* is that MRT from VIVA to Fortuna is just an assumption. It is also unknown if the decline of cell count from Fortuna continues beyond Jakobsli. Therefore, MRT from VIVA to Fortuna needs to be established and more cell count measurement beyond Jakobsli pumping station are needed before a convincing cell count growth rate equation in drinking water from VIVA can be determined. With the available data, this thesis fails to answer the two research questions that were raised for this thesis:

- What is the growth rate of bacterial cell count present in treated water from VIVA during distribution?
- Can bacterial cell count be used to determine hydraulic residence time of water in DWDS?

With regards to the last question, the results suggest that it is feasible to determine hydraulic residence time using bacterial cell count, as there are definitive growth and decline of bacterial cell count in the distribution system, but more data is needed for a firmer conclusion.

9.3.5 Cell Count as Parameter for Source Trace Analysis

Since cell counts were not measured at Benna DWTP, it is uncertain if the cell count range at Benna differs or are similar to VIVA. As parameters for source trace analysis must be distinguishable for different sources, it is difficult to confirm how suitable cell counts are for source trace analysis in Trondheim DWDS.

It is also preferable if parameters for source trace analysis is conservative. This has not been the case for bacterial cell counts as both growth and decline has been observed. It is also uncertain if cell counts grow under distribution or if this is only in the tunnel between VIVA and Fortuna. Likewise, it is uncertain if cell counts decline under distribution or if this is an exception between Fortuna and Jakobsli pumping station.

Nonetheless, it might be feasible to use bacterial cell counts as parameter for source trace analysis if cell counts between Benna DWTP and VIVA are extremely different and distinguishable from each other, and if the cell counts from the two water sources exist in their own idiosyncratic cell count range, even after growth or decline during distribution. If for instance growth or decline rate of cell counts does not allow for water from Benna and VIVA to be identical and cell count range from the two sources are distinguishable, then bacterial cell count can be used as a parameter for source trace analysis. Illustration of these situations are presented in *Figure 30*. Which one of the possible situations that exist in Trondheim DWDS remains unanswered in this thesis and is left for future research.

