Master's thesis

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

Sang Munn Kim

Attachments

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
June 2022

NTNU
Norwegian University of
Science and Technology

Sang Munn Kim

Attachments

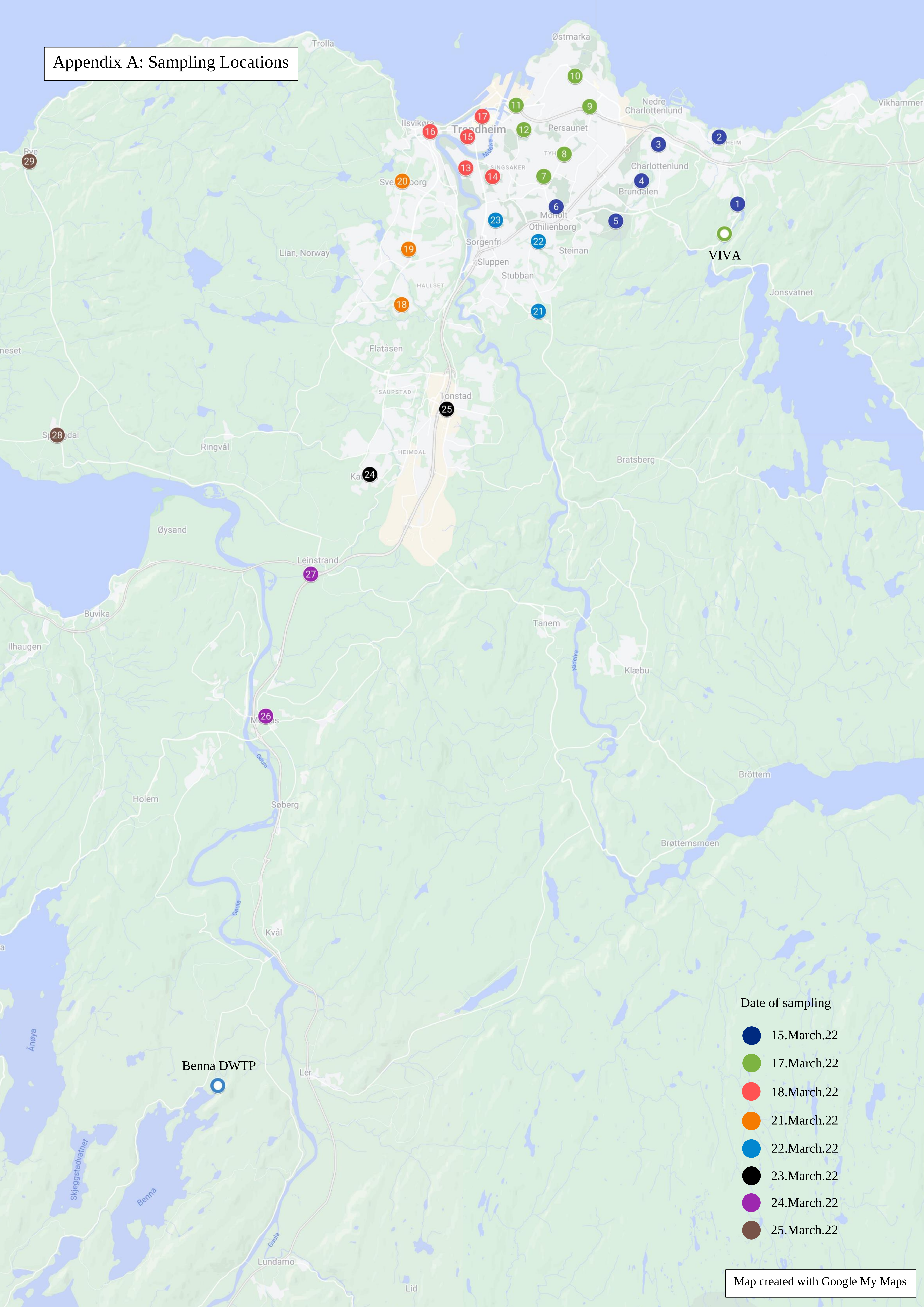
Source Trace Analysis: Investigating Hydraulic Limits and Cell Count in Trondheim Drinking Water Distribution System

Master's thesis in Civil and Environmental Engineering
Supervisor: Cynthia Hallé
Co-supervisor: Marius M. Rokstad, Michael B. Waak
June 2022

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

NTNU
Norwegian University of
Science and Technology

Appendix A: Sampling Locations



Appendix A – Table 1

Date and time of sampling and measured temperature of flushed water at sampling.

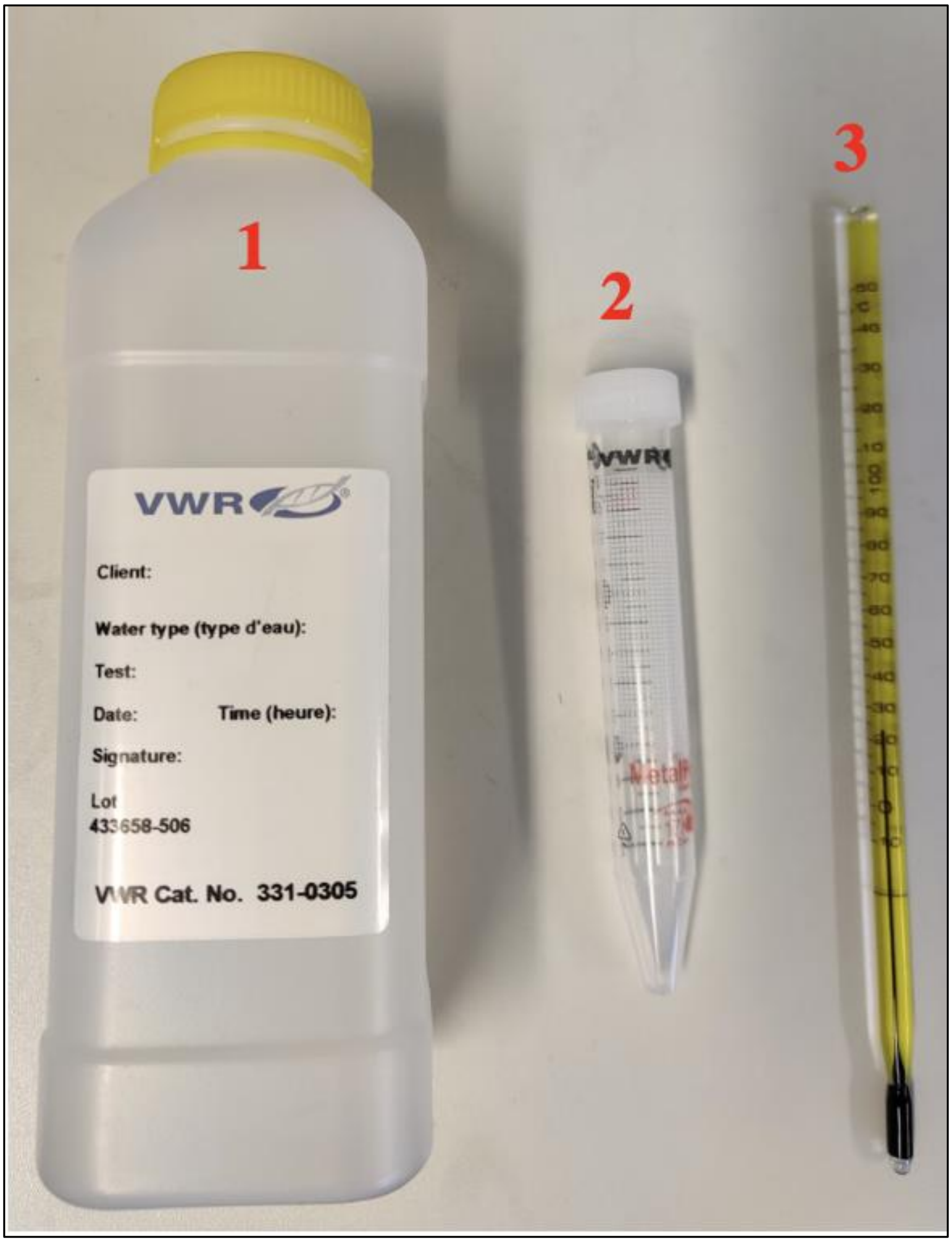
Sampling Location	Date of Sampling [ddmmyy]	Time [24:00]	Temperature of water at sampling [°C]
1	15.03.22	10:06	3,5
2	15.03.22	10:50	5
3	15.03.22	11:22	3
4	15.03.22	11:53	5
5	15.03.22	12:20	4
6	15.03.22	12:43	3,5
7	17.03.22	08:35	5,5
8	17.03.22	09:10	5,5
9	17.03.22	09:25	7
10	17.03.22	09:48	4
11	17.03.22	10:15	5
12	17.03.22	10:50	9
VIVA	17.03.22	14:00	-
13	18.03.22	08:45	4
14	18.03.22	09:15	4
15	18.03.22	09:45	4
16	18.03.22	10:10	6
17	18.03.22	10:35	5
18	21.03.22	09:55	7
19	21.03.22	10:15	4
20	21.03.22	10:40	7
21	22.03.22	08:30	4
22	22.03.22	09:10	7
23	22.03.22	11:10	4,5
Benna DWTP	22.03.22	-	-
24	23.03.22	10:45	7
25	23.03.22	11:05	5
26	24.03.22	10:00	4
27	24.03.22	10:40	4
28	25.03.22	09:45	6,5
29	25.03.22	10:05	3,5

Appendix B: Equipment

Equipment - Sampling for Source Trace Analysis

Equipment List 1. Equipment for Sampling.

1. General water sampling bottle 500 mL, yellow cap, non-sterile, VWR
2. Metal-free centrifuge tubes 15 mL, polypropylene, sterile, VWR
3. Liquid in glass thermometer, VWR
4. Refrigerator, Bosch




4

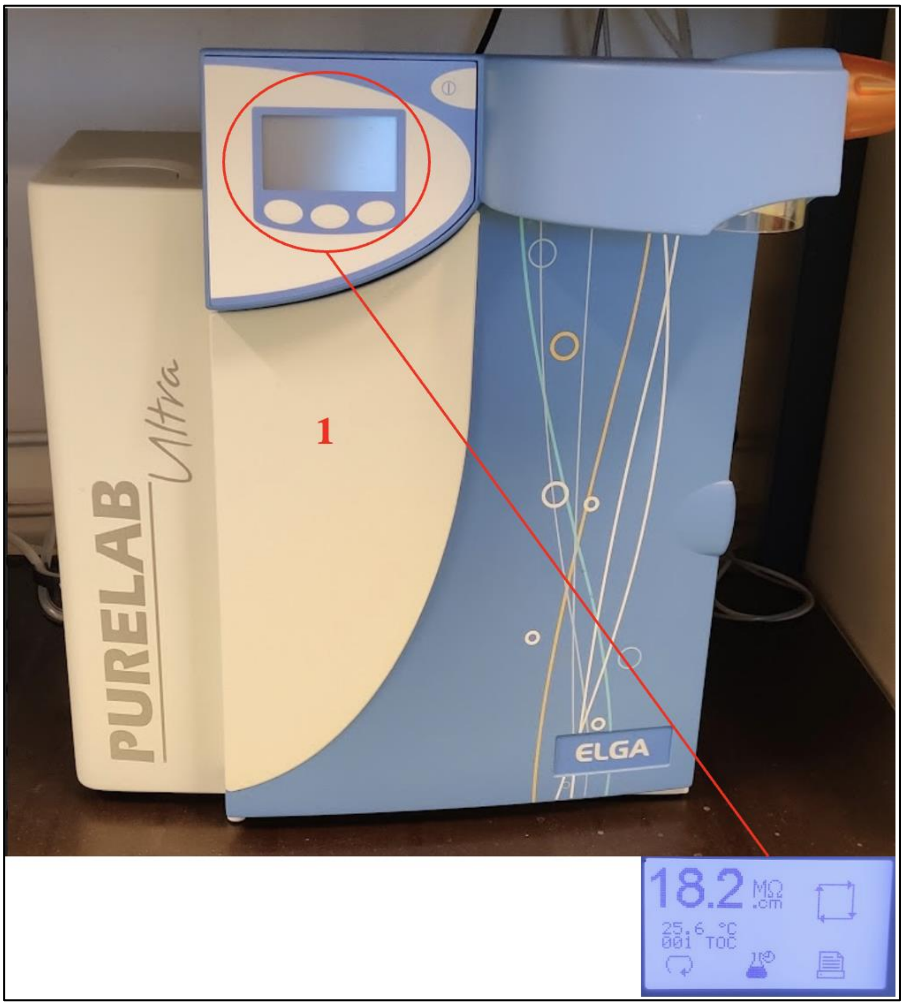

4

Equipment - Copper Analysis

Summary of equipment and chemicals that were utilized for copper analysis are presented in Equipment List 2. The list also includes items and equipment that were used for calibration purposes and interference analysis.

Equipment List 2. Copper Analysis

1. ELGA PURELAB Ultra Genetic for ultrapure water
2. DR3900 Spectrophotometer for water analysis, Hach Company
3. SBA 52 Digital analytical scale, Scaltec
4. Manual single channel pipette 0.5-5 mL, Finnpipette
5. Manual single channel pipette 40-200 μL, Finnpipette
6. Pipette tips for 0.5-5 mL
7. Pipette tips for and 40-200 μL
8. 4 Sample cell 10mL, 1inch Square Glass, Hach Company
9. Beaker, 150mL, VWR
10. Volumetric flask with stopper, 50 mL, VWR
11. Paper Tissue
12. Lens tissue paper, Assistant
13. Copper standard solution 100mg/L, Hach Company
14. Copper masking reagent powder pillows for 10 mL samples, Hach Company
15. Porphyrin 1 reagent powder pillows for 10 mL samples, Hach Company
16. Porphyrin 2 reagent powder pillows for 10 mL samples, Hach Company
17. Nitric acid solution 1 M (no picture)
18. Single use laboratory rubber gloves (no picture)
19. Lab coat (no picture)
20. Safety glasses (no picture)

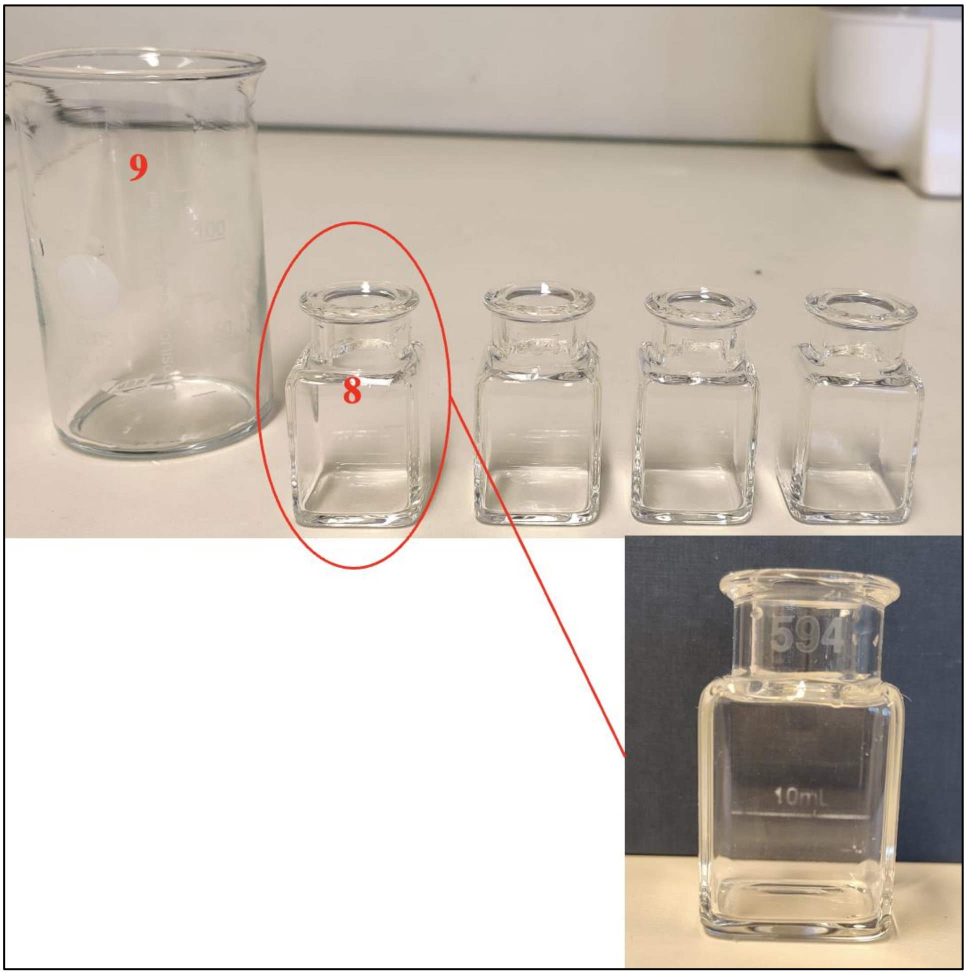

PURELAB
Ultra
1
ELGA
18.2 MΩ.cm
25.6 °C
001 TOC


DR 3900
2
LANGE


3
SBA 52 Max 2200 g d = 0.01g
SCALTEC
0.00 g
CAL / CF
FUNCTION
ON/OFF
TARE
PRINT

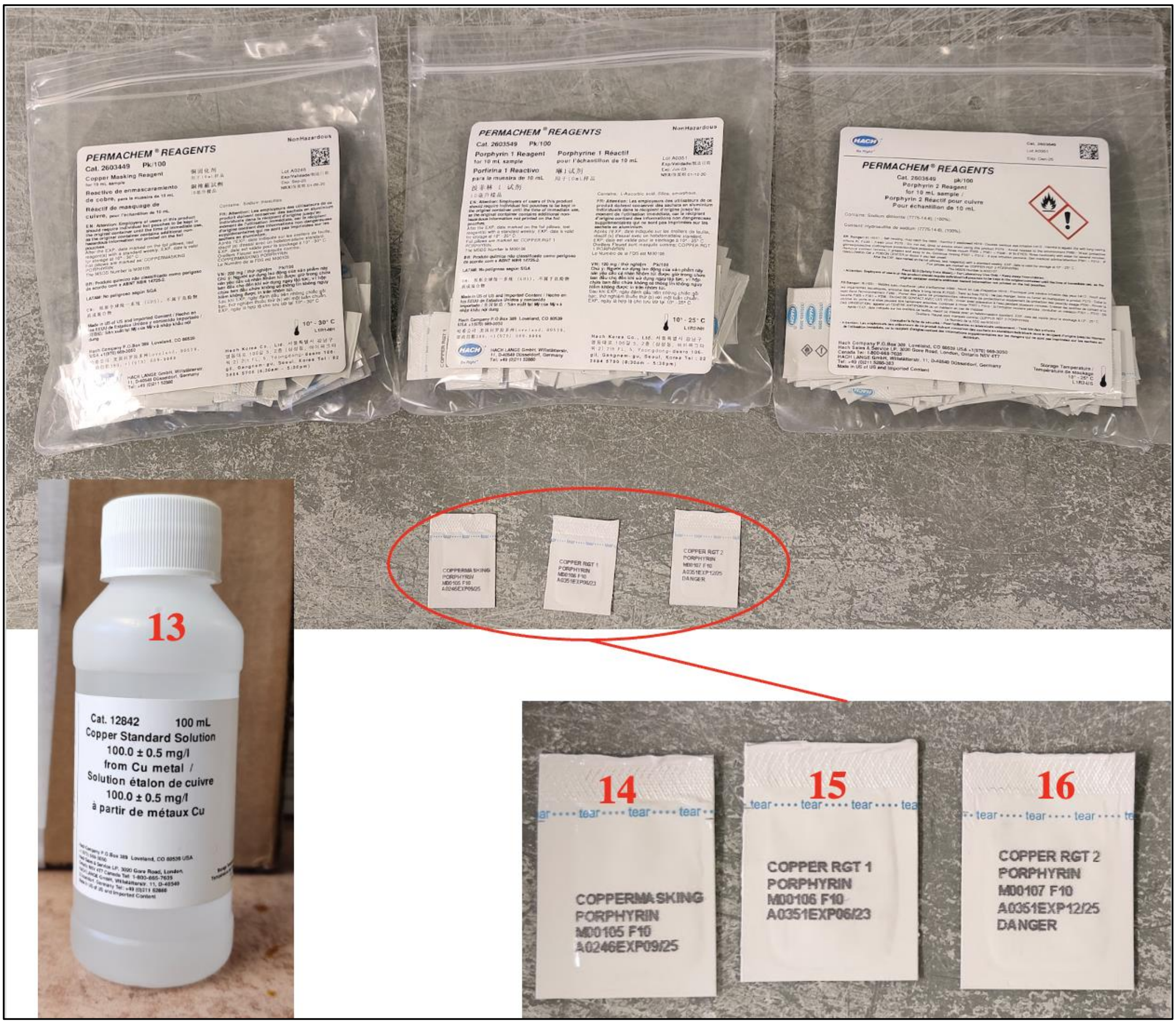

4
5


6
7


9
8
594
10mL


10

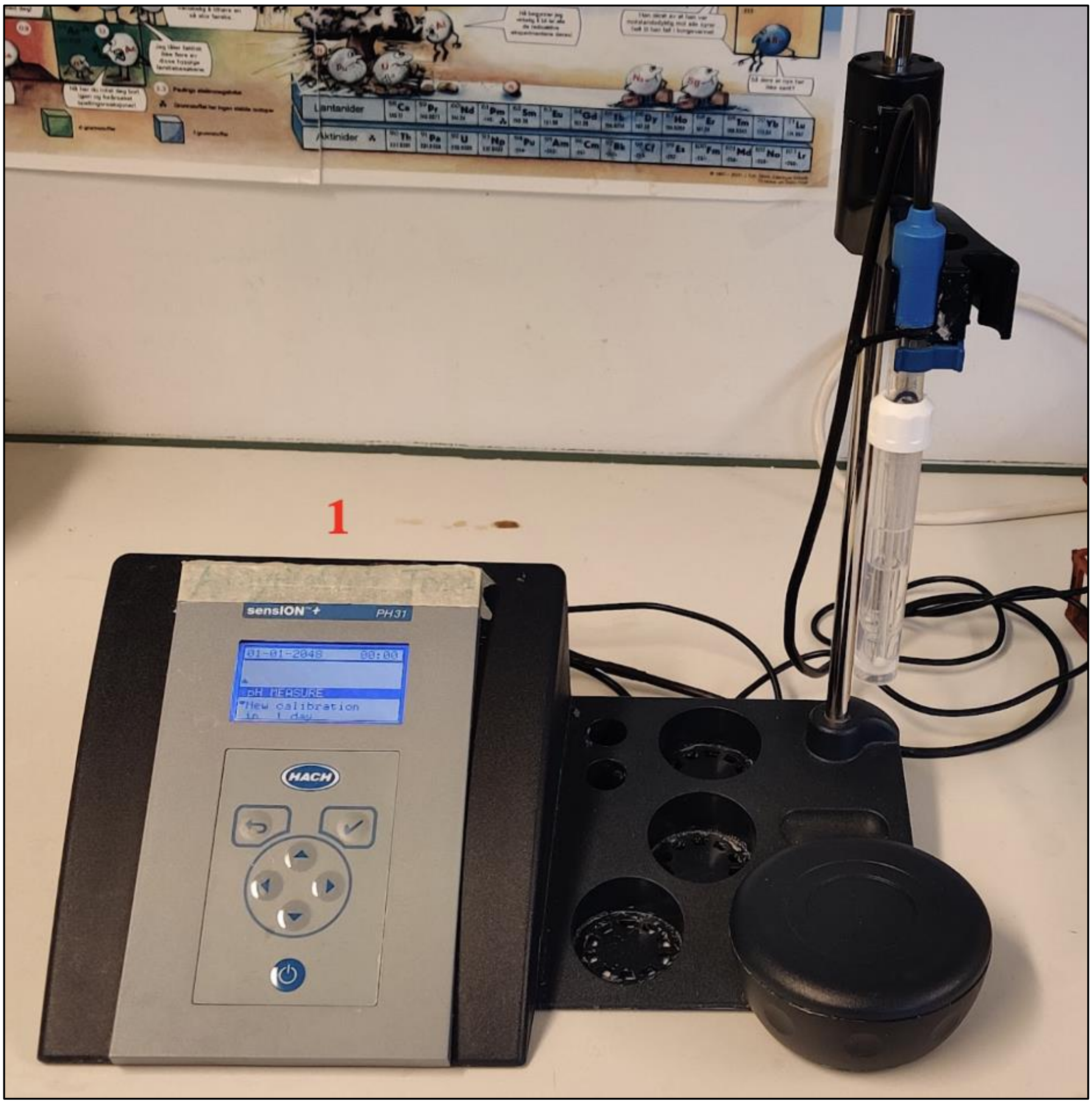

11
12
Assistent
Linsenpapier,
Spezialpapier zur Reinigung von optischem Glas, ca. 90 x 72 mm, 500 Blatt
No. 1019

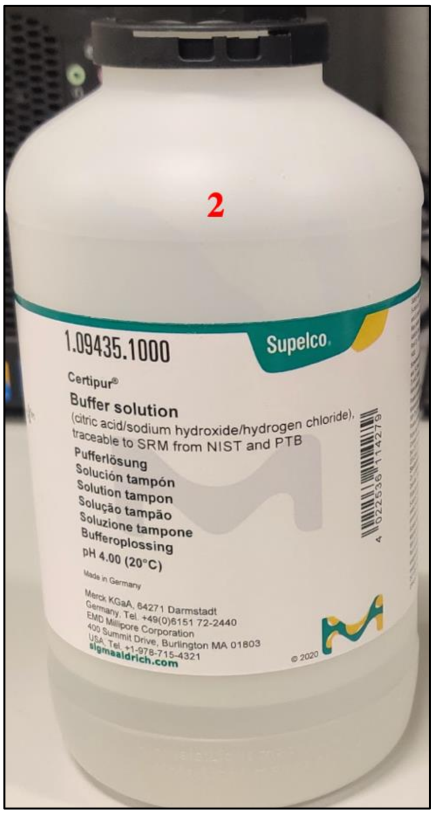

PERMACHEM® REAGENTS
13
Cat. 12842 100 mL
Copper Standard Solution
100.0 ± 0.5 mg/l
from Cu metal /
Solution étalon de cuivre
100.0 ± 0.5 mg/l
à partir de métaux Cu
14
COPPERMASKING
PORPHYRIN
M00105 F10
A0246EXP09/25
15
COPPER RGT 1
PORPHYRIN
M00106 F10
A0351EXP06/23
16
COPPER RGT 2
PORPHYRIN
M00107 F10
A0351EXP12/25
DANGER

Equipment - pH Analysis

Equipment List 3. pH Analysis

1. pH meter, SensION+ pH31, Hach Company
2. Buffer solution, pH 4, Supelco
3. Buffer solution, pH 7, Supelco
4. Buffer solution, pH 10, Supelco
5. Magnetic stir bars
6. Glass test tubes with flat bottom
7. 3 Plastic bottle containers for buffer solution
8. Laboratory wash bottle