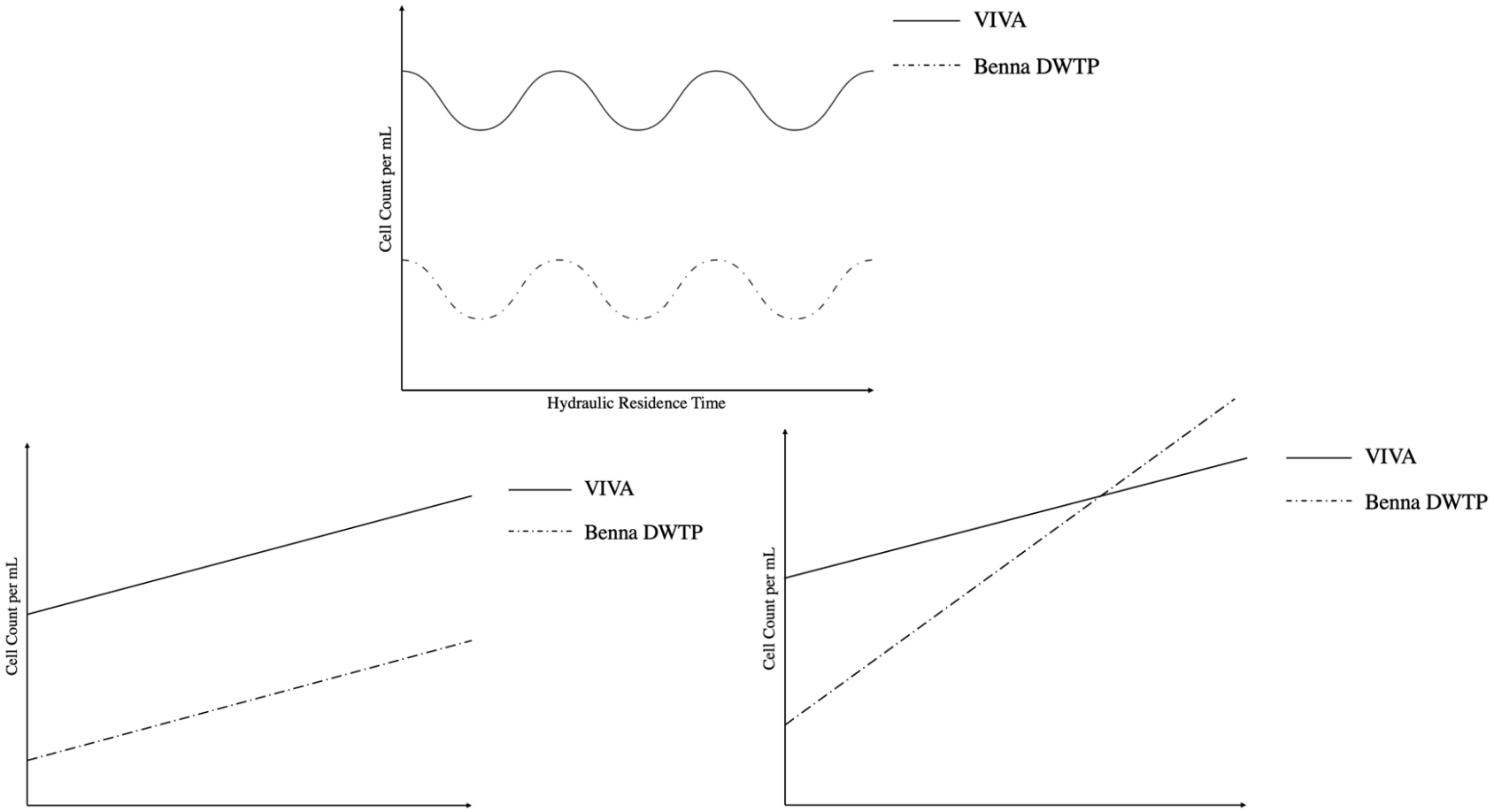

Figure 30. Illustrations of how cell counts at VIVA and Benna DWTP in distribution system might behave and exist. **Top:** Cell count range of VIVA and Benna DWTP might be different and distinguishable from each other, making it possible to use cell count as parameter for source trace analysis. **Bottom Left:** Cell counts from the two sources might experiences growth, but the growth rate does not allow for cell count from the two sources to be the same, making it still useful as a parameter for source trace analysis. **Bottom Right:** Cell count in water from e.g. Benna DWTP might have faster growth rate than VIVA, in which case water from Benna DWTP have similar cell counts as water from VIVA at a certain hydraulic residence time, making it unfeasible to distinguish water from VIVA and Benna DWTP, and thus making bacterial cell count not suited to be used as a parameter for source trace analysis.

10 Conclusion

Parameter study for source trace analysis was conducted through field work where concentration of copper, pH, conductivity, and color in drinking water from VIVA were analyzed for conservativeness. The results showed that whilst copper and pH in drinking water experiences change during distribution, conductivity and color remains more or less constant during distribution in Trondheim DWDS, thus proving to be parameters that are suited for source trace analysis. Conductivity analysis have however been significantly easier, faster, and cheaper than color analysis of water. Due to conductivity meters are more available and easier to use than UV/VIS spectroscopy for measuring color, it is recommended that conductivity are used as a parameter for future source trace analysis if done by field work.

Even though source trace analysis could not be performed through field work due to Benna DWTP being out of operation during study period, simulation with WDM provided an estimation of hydraulic limits of the two treatment plants in Trondheim as well as identification of mixing areas in the distribution system. The results revealed that most of northern and eastern part of Trondheim DWDS have water mainly supplied by VIVA. Significant mixing areas are observed in the middle to southern part of Trondheim. Areas that are mainly supplied by Benna DWTP are limited to southern part of Trondheim around Kolstad pumping station, where the connection between Benna DWTP and Trondheim DWDS are made.

Results from automated flow cytometry have shown that bacterial cell counts exist in a stable range that are idiosyncratic for each location, making it possible to distinguish locations from each other by observing bacterial cell count. Higher cell count range in Fortuna pumping station than VIVA suggest that there are bacterial cell count growth occurring in the 1.1km rock blasted tunnel between VIVA and Fortuna pumping station. However, the growth did not continue to the rest of distribution system as evidenced by decline of bacterial cell count from Fortuna pumping station to Jakobsli pumping station. Whether this decline of cell counts continues further in the distribution system is uncertain and remains to be investigated.

Tracer study was a success, which allowed to establish MRT from VIVA to Jakobsli, but due to the uncertainty that exist for whether growth of cell counts only exist in the tunnel or decline of cell counts continues from Jakobsli to rest of the distribution system, it has been difficult to establish mathematical statement that relates cell count growth to hydraulic residence time. As a result, conclusion cannot be made in this thesis and more cell count measurements are needed to properly determine bacterial cell count growth rate for water in Trondheim DWDS.

11 Outlook

Future research related to source trace analysis in Trondheim DWDS can attempt on performing source trace analysis through field work with conductivity data when Benna DWTP are back in operation. The results can then be used to compare and observe if there are good agreement between field data and simulation results from WDM. Furthermore, calibration of WDM of Trondheim with regards to source tracing can be attempted with data from field work. Calibrated WDM can be used to simulate and perform source trace analysis with focus on investigating hydraulic limits of critical units in the distribution system such as storage tanks and pumping station and make assessments of how far pollution can spread from these units to the rest Trondheim DWDS. The consequent results will be able to illustrate the vulnerability of contaminated drinking water in Trondheim as a result of pollution from storage tanks/pumping stations.