2
1.09435.1000
Supelco
Certipur®
Buffer solution
(citric acid/sodium hydroxide/hydrogen chloride),
traceable to SRM from NIST and PTB
Pufferlösung
Solución tampón
Solution tampon
Solução tampão
Soluzione tampone
Bufferoplossing
pH 4.00 (20°C)
Made in Germany
Merck KGaA, 64271 Darmstadt
Germany, Tel. +49(0)6151 72-2440
EMD Millipore Corporation
400 Summit Drive, Burlington MA 01803
USA, Tel. +1-978-715-4321
sigmaaldrich.com
© 2020


3
4
1.09439.1000
Supelco
Certipur®
Buffer solution
(di-sodium hydrogen phosphate/potassium
dihydrogen phosphate), traceable to SRM from
NIST and PTB
Pufferlösung
Solución tampón
Solution tampon
Solução tampão
Soluzione tampone
Bufferoplossing
pH 7.00 (20°C)
1.09438.1000
Certipur®
Buffer solution
traceable to SRM from NIST and PTB
Pufferlösung
Solución tampón
Solution tampon
Solução tampão
Soluzione tampone
Bufferoplossing
pH 10.00 (20°C)
sigmaaldrich.com


5


6

7


8

Equipment - Conductivity Analysis

Equipment List 4. Conductivity Analysis

1. Microprocessor conductivity meter, LF537, WTW
2. Laboratory water bath, GFL
3. Test tube rack
4. Glass test tubes with flat bottom (see Equipment List 3. pH Analysis)
5. ELGA PURELAB Ultra Genetic for ultrapure water (see Equipment List 2. Copper Analysis)

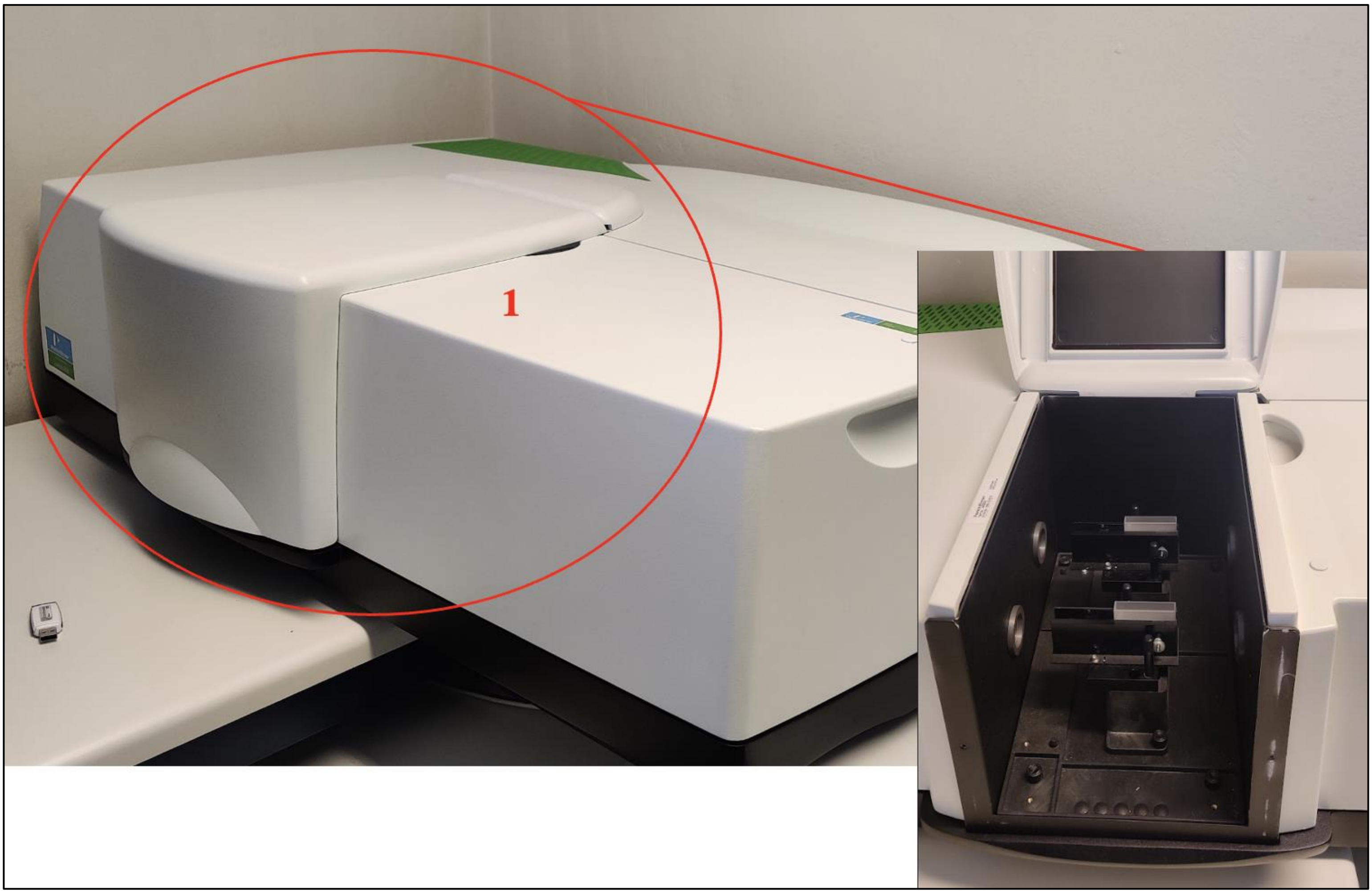

2

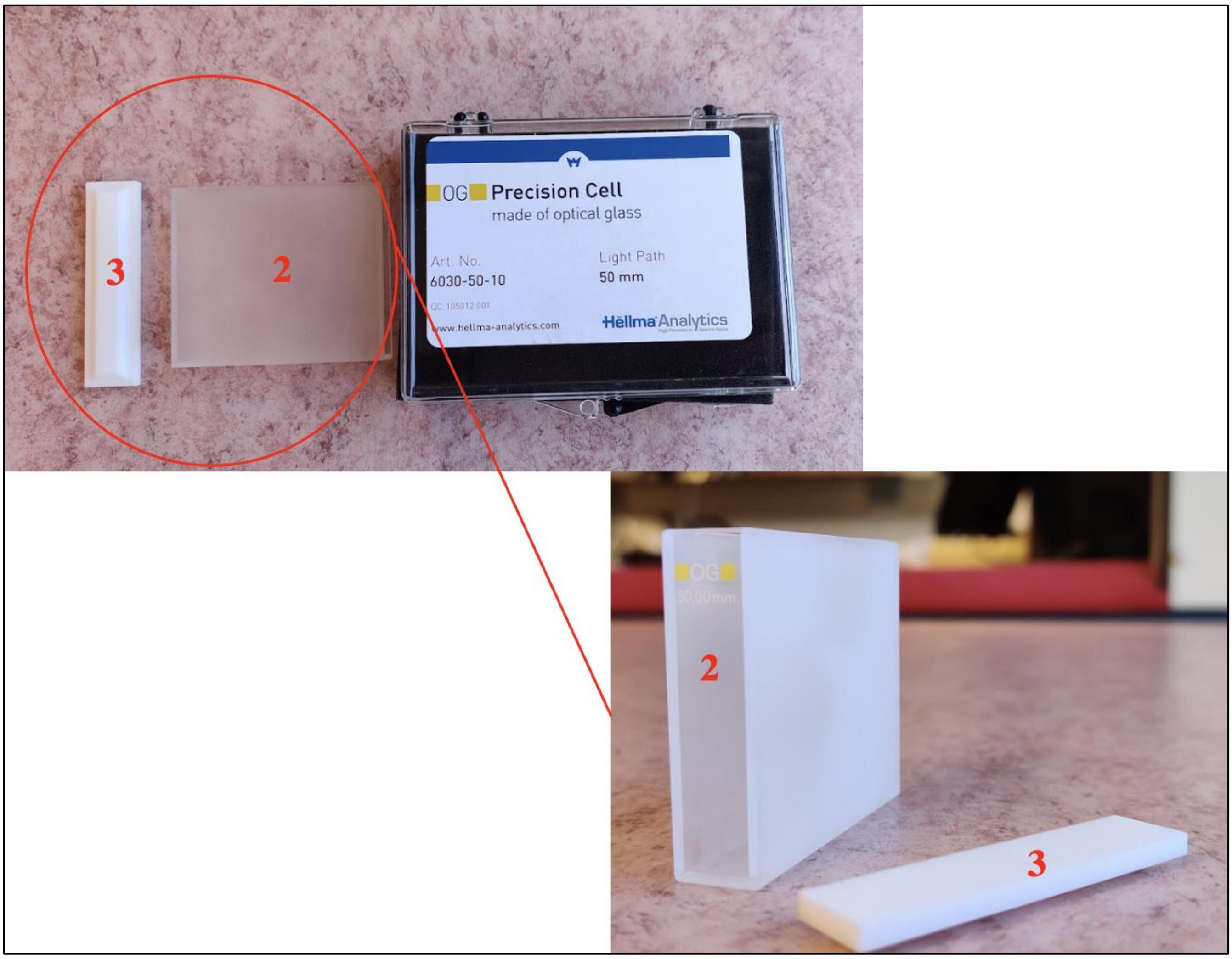

3

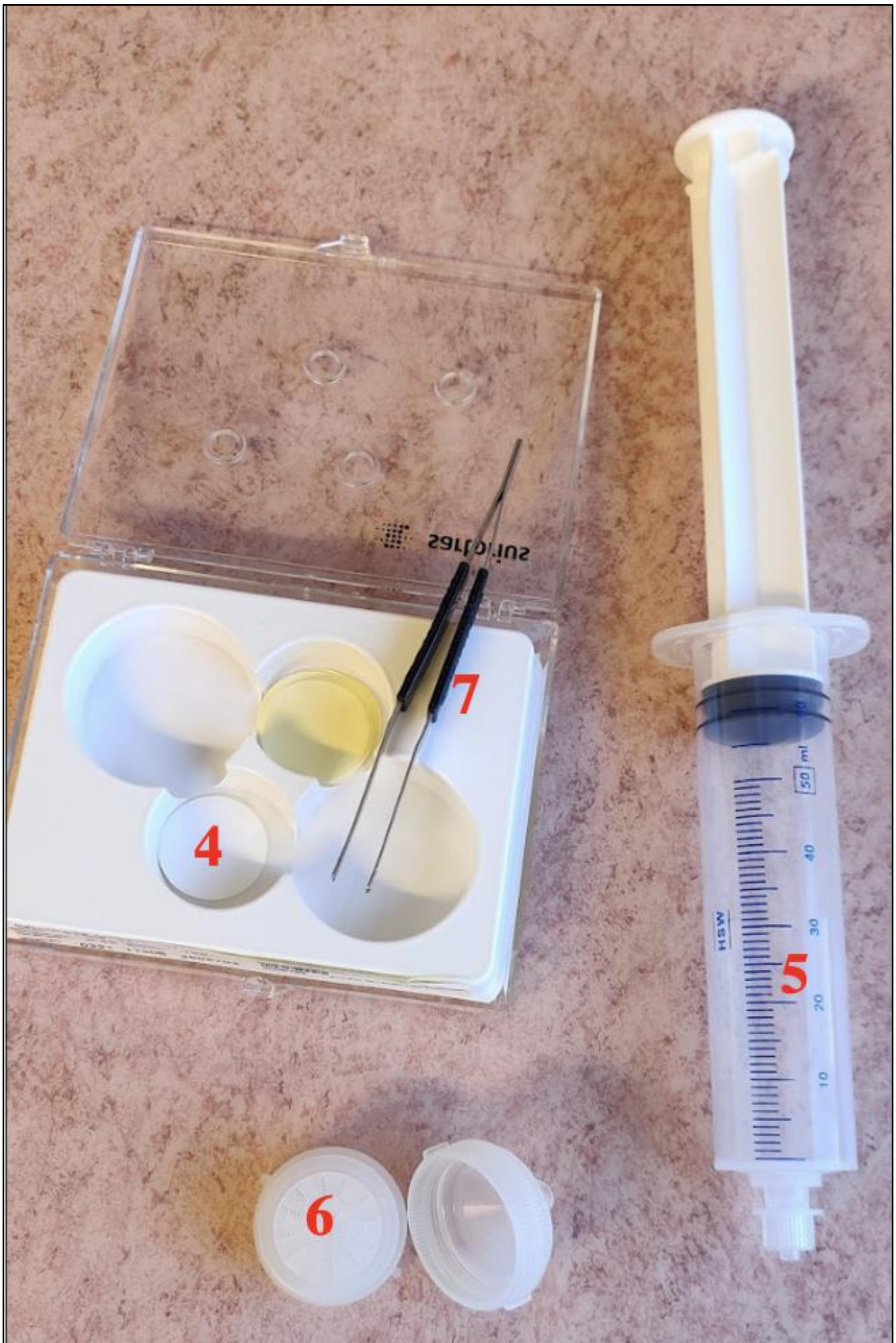
Equipment - Color Analysis

Equipment List 5. Color Analysis

1. UV/VIS spectroscopy spectrophotometer, Lambda 650, Perkin Elmer
2. 2 Glass cuvettes, 50mm
3. Glass cuvette top
4. Cellulose filter paper 25mm
5. Chemistry syringe 50mL
6. Membrane holder 25mm
7. Pincette
8. Glass test tubes with flat bottom (see Equipment List 3. pH Analysis)
9. Paper tissue (see Equipment List 2. Copper Analysis)
10. Lens paper tissue (see Equipment List 2. Copper Analysis)



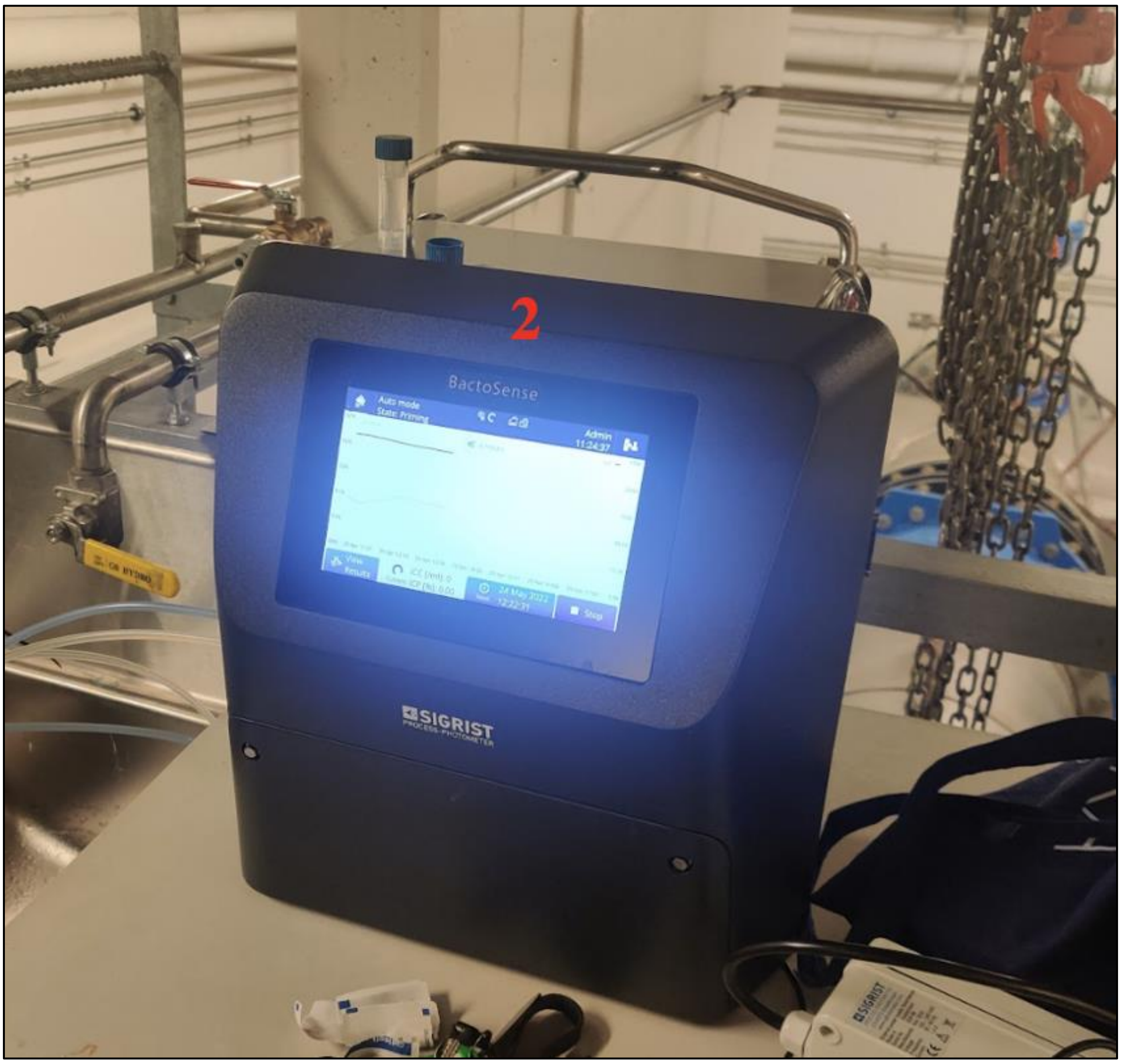

3
2
OG Precision Cell
made of optical glass
Art. No.
6030-50-10
Light Path
50 mm
www.hellma-analytics.com
Hellma Analytics
OG
2
3

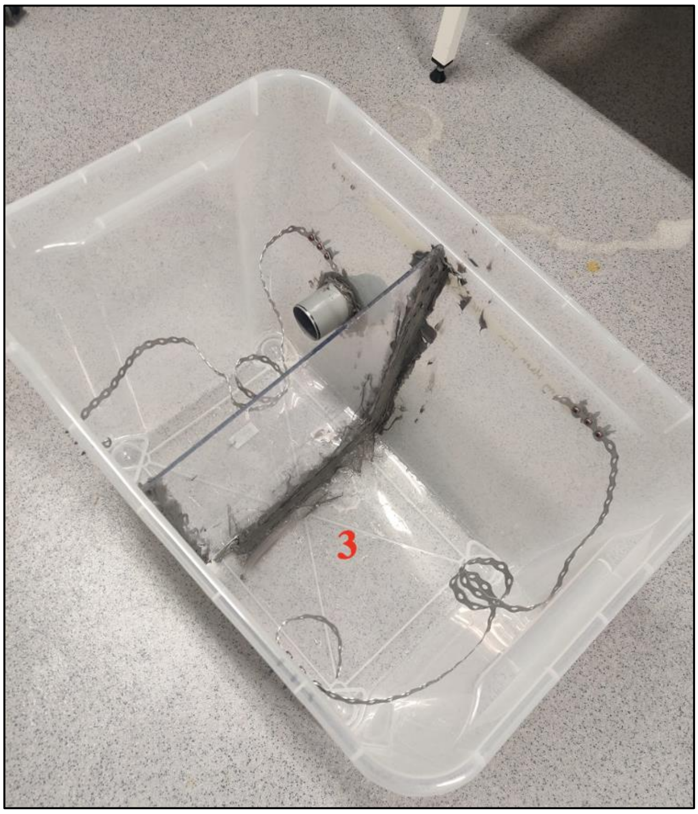

7
4
5
6

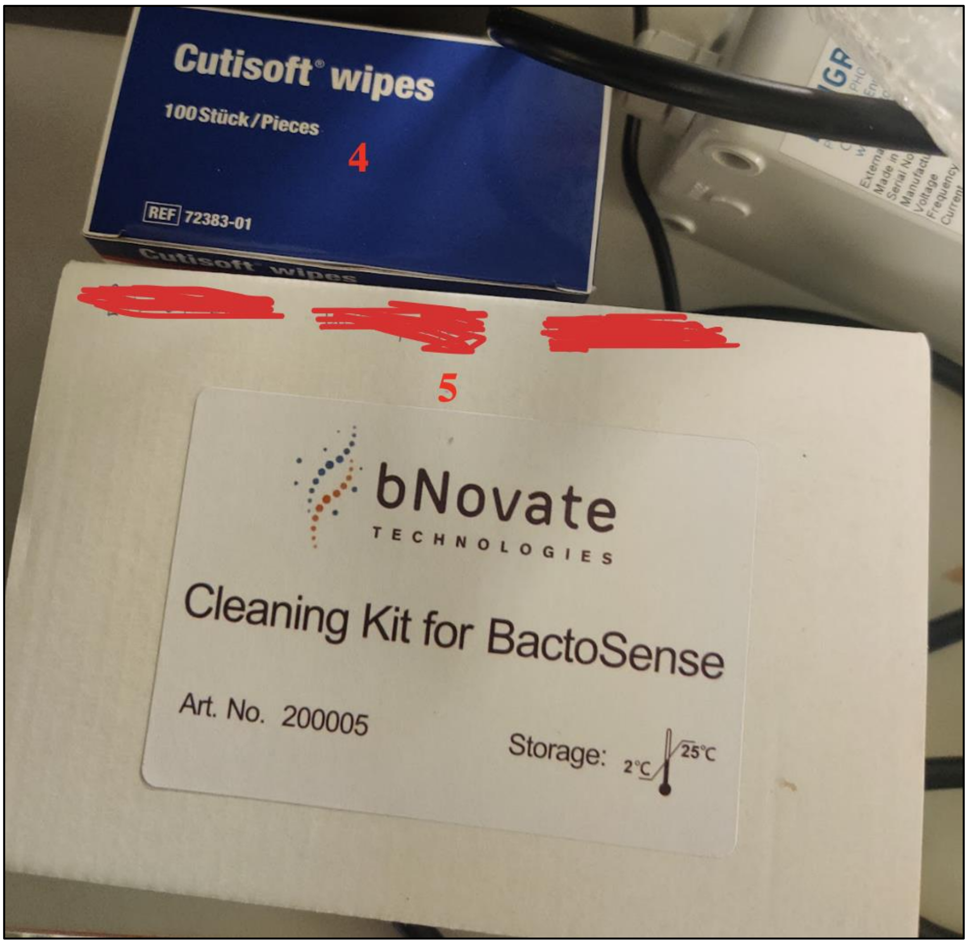
Equipment – Tracer Study and Flow Cytometry in Trondheim

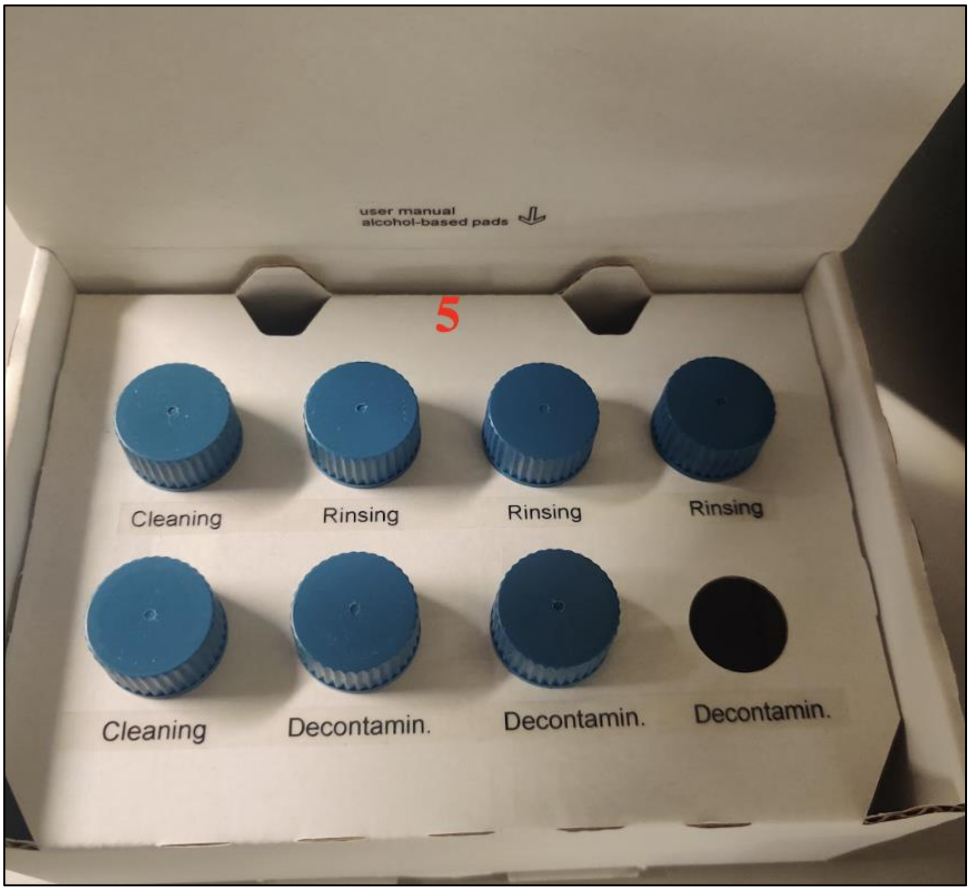
Equipment List 6. Tracer Study and Flowcytometry

1. Campbell Scientific CR200 data logger in a protective case with conductivity probe attached.
2. bNovoate Techonlogy BactoSense, Flowcytometry
3. 70 L Plastic Box with modifications
4. Cutisoft wipes
5. bNovate cleaning kit for BactoSense
6. VWR MU6100H, Portable conductivity meter


2
BactoSense
SIGRIST
PROCESS-PHOTOMETER


3


Cutisoft® wipes
100 Stück/Pieces
4
REF 72383-01
5
bNovate
TECHNOLOGIES
Cleaning Kit for BactoSense
Art. No. 200005
Storage: 2°C 25°C

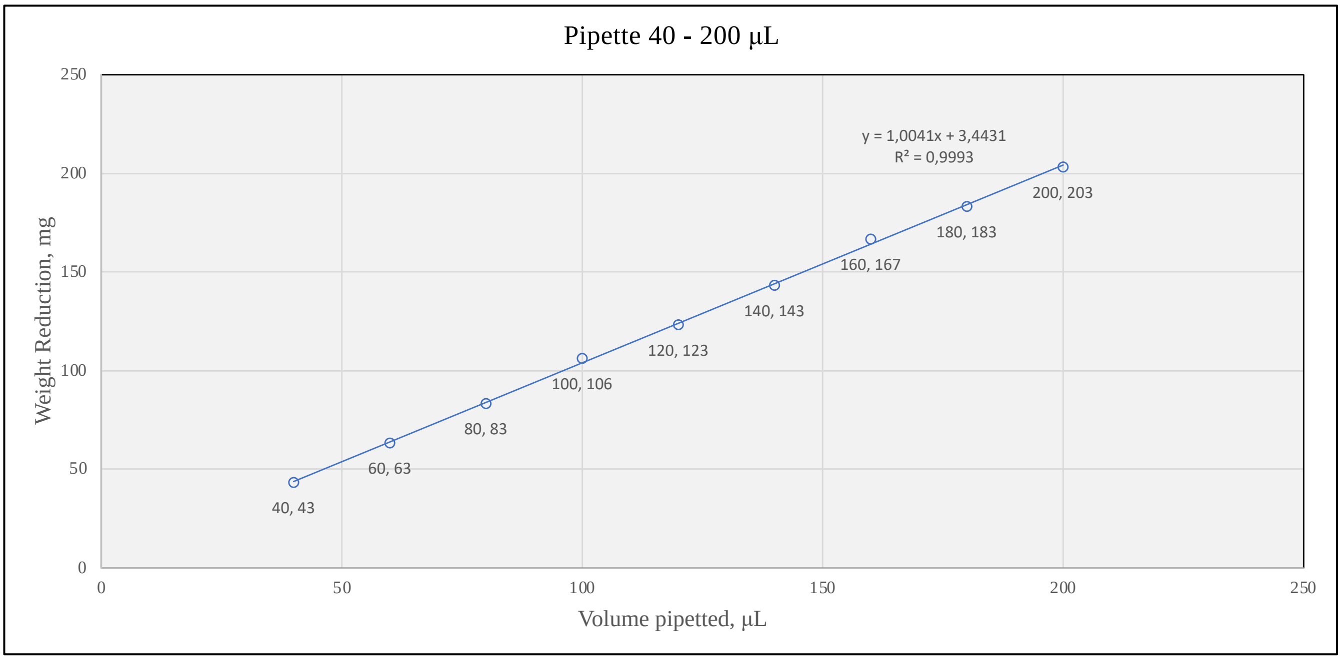

user manual
alcohol-based pads
5
Cleaning
Rinsing
Rinsing
Rinsing
Cleaning
Decontamin.
Decontamin.
Decontamin.