Future research related to investigation of bacterial cell counts as a parameter for source trace analysis needs to investigate if bacterial cell counts in drinking water from Benna DWTP exist in a different cell count range than water from VIVA. If yes, investigation of drinking water from the two sources can be distinguishable from each other in the distribution system have to be determined. This requires investigation of growth rate of cell count to assess if cell count in water from Benna DWTP does not become the same as cell count in water from VIVA during distribution. Bacterial cell count growth rate can also be used to relate cell count to hydraulic residence time, developing a method to determine water age for locations in the distribution system by observing cell count. In this thesis, attempt to develop relationship between cell count and hydraulic residence time has required performing tracer study from VIVA to Jakobsli pumping station, in order to determine MRT from VIVA to Jakobsli pumping station, which has required extensive effort. Future work can therefore attempt on using simulation data of water age from WDM instead of performing tracer study, to reduce the workload of finding MRT to desired locations. Water age data from simulation can then be used to relate with cell count data to determine growth rate of bacterial cell count in Trondheim DWDS.

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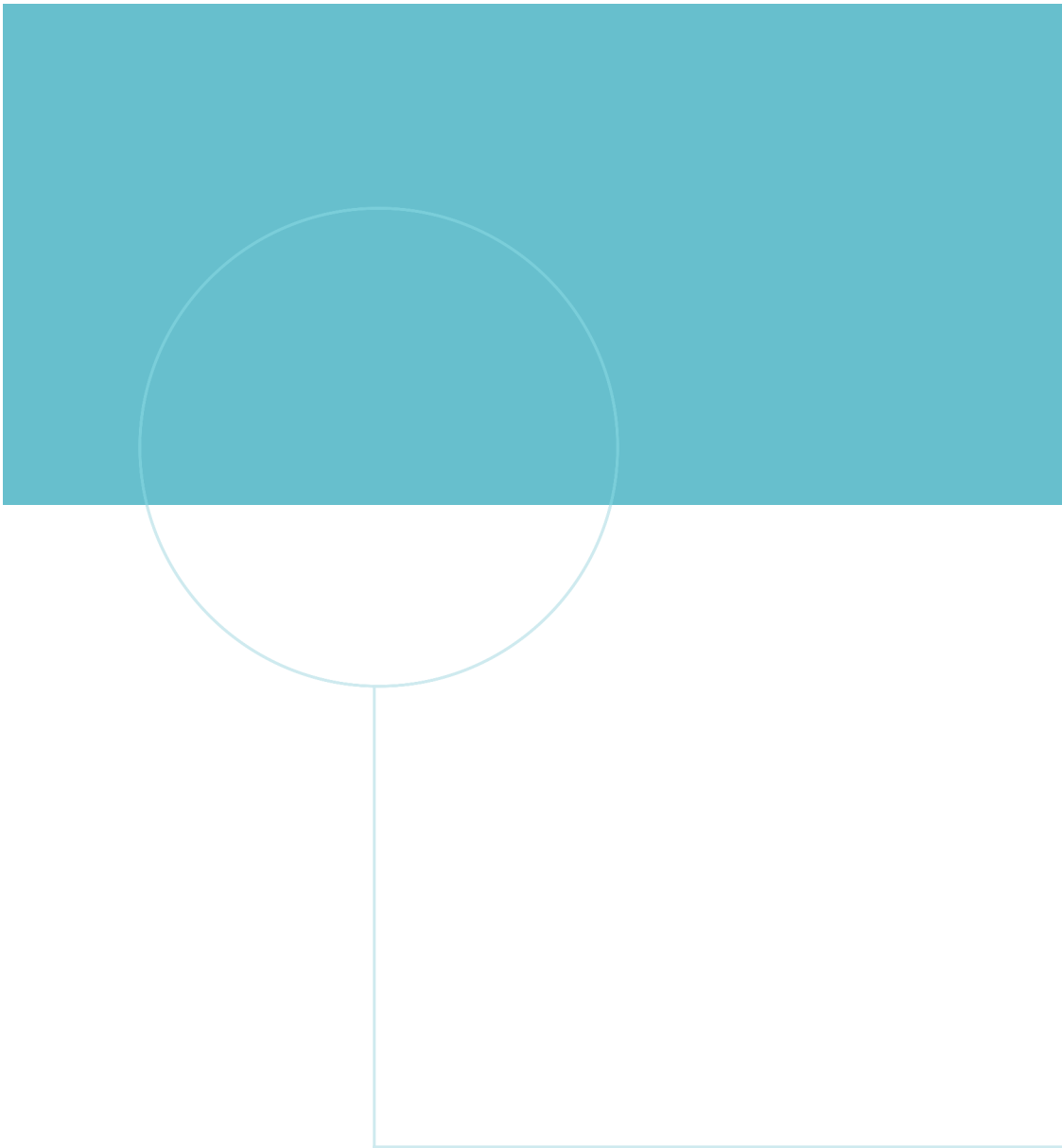

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