6
227.0 mV
25 °C
0.0 µS/cm
22.1 °C
F1
F2
VWR
MODE
CAL
STR
OK
HOLD
RCL
MU 6100 H

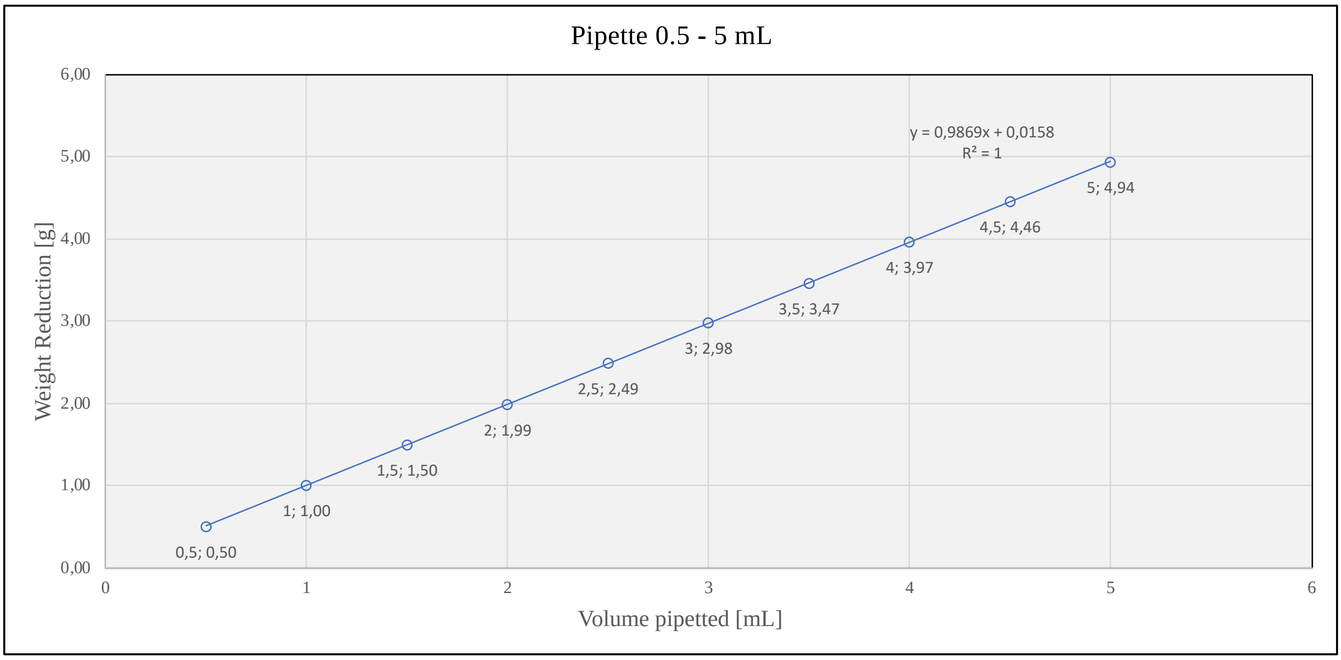
Appendix C: Calculations and Calibration Curves

1. Pipettes - Results

Pipette 40 - 200 µL					
Pipetted Volume [µL]	Weight Reduction [g]				
	1	2	3	Average	Average [mg]
40	0,04	0,05	0,04	0,043	43
60	0,06	0,07	0,06	0,063	63
80	0,08	0,08	0,09	0,083	83
100	0,1	0,12	0,1	0,106	106
120	0,13	0,12	0,12	0,123	123
140	0,14	0,15	0,14	0,143	143
160	0,17	0,17	0,16	0,167	167
180	0,18	0,18	0,19	0,183	183
200	0,2	0,21	0,2	0,203	203



Pipette 0.5 - 5 mL				
Pipetted Volume [mL]	Weight Reduction [g]			
	1	2	3	Average
0,5	0,5	0,5	0,5	0,50
1	1,01	1	1	1,00
1,5	1,5	1,49	1,5	1,50
2	2	1,98	1,99	1,99
2,5	2,5	2,49	2,49	2,49
3	2,97	2,98	2,99	2,98
3,5	3,48	3,47	3,45	3,47
4	3,99	3,96	3,96	3,97
4,5	4,48	4,44	4,45	4,46
5	4,95	4,91	4,96	4,94



2. Spectrophotometry

2.1 Dilution Calculation

Required volume of 100 mg/L Cu to dilute 100 mg/L Cu to 1 mg/L in a 50 mL volumetric flask:

$$C_1 \cdot V_1 = C_2 \cdot V_2 \qquad (1)$$

$$100\,\frac{\text{mg}}{\text{L}} \cdot V_1 = 1\,\frac{\text{mg}}{\text{L}} \cdot 50\text{ mL} \qquad 2$$

$$V_1 = \frac{1}{100} \cdot 50\text{ mL} \qquad 3$$

$$V_1 = 0.5\text{ mL} \qquad 4$$

Required volume of 1 mg/L Cu to dilute 1 mg/L Cu to 10 μg/L in a 10 mL sample cell:

$$C_1 \cdot V_1 = C_2 \cdot V_2 \qquad 1$$

$$1\,\frac{\text{mg}}{\text{L}} \cdot V_1 = 10\,\frac{\mu\text{g}}{\text{L}} \cdot 10\text{ mL} \qquad 2$$

$$1000\,\frac{\mu\text{g}}{\text{L}} \cdot V_1 = 10\,\frac{\mu\text{g}}{\text{L}} \cdot 10\text{ mL} \qquad 3$$

$$V_1 = \frac{10}{1000} \cdot 10\text{ mL} \qquad 4$$

$$V_1 = 0.1\text{ mL} = 100\ \mu\text{L} \qquad 5$$

Required volume of 1 mg/L Cu to dilute 1 mg/L Cu to 20 μg/L in a 10 mL sample cell:

$$C_1 \cdot V_1 = C_2 \cdot V_2 \qquad 1$$

$$1\,\frac{\text{mg}}{\text{L}} \cdot V_1 = 20\,\frac{\mu\text{g}}{\text{L}} \cdot 10\text{ mL} \qquad 2$$

$$1000\frac{\mu g}{L}\cdot V_1 = 20\frac{\mu g}{L}\cdot 10\ mL \quad (3)$$

$$V_1 = \frac{20}{1000}\cdot 10\ mL \quad (4)$$

$$V_1 = 0.2\ mL = 200\ \mu L \quad (5)$$

Required volume of 1 mg/L Cu to dilute 1 mg/L Cu to 50 μg/L in a 10 mL sample cell:

$$C_1\cdot V_1 = C_2\cdot V_2 \quad (1)$$

$$1\frac{mg}{L}\cdot V_1 = 50\frac{\mu g}{L}\cdot 10\ mL \quad (2)$$

$$1000\frac{\mu g}{L}\cdot V_1 = 50\frac{\mu g}{L}\cdot 10\ mL \quad (3)$$

$$V_1 = \frac{50}{1000}\cdot 10\ mL \quad (4)$$

$$V_1 = 0.5\ mL \quad (5)$$

Required volume of 1 mg/L Cu to dilute 1 mg/L Cu to 100 μg/L in a 10 mL sample cell:

$$C_1\cdot V_1 = C_2\cdot V_2 \quad (1)$$

$$1\frac{mg}{L}\cdot V_1 = 100\frac{\mu g}{L}\cdot 10\ mL \quad (2)$$

$$1000\frac{\mu g}{L}\cdot V_1 = 100\frac{\mu g}{L}\cdot 10\text{ mL} \quad (3)$$

$$V_1 = \frac{100}{1000}\cdot 10\text{ mL} \quad (4)$$

$$V_1 = 1.0\text{ mL} \quad (5)$$

Required volume of 1 mg/L Cu to dilute 1 mg/L Cu to 200 μg/L in a 10 mL sample cell:

$$C_1\cdot V_1 = C_2\cdot V_2 \quad (1)$$

$$1\frac{mg}{L}\cdot V_1 = 200\frac{\mu g}{L}\cdot 10\text{ mL} \quad (2)$$

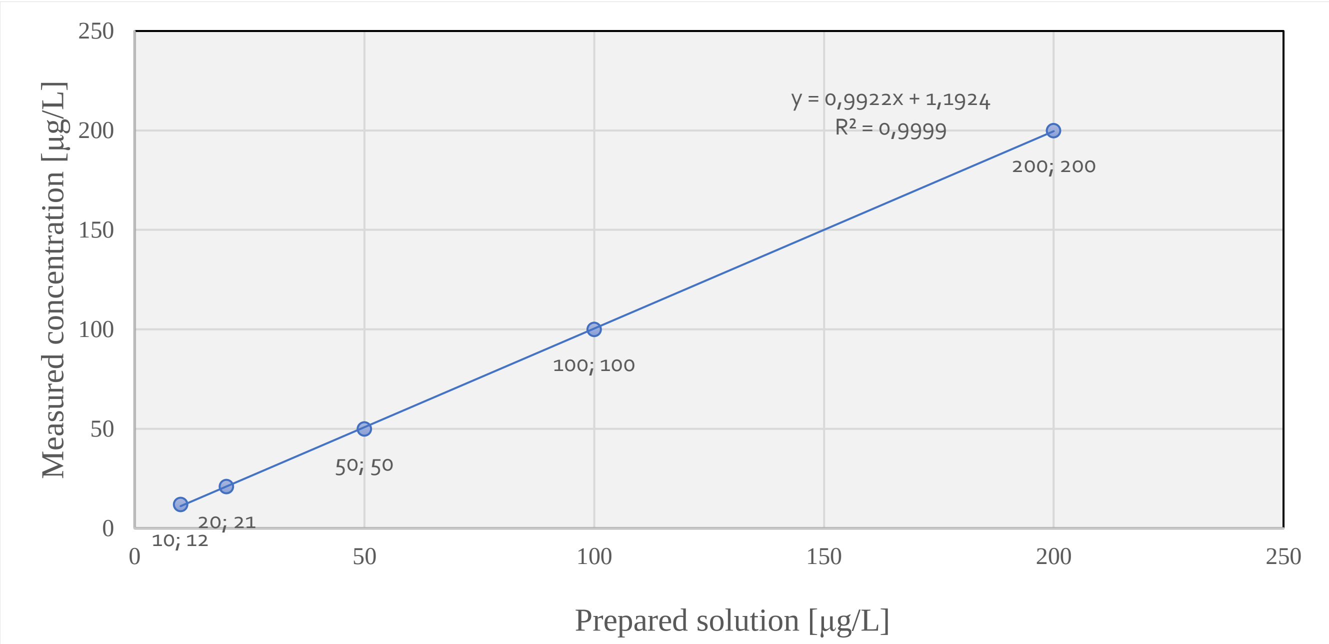
$$1000\frac{\mu g}{L}\cdot V_1 = 200\frac{\mu g}{L}\cdot 10\text{ mL} \quad (3)$$

$$V_1 = \frac{200}{1000}\cdot 10\text{ mL} \quad (4)$$

$$V_1 = 2.0\text{ mL} \quad (5)$$

2.2 Result – Calibration Curve - Spectophotometry

Concentration of the prepared standard solution [µg/L]	Measured concentration [µg/L]
10	12
20	21
50	50
100	100
200	200



3. Standard Addition

3.1 Calculation for Dilution

Required volume of 100 mg/L Cu to dilute 100 mg/L Cu to 4 mg/L in a 50 mL volumetric flask:

$$C_1 \cdot V_1 = C_2 \cdot V_2 \tag{1}$$

$$100\frac{\text{mg}}{\text{L}} \cdot V_1 = \frac{4\text{mg}}{\text{L}} \cdot 50\ \text{mL} \tag{2}$$

$$V_1 = \frac{4}{100} \cdot 50 \text{ mL} \qquad 3$$

$$V_1 = 2.0 \text{ mL} \qquad 4$$

3.2 Calculation – Expected Concentration after Spiking

The initial sample without spike was measured to have 22.936 μg/L Cu. Theoretical concentration for the spike samples after spiking with spike volume of 0.1, 0.2 and 0.3 mL of 4 mg/L Cu standard was calculated to be 62.313, 100.92 and 138.77 respectively. Calculations were done by using following equation [66]:

$$\text{Theoretical Concentration} = \frac{C_u \cdot V_u + C_s \cdot V_s}{V_u + V_s}$$

Where:

C_u = Original measured concentration of unspiked sample

V_u = Volume of sample to which the spike is added

C_s = Concentration of the standard used to spike

V_s = Volume of standard used to spike

Theoretical concentration of sample after 0.1 mL spike with 4 mg/L Cu standard:

$$\text{Theoretical Concentration} = \frac{22.936 \frac{\mu g}{L} \cdot 10mL + 4000 \frac{\mu g}{L} \cdot 0.1mL}{10mL + 0.1mL} \qquad 1$$

$$\text{Theoretical Concentration} = 62.313\ \frac{\mu g}{L} \quad 2$$

Theoretical concentration of sample after 0.2 mL spike with 4 mg/L Cu standard:

$$\text{Theoretical Concentration} = \frac{22.936\frac{\mu g}{L} \cdot 10mL + 4000\frac{\mu g}{L} \cdot 0.2mL}{10mL + 0.2mL} \quad 1$$

$$\text{Theoretical Concentration} = 100.92\ \frac{\mu g}{L} \quad 2$$

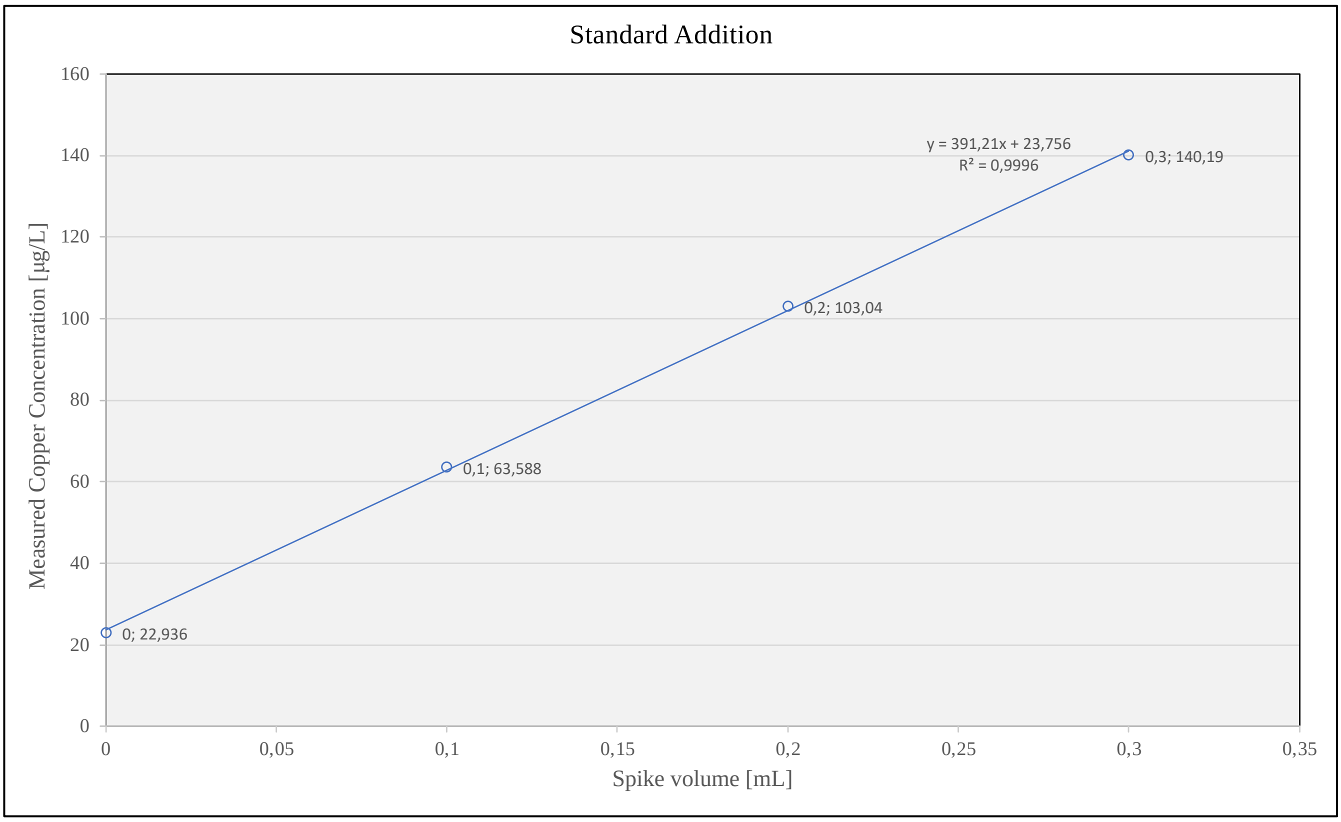
Theoretical concentration of sample after 0.3 mL spike with 4 mg/L Cu standard:

$$\text{Theoretical Concentration} = \frac{22.936\frac{\mu g}{L} \cdot 10mL + 4000\frac{\mu g}{L} \cdot 0.3mL}{10mL + 0.3mL} \quad 1$$

$$\text{Theoretical Concentration} = 138.77\ \frac{\mu g}{L} \quad 2$$

3.3 Result – Standard Addition Method

Spiked Voume [mL]	Measured Value [µg/l]	Expected Value [µg/l]	% Recovery
0	22,936		100
0,1	63,588	62,313	102
0,2	103,04	100,92	102,1
0,3	140,19	138,77	101



4. Temperature Correction Factor Calculation.

To be able to compare conductivity values of water at VIVA and Benna DWTP from 2020 to values that were measured during field work of March 2022, conductivity values from 2020 were converted from conductivity with reference temperature 20 °C to 25 °C. The correction factor that was used was obtained from Table 3 in *Europe Standards for Water quality – Determination of electrical conductivity (=EN 27888:1993)*

Conductivity at VIVA 2020 value, from reference temperature 20 °C to 25 °C:

$$\text{Conductivity}_{25°C} = \text{Condcutivity}_{20°C} \cdot 1.116 \quad (1)$$

$$\text{Conductivity}_{25°C} = 128\,\frac{\mu S}{cm} \cdot 1.116 = 143\,\frac{\mu S}{cm} \quad (2)$$

Conductivity at Benna DWTP 2020 value, from reference temperature 20 °C to 25 °C:

$$\text{Conductivity}_{25°C} = \text{Condcutivity}_{20°C} \cdot 1.116 \quad (1)$$

$$\text{Conductivity}_{25°C} = 98.5 \frac{\mu S}{cm} \cdot 1.116 = 110 \frac{\mu S}{cm} \quad (2)$$

5. Tracer Study with NaCl

5.1 Theoretical Increase in Conductivity

Concentration of NaCl in a fully saturated salt brine at 15°C:

$$\text{Concentration of NaCl} = \frac{358.7g}{358.7g + 1000g} = 26.4\ \% \quad (1)$$

Calculating increase of conductivity as a result of injection of 2.31 L/min of fully saturated brine onto 775 L/s treated water:

Step 1. Determining first how much L/s, 2.31 L/min saturated brine corresponds to.

$$2.31\ \text{L/min} = 2.31 \frac{L}{60s} = 0.0385\ L/s \quad (1)$$

Step 2. Determining how much gram NaCl per second is injected from brine to treated water.

$$\text{Brine}_{\text{injected per second}} = 0.0385\ \text{L/s} = 0.0385 \frac{kg}{s} = 38.5 \frac{g}{s} \quad (2)$$

$$\text{NaCl}_{\text{injected per second}} = 38.5\frac{\text{g}}{\text{s}} \cdot 26.4\% = 10.164\frac{g}{s} \qquad 3$$

Step 3. Determining increase of NaCl concentration in the treated water as a result of brine injection.

$$\Delta c_{\text{NaCl}} = \frac{10.164 \text{ g/s}}{775\frac{\text{L}}{\text{s}} + 0.0385\frac{\text{L}}{\text{s}}} = 0.0131\frac{\text{g}}{\text{L}} = 13.1 \text{ mg/L} \qquad 4$$

Step 4. Determining increase of conductivity as a result of increase in NaCl, using *Eq. 12*.

$$\Delta\text{Conductivity} = \Delta\text{EC} = \frac{\text{TDS}}{\text{K}} = \frac{13.1\ mg/L}{0.5} = 26.2\ \mu\text{S/cm} \qquad 5$$

5.2 Mean Residence Time – Jakobsli Pumping Station

Eq.10 was utilized to calculate mean residence time of tracer in Trondheim DWDS from VIVA to Jakobsli pumping station. Since measurement was taken every 10 minutes, this meant that: $\Delta t_i = 10$ min. Since Δt_i is constant, the equation could be simplified:

$$MRT = \frac{\int_0^\infty tC\ dt}{\int_0^\infty C\ dt} = \frac{\sum_{i=0}^{\infty} t_i C_i \Delta t_i}{\sum_{i=0}^{\infty} C_i \Delta t_i} \qquad 1$$

$$\rightarrow MRT = \frac{\sum_{i=0}^{\infty} t_i C_i}{\sum_{i=0}^{\infty} C_i} \qquad 2$$

Using average conductivity 114.43µS/cm as baseline conductivity, first increase above this baseline was observed 15:40. This is interpreted as the first sign of tracer material arriving Jakobsli pumping station. Conductivity at Jakobsli pumping station came down to the baseline again at 18:30, which is interpreted as sign of the last trace of tracer material leaving Jakobsli pumping station. These observations can be seen under column nr.4 in the spreadsheet below.

0	1	2	3		4	5
i	Date	t_i = elapsed Time [h]	C, conductivity [μS/cm]		C_i = C - C_average [μS/cm]	t_i × C_i
1	01/06/2022 15:40	5,70	115,13		0,7	4,0
2	01/06/2022 15:50	5,87	117,14		2,71	15,9
3	01/06/2022 16:00	6,03	120,36		5,93	35,8
4	01/06/2022 16:10	6,20	124,61		10,18	63,1
5	01/06/2022 16:20	6,37	129,1		14,67	93,4
6	01/06/2022 16:30	6,53	133,38		18,95	123,8
7	01/06/2022 16:40	6,70	136,38		21,95	147,1
8	01/06/2022 16:50	6,87	137,39		22,96	157,7
9	01/06/2022 17:00	7,03	136,37		21,94	154,3
10	01/06/2022 17:10	7,20	133,53		19,1	137,5
11	01/06/2022 17:20	7,37	129,59		15,16	111,7
12	01/06/2022 17:30	7,53	125,33		10,9	82,1
13	01/06/2022 17:40	7,70	121,58		7,15	55,1
14	01/06/2022 17:50	7,87	118,57		4,14	32,6
15	01/06/2022 18:00	8,03	116,68		2,25	18,1
16	01/06/2022 18:10	8,20	115,56		1,13	9,3
17	01/06/2022 18:20	8,37	114,85		0,42	3,5
18	01/06/2022 18:30	8,53	114,49		0,06	0,5
				Sum	180,3	1245,3

Column 4 calculates denominator of *Eq.10* and column 5 calculates numerator of *Eq.10*:

$$MRT = \frac{\sum_{i=0}^{\infty} t_i C_i}{\sum_{i=0}^{\infty} C_i} = \frac{1245.3}{180.3} = 6.9h \tag{3}$$

MRT = 6.9 is calculated with elapsed time that initiated when tracer injection started. However, tracer material was first observed to leave VIVA after 20 minutes of injection. Therefore, the correct MRT from VIVA to Jakobsli are 20 minutes slower:

$$MRT_{VIVA-Jakobsli} = 6.91\ h - 20\ \text{min} = 6.9h - \frac{20}{60}h = 6.6h \tag{4}$$

Appendix D: Preparatory Work

Source Trace Analysis and Water Age in Drinking Water Distribution System in Trondheim, Norway

TVM4510 - Water and wastewater engineering, specialization project

Sang Munn Kim

Submission: December 2021

Supervisor: Cynthia Hallé, Marius M. Rokstad, Michael B. Waak

Norwegian University of Science and Technology

Department of Civil and Environmental Engineering

Abstract

Water quality in drinking water distribution systems have tendency to deteriorate during period of transportation from drinking water treatment plant till it is consumed by recipients. The reactions that occur in the distribution systems are numerous and multivariate, but these reactions are often time dependent. Hence, deterioration of water quality can in general be related to hydraulic residence time, also known as water age. Another issue that are present in drinking water distribution system are mixing of water. This occurs in distribution system that are supplied by more than one water source. Although several water sources increase redundancy, mixing can result in reduced quality and aesthetics. In addition, statistical classification of water source to locations within distribution system becomes more difficult when several water sources are present. The process of identifying the origin of water within distribution system are referred as source trace analysis. This paper investigates methods that can determine hydraulic residence time and perform source trace analysis in Trondheim Norway. This paper is a prework to MSc thesis that are expected January – June 2022 and was done in relation to Norwegian University of Science and Technology. Based on existing academic literatures and the tracer study that was performed in Trondheim municipality in year 2020, tracer studies are deemed the best suited method to obtain real life data of water age in Trondheim distribution system. For source trace analysis, the feasibility of fingerprint analysis approach was investigated, and the use of tracers and machine learning classifiers was briefly explored. The condition that are present in Trondheim drinking water distribution system facilitates all three source trace analyses approach to be performed. The feasibility of tracer study and source trace analyses ultimately depends on permission to conduct experiment on Trondheim drinking water distribution system, which can be authorized by Trondheim municipality. In addition, the feasibility of tracer study and source trace analyses depends on the condition that are at hand in the distribution system in regard to operational status for drinking water treatment plants in Trondheim municipality for period January – June 2022. These uncertainties remain to be clarified prior to start of next year's MSc thesis.

Abbreviation

DWDS - Drinking water distribution system

DWTP – Drinking water treatment plant

WDM – Water Distribution Model

NTNU - Norwegian University of Science and Technology

VIVA – Vikelvdalen Vann Behandlings Anlegg (*Vikelvdalen Water Treatment Plant).*

Table of Content

List of Figures

List of Tables

List of Equations

1. Introduction

Water scarcity, water pollution and poor sanitation is one of the leading reasons to diseases and death around the globe. Basic access to safe drinking water is therefore considered to be crucial for health and development of human lives [1-3]. It is for these reasons that the United Nations have set access to safe drinking water as one of the fundamental human rights and authorities should ensure clean and safe drinking water is produced and received by inhabitants. Water utilities in Norway achieves this by typically collecting water from groundwater, lakes, and rivers. Thereafter the water is treated at drinking water treatment plants (DWTP) before it is distributed through drinking water distribution systems (DWDS) [4]. In larger urban areas, water often travels through several kilometers of various infrastructures after it leaves DWTP before it is consumed. Although water quality may be satisfactory with regards to set guidelines for drinking water before the water leaves the treatment plant, it can be challenging for those in management to confirm the water received by recipients have the same satisfactory quality. This is due to the fact that water quality typically deteriorates with increasing hydraulic residence time [2, 5-7]. Hence, in order for the utilities to ensure that satisfactory water quality is received by inhabitants, hydraulic residence time, also known as water age, need to be minimized. In general, water age increases the further the water has to travel before it is consumed. Factors such as low demand, pressure, flow path, over dimensioned pipes and system configurations in valves and storage tanks also influences water age [6, 8]. The challenge of minimizing water age in DWDS is therefore complex with several factors playing a role. In Trondheim Norway, there have been an effort to obtain data of water age in the distribution system where the goal was to calibrate and improve water distribution model (WDM) of Trondheim to have a more accurate model to predict water age [9, 10]. The effort was successful but further calibration effort to improve the WDM was advocated.

DWDS with more than one water source can experience water degradation in areas where there are mixing of water [4]. In Trondheim municipality, water is supplied from two water sources, and there have been an interest by the utility to have location of the mixing zones. Additional information such as the percentage of contribution from each water sources are desired. Source trace analysis, which aims to determine which water source water in a sampling point originates from, is therefore relevant for this assignment [4]. From asset management point of view, information regarding what water sources is supplying where in the DWDS are important for making strategies in cases of emergencies. For instance, in a case of contamination from one of the water sources in Trondheim, the utilities can use the information to shut down critical valves to contain the contamination before it spreads through the whole system. Furthermore, the data can be used identify which areas are most likely to be affected and notify the residents in the relevant areas. By knowing which water source supplies what areas in DWDS, the utilities can make quick assessment on the extent of spreading of the contamination. However, due to constantly changing pressure, flow, and demand in DWDS, areas where mixing occurs are not constant. Similarly to water age, it is influenced by several factors and can therefore be challenging to determine where mixing occurs and to what extent the areas are supplied by the two water sources [4]. In Trondheim municipality, there have been no previous works that have attempted to obtain data regarding this issue.

The main objective for this paper has been to investigate and prepare for a suitable strategy to determine water age and perform water source tracing in the DWDS in Trondheim, Norway. For the purpose of ensuring safe water is provided by the utilities in Trondheim DWDS, more work in the topics water age and source tracing are needed. WDM that can more accurately determine water age in the DWDS can aid in improved water quality monitoring. Having more knowledge of source contribution from the two water sources can lead to better strategies and decision making for risk management.

This paper is a prework for MSc thesis that are planned to be performed January to June 2022 by the same author of this paper and was performed in relation to the course *TVM4510 - Water and wastewater engineering, specialization project* offered at Norwegian University of Science and Technology (NTNU). The future MSc thesis will also be performed for NTNU, and the topic will be related to water age and source trace analysis of drinking water distribution system in Trondheim, Norway. This paper and the future MSc thesis is a continuation work of MSc thesis *Modeling of Water Age in the Drinking Water Distribution System of Trondheim Kommune by Jon Kristian Rakstang,* published in June 2020 [10]. The main objective of the thesis was to provide estimates of water age in Trondheim DWDS by using hydraulic model utilized by the utilities in Trondheim municipality and compare the result with field measurement obtained by a full scale NaCl tracer study in Trondheim. Due to this paper and the future MSc thesis being a continuation work of *Modeling of Water Age in the Drinking Water Distribution System of Trondheim Kommune* [10], overlap of same data and information in objectives, research questions, literature review and methodology are expected to occur.

2. Objectives

The main objective for this paper is to get familiar with the topic water age and source trace analysis. Furthermore, a strategy on how to determine water age and how to perform source trace analysis in Trondheim DWDS will be explored and presented in this paper. The plan is to use the presented strategies in the MSc thesis. With these objectives in mind, following questions were made:

- How is water age related to water quality in a drinking water distribution system?
- How can source trace analysis benefit water management?
- How can water age be determined in drinking water distribution system in Trondheim?
- How can source trace analysis be performed in DWDS in Trondheim?

The objectives for this paper are presented in *Table 1*.

Table 1. Overview of objectives

Get familiar with:	Water age and water quality in DWDS
	Source trace analysis in DWDS
Propose a strategy on:	How to determine water age in DWDS in Trondheim
	How to perform source trace analysis in DWDS in Trondheim

Information regarding water age and source trace analysis in DWDS will be gathered and explored by researching existing literatures. These literatures will mostly consist of academic papers and governmental guidelines. The findings will then be presented.

Strategy on how to perform water age and source trace analysis in Trondheim DWDS will be proposed based on existing papers and literatures. Adjustments of methods from previously done experiments will be suggested to accommodate differences of DWDS in Trondheim and study areas of the explored papers.

The objectives in future MSc thesis will be to perform the experiments to obtain data on water age and source contribution from water sources in Trondheim DWDS. The obtained data of water age will then be used on calibration work for the WDM of Trondheim DWDS utilized by Trondheim municipality. The WDM will be calibrated to increase accuracy in regard to water age. The data obtained from source trace analysis will be used to map areas where there are mixing. Furthermore, percentage of contribution from each water sources will be calculated in the areas where mixing occurs.

The structure of this paper is made up of first introducing the objectives for this paper. Thereafter, the study area and its details are presented before short review are made about the relationship between water age and water quality. After this step, suitable strategy to determine water age in Trondheim DWDS for the MSc thesis are presented and discussed. This is followed by presentation of suitable strategy to perform source trace analysis in Trondheim DWDS. Contingency plan in case when Benna DWTP is out of service during next year's MSc thesis are discussed at the end.

3. Study Area

As of second quarter of 2021, Trondheim was registered to have 207 415 inhabitants, resulting as the third most populous municipality in Norway [11, 12]. Trondheim waterworks, *Trondheim vannverk,* are responsible to supply Trondheim municipality with safe and clean drinking water on behalf of Trondheim municipality. In addition, Trondheim waterworks supplies neighboring municipalities, Malvik municipality and Melhus municipality [13]. These municipalities have 14 319 and 17 034 inhabitants, respectively [14, 15]. Klæbu municipality, a former municipality in Norway, and Trondheim municipality merged together in 01.01.2020. As a consequence, Klæbu municipality is now part of Trondheim municipality [16]. It was registered that Klæbu municipality had 6076 inhabitants in 2019 [17].

There are two main water sources that supplies the municipalities: Jonsvatnet lake and Benna lake, *Figure* 1. Jonsvatnet lies in Trondheim municipality while Benna lies in Melhus municipality. Additionally, Fremo waterworks supplies former Klæbu municipality with Fremo groundwater [13]. Fremo groundwater lies in Melhus municipality. Location of Fremo is not specified in *Figure* 1.

In *Figure* 1, blue line illustrates the location of the water main line, striped blue and white line illustrates the tunnels from water sources to treatment plants, purple line illustrates municipality borders and checkered area with black lines illustrates drainage basins for the two water sources. Total length of pipes in Trondheim municipality is estimated to be 1700km [13]. Surrounding areas of the two water sources are restricted with various degrees to prevent pollution, contamination or even sabotage [13]. DWDS in Trondheim are composed of various elements. Of the 1700km of pipelines that exist in Trondheim, 800km are managed by the municipality, while the rest are private. Other elements managed by Trondheim municipality includes 7km of tunnels, 7000s manholes, 20 pumping stations and 12 storage basins/elevation pools [13].

Jonsvatnet is the primary water source for Trondheim municipality and Malvik municipality, whilst Benna is the primary water source for Melhus municipality [13]. Through the MeTroVann project between Trondheim and Melhus municipality in period 2011 - 2016, DWDS on each of these municipalities were connected through 24km long main water pipe. The purpose was to create a reserve water source to each of the municipality. Former Klæbu municipality have their own water supply from Fremo groundwater reserve. Water distribution network in Klæbu are not connected with network in Trondheim [13]. However, there is a wish to connect the two networks as groundwater from Fremo is of excellent quality. It is also the second largest ground water reserve in Norway [13, 18, 19]. The incentive is to have Fremo as a reserve water source for Trondheim municipality in addition to Jonsvatnet and Benna. In normal operation, Jonsvatnet supplies majority of Trondheim municipality and Benna supplies Melhus municipality and small parts of Trondheim [20].

Figure 1. Drinking Water Distribution System managed by Trondheim Waterwork [13]

Water from Jonsvatnet is treated in drinking water treatment plant, VIVA, before it supplies the majority of Trondheim municipality. Water from Jonsvatnet is withdrawn at the depth of 50m and transported through 4km rock blasted tunnel before it is treated. Treatment methods in VIVA includes sieving, carbonation, filtration with limestone, chlorination with sodium hypochlorite (NaOCl) and ultraviolet (UV) filtration in the order mentioned [13, 21]. Benna water treatment plant follows a similar but simpler treatment process which consist of sieving, UV filtration and chlorination with sodium hypochlorite (NaOCl) in the order mentioned. Withdrawing of water from Benna takes place at 32m of depth, which after the water is transported through roughly 600m long rock blasted tunnel [13]. Main goal for VIVA is to produce sanitary safe drinking water and corrosion stable drinking water that limits corrosion on pipes that water is in contact with [21]. Fremo waterworks withdraws water from groundwater with the use of three pumps and thereafter sends the water to a basin where it is treated with UV filtration for disinfection. Due to the water having a natural high quality, only a simple procedure is followed [18, 19]. Overall, drinking water in Trondheim municipality is described to be of excellent quality [22].

In general, water infrastructures in Norway have been through good improvements during the last few decades due to government initiative to increase investments in water sector by setting higher importance on drinking water and sewage infrastructure [23]. For instance, Trondheim municipality have set a plan to spend 2125MNOK for maintenance and improvements for drinking water distribution system for 2017-2028 [13]. Nevertheless, the replacement rate for old pipes in Norway are considered to be too slow. Broken pipelines are common in Norway, and it is estimated around a third of the water produced is lost to leaks before it reaches consumers. Compared to other countries with similar infrastructure, water loss in Norway is much higher [23]. In Trondheim, water loss was calculated to be between 28.3% and 31.6% of produced water between 2007 – 2014 [13]. Breaks and leakages increases the risk and vulnerability for contamination in water main and distribution pipes, especially if there are pressure drops which can then suck in whatever materials or liquids that surrounds the pipe. This risk and vulnerability is exacerbated by the fact that water pipelines are often in same ditch as sewage and drainage pipeline [23].

Size and complexity of DWDS in Trondheim, makes it challenging to determine accurate water age in the system. The same applies for source tracing. Since there are many factors, parameters and elements in the system that are constantly changing, water age and source contribution is not constant. There will therefore not be one value for water age and source contribution that can be applicable for every condition. Regardless, study of how water age and source contribution can be determined in Trondheim DWDS will be explored in this paper.

4. Water Age and Water Quality

There are no specific requirements from authorities for upper threshold for water age in Norway. Still, existing standards in water industry and requirements from municipalities in Norway requires that high hydraulic residence time should be avoided as it is linked to degradation in water quality [24, 25]

Water quality deterioration in DWDS are related to chemical reactions in the bulk flow and physical interactions between pipe wall and water [5]. The chemical reactions and other related processes are often multivariate and differs in reaction order making it hard to have control over the exact state of water quality all the time [4, 7]. For instance, biofilms are common occurrences in DWDS, existing usually in the surface area of containers or pipes. The biofilms can pose as a suitable habitat for microbial growth for waterborne pathogens, where it can multiply and later detach itself to further spread itself through the system. In addition, biofilms are linked to further water quality deterioration through corrosion of pipes and malodors [6, 26, 27]. Due to these problems, it is common practice for DWTP to use chlorination method to add disinfectant residual to limit regrowth [28]. Although residual chloramine is shown to suppress waterborne pathogens, chlorination present new set of challenges [27]. Effects of chlorination are formation of toxic by-products such as halogenated organic compounds, altered taste and odors [28]. Biofilms, corrosion, and formation of by products from chlorination are one of the many processes that can take place from when water leaves DWTP to when water is received by the recipients in the DWDS. Consequently, the many chemical and physical processes that is occurring in DWDS makes water quality monitoring a challenging task. However, many of these processes are kinetic in nature and determining hydraulic residence time in DWDS as well as water temperature, can prove to be a far simpler and useful method to determine overall water quality [4, 5, 7]. Even though water age can be an useful indicator for general degradation of water quality, it is a poor indicator for specific microbial water quality [7].

United States Environmental Protection Agency, a federal government agency in United States present some water quality issues related to water age in report *Effects of Water Age on Distribution System Water Quality* [5, 29]. *Table* 2 summarizes water quality problems associated with water residence time in DWDS [5].

Table 2. Water quality problem associated with water age [5]

Summary of water quality problems associated with water age		
Chemical Issues	**Biological Issues**	**Physical Issues**
*Disinfection by-product Formation	*Disinfection by-product Biodegradation	Temperature increases
Disinfectant decay	*Nitrification	Sediment Deposition
*Corrosion control effectiveness	*Microbial regrowth/ recovery/ shielding	Color
Taste and odor	Taste and odor	

**Denotes watery quality problem with direct potential public health impact*

Several of these water quality issues are also linked to negative human health impact. For instance, prolonged exposure to e.g. disinfectant byproduct is believed to be carcinogenic [5]. Disinfectant decay increase with water age and this in turn increases bacteria growth. If the water age is too high, residual disinfectant will decay enough that unwanted microbial substances can grow. This can include biofilms, which can create a suitable habitat for microbial growth and also act as reservoir for pathogens [27]. Higher water age is also linked to cause increased water temperature. This can be problematic as high temperature in water is further linked to several water quality degradation processes. Reaction kinetics of chemical reactions in the bulk flow may increase [7]. Higher temperature also creates a more suitable growth environment for microbes and pathogens, including legionella [27]. This process can be exacerbated by faster disinfectant decay at higher temperatures, meaning higher required disinfectant dose is needed for higher water age [5]. With average temperature expected to rise as a result of the climate change, microbial problems in DWDS may increase in the future.

Evidently, water quality issues in DWDS are multivariate and complex. Monitoring water quality by monitoring water residence time can therefore be a much easier method than to have many specific water parameters to monitor. Even though water age is a poor indicator for specific microbial water quality issues, utilities can gain a general picture of the condition in the distribution system by observing water age [5, 7]. Areas where water age is identified to be high can be further investigated to check for any water quality issues. Locations where there are consistent high water age can be presumed to have degraded water quality and suitable measures can then be performed to ensure good water quality. Information with regards to average water age throughout DWDS can also be a useful tool in scenarios where contamination are suspected in e.g. the water source. Available information of water age can also be used to deduct how fast contaminants can spread within the network and this information can in turn be used for emergency preparedness.

5. Determining Water Age in Trondheim

As already explored, water age can be a useful parameter that utilities of DWDS can investigate to assess overall water quality in the network. To determine water age, there are several potential approaches that can be applied. In last year's MSc thesis *Modeling of Water Age in the Drinking Water Distribution System of Trondheim Kommune* [10], tracer study using NaCl was performed to determine water age in Trondheim DWDS. The thesis demonstrated that a full scale tracer study with NaCl is feasible in Trondheim DWDS. At the time of the study, DWTP was not in operation and tracer study was only conducted from VIVA. The process of tracer study with NaCl proved to be relatively simple and stratighforward. This leads to believe that experiment can easily be reproduced. The thesis uncovered that the WDM used by the utility in Trondheim consistently underestimates water age, proving that the model is inaccurate in simulating hydraulic residence time. As one of the conclusions in the thesis, additional calibration effort were reccomended to reduce inaccuracies and to further validate the model [10]. Since tracer study was not conducted from Benna DWTP, there were little discovery of information of water age from Benna. This task remains to be performed for the future MSc thesis.

5.1 Performing tracer study in Trondheim

Generally, a tracer study involves adding or removing tracer chemical at the outflow of DWTP. The cocentration of the tracer is then measured over time in areas of interest within DWDS. The data gathered on concentration change of tracer in water can then used to calculate flow path and hydraulic residence time [4]. More details on how tracers studies can be performed to determine hydraulic residence time are summarized in *Appendix 1.*The paper that are presented as *Appendix 1*, is a term paper that were produced in relation to the course *TVM4141 - Water and Wastewater Systems, Advanced Course* in NTNU, written by the same author of this paper. The objective of the paper was to investigate:

- How can tracer studies be used to determine hydraulic residence time?
- What are the typical steps and criteria in a tracer study?
- What are the typical challenges of performing a tracer study?

One of the conclusions that were made in the paper was that it is easier to perform tracer study by removal rather than injection of a chemical compound from existing water treatment operation, e.g. temporaily shut down of fluoride feed in a DWTP. Subsequent concentration drop of fluoride in water can then be measured and used to determine hydraulic residence time. The feasibility of removing a chemical compound that are used in treatment process at VIVA and Benna DWTP remains uncertain and needs to be investigated.

Since it has already been demonstrated that a tracer study with NaCl is feasible in Trondheim, the same experiment can be performed again for MSc thesis next year to determine water age. The disadvantage of using the same approach is that there will be limited gain of new knowledge on how to perform tracer studies in Trondheim. However, the benefit of using the same method is that less effort have to be spent to prepare for the tracer study and more effort can be spent to gather data that can be used for calibration work. In addition to the benefit of less effort for preparation, there are limited alternative option that can be used to perform tracer study in Trondheim. The water treatment process in VIVA and Benna DWTP does not use fluoride nor coagulants that can be swapped for alternative coagulants than could be used as tracer compound [13]. In the previous tracer study in Trondheim, the brine that was injected as the tracer was produced onsite [10]. This was possible because VIVA uses sodium hypochlorite (NaOCl) as a disinfection step, which is produced onsite by electrolysis of brine solution. For this reason, VIVA already has a storage tank with NaCl which can be used to create brine that can used as the tracer compound [10, 13]. At Benna DWTP, sodium hypochlorite is also added, but this is produced offsite. Therefore, there are no equipment availble at Benna DWTP that can be used to create brine for tracer study. As one of the finding in *Appendix 1*, there are advantage of choosing a tracer compound that can be produced onsite in the treatmentplants. This is because large amount of tracer compound is typically needed and thus producing the tracer compound offsite and transporting the tracer to the treatmentplant to inject in the outflow can require extensive effort. In addition, injecting compounds that are not already present in DWTP will require authorization from the management in Trondheim waterworks which further complicates the process. This reason is also why it is easier to remove a chemical compound in the treatment process such as fluoride, and then measure expected concentration drop as this process does not require a tracer is produced. As a consequence, the feasibility of adding or removing a tracer compound other than NaCl from Benna DWTP has to be investigated in the MSc thesis. For VIVA, since there is already a method to produce brine, NaCl as the tracer compound is considered as the best option. Temporarily shutting down addition of sodium hypochlorite (NaOCl) at Benna to trigger concentration drop of free chlorine OCL^{-} and HOCL could possibly be used as a tracer. However, sodium hypochlorite (NaOCl) is used as one of disinfection step along with UV light [13]. The feasibility of this process have to be checked with Trondheim waterworks, but it is hypothesized unlikely as the consequence of temporarily removing sodium hypochlorite (NaOCl) is that Benna will only have one hygienic barrier and be vulnerable for bacteria and pathogens in the water for the duration of the experiment.

Alternative compounds that could be used as tracers have to be investigated and consolidated with people in Trondheim waterworks. Some example of tracer compounds that can be used for tracer studies are presented in the report *Effects of Water Age on Distribution System Water Quality* [5] and are as follows: fluoride, sodium chloride, calcium chloride, lithium chloride and coagulants. The important points to check will be to make sure that the compound is safe for consumption, permitted by Trondheim waterworks and within the regulation. Additional things to note according to United States Environmental Protection Agency are, ‘’consideration of the tracer chemical stability, continued regulatory compliance, and customer perceptions must be included in the planning and implementation of a tracer study’’ [5].

5.2 Sampling points

Before performing the tracer study, sampling points have to be determined. Last year’s MSc thesis had sampling points well distributed within the DWDS in Trondheim, acquiring water age data for most of the zones in Trondheim DWDS, *Figure 2*.

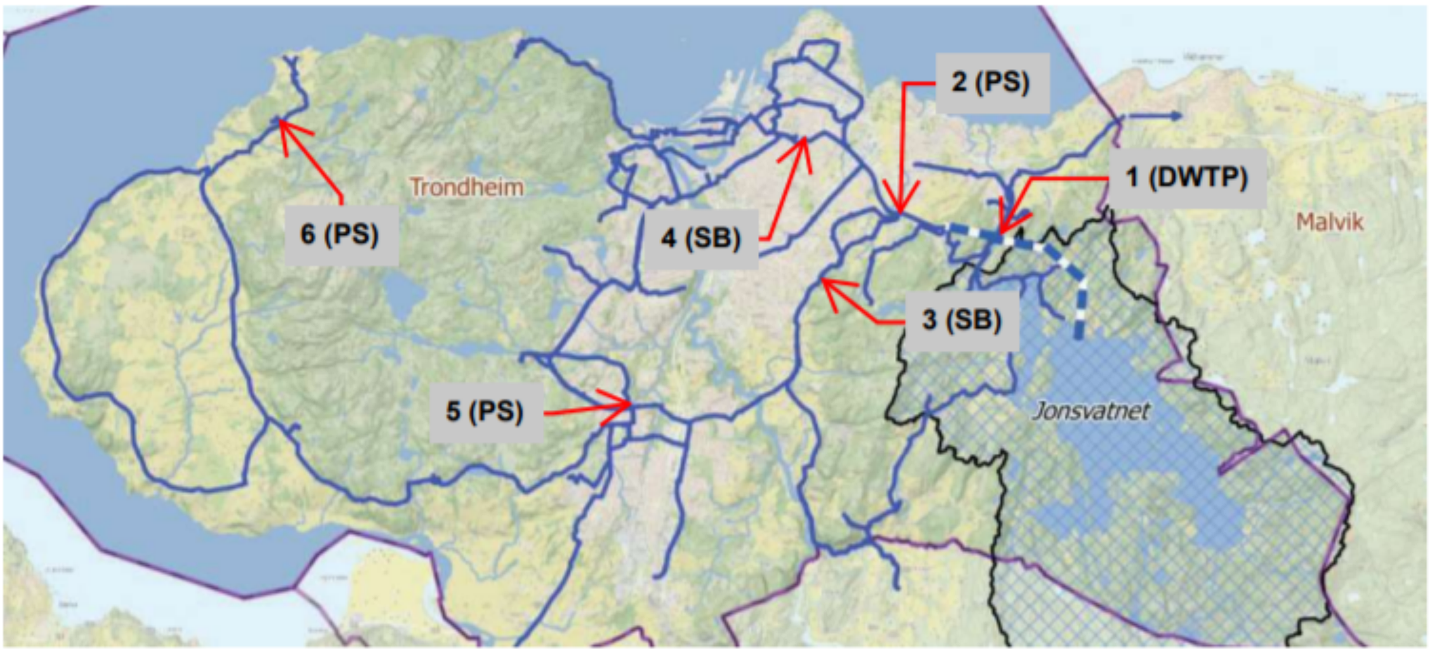


Figure 2. Sampling points used in tracer study from previous MSc thesis [10]

For the next year MSc thesis, the goal is to perform tracer study simultaneously with source trace analysis. The goal of the tracer study is to obtain water age data of Trondheim DWDS and the goal of source trace analysis is to obtain data of where in the network there are mixing and map which water source supplies what areas in the network in general. Therefore, sampling points will have to be established well spread throughout DWDS similar to shown in *Figure 2*. It might also be relevant to establish sampling points in areas where complaints have been registered in regard to water quality or where Trondheim waterworks know there are challenges to water quality and water age. Distribution network in the city center are characterized by complicated hydraulics with loops and flow paths, which might make it more difficult for WDM to accurately simulate water age in the area. Sampling points near city center might therefore be beneficial to obtain data on water age that can be used for calibration studies. Ultimately, sampling points will have to be established in locations where water outlets accessible to withdraw water for further experimentations. Total amount of sampling points that can be established will be determined by the available measuring equipment that are at hand in NTNU. This will have to be clarified with NTNU prior to the experiment.

Previous tracer study by *Jon Kristian Rakstang* [10] had 6 sampling points while only having 3 measuring tools. This was made possible by relocating the measuring equipments from initial sampling points to sampling points that were estimated to experience arrival of tracer peak later. This approach can be relevant for the future tracer study as the same limitations on number of available equipments are likely to be present. Challenging aspect of using this approach is that one could miss the arrival of tracer in the period of relocation. This challenge has to be taken into consideration when making the strategy of relocation.

6. Source Trace Analysis

In the context of DWDS source trace analyses is the methods that aims to track and determine the source of a substance in DWDS where the substance may have originated from more than one potential water source. Fingerprint study could be a relevant method for source tracing in DWDS. The fingerprint of water is understood as the characteristics of the water quality of a water source. Parameters such as pH, color or natural organic matter (NOM), are examples of things that can be characteristic of a source. If the differences in water quality are significant, calculation can be made to determine the source of water in e.g. junction nodes. To illustrate, if a DWDS has two water sources that have significant differences in color, one approach can be to measure color of water in the area of interest and relate the measured color to a water source that has the most alike value. Water from each source can also mix with each other in various locations in the network, and this can result in unwanted water quality such as reduced aesthetic, taste, or odor. This is due to the differences in various water quality parameters from each water sources. The significance of the mixture depends on the characteristics and variation of water quality from each source [4].

There are many applications for source tracing, but for a DWDS, a useful application can be to map what water source is supplying what areas in the DWDS, locate where the network is experiencing mixing, and determine the extent of contribution from each source throughout DWDS. Among other things, the information can come to use when the utility needs to know how far pollutions can spread from a particular water source or a DWTP. It can also be used as a method to determine the source of a pollution [4]. Obtaining knowledge of how pollution can spread throughout in DWDS can be one of the things in risk assessment that are of interest for waterworks. Trondheim waterworks have expressed desire to have more knowledge of how and to what extent Jonsvatnet and Benna supplies water in Trondheim. The topic of source tracing for risk assessment have become especially relevant in the following years after the water incident in Askøy 2019. The incident was a result of an outbreak of bacteria *Campylobacter* that arose in a water tank which was a passing point for water before supplying Askøy municipality. The incident affected 10,000 - 15,000 inhabitants and caused illness for 2000 inhabitants and is linked to 2 casualties [30].

In normal operation, Jonsvatnet supplies majority of Trondheim municipality while Benna supplies parts of Trondheim. However, how much each water source contributes to Trondheim is unknown. The water mains that connects Benna with DWDS in Trondheim are 24km long and the connection are made in Kolstad pumping station located at the southern part of Trondheim [13, 20, 31]. The location of the pumping station can be observed in *Figure 3*. The black squares implies storage tanks while triangles implies pumping stations. The location of VIVA, are observed in north-east of the map, illustrated as a blue square. The areas that are in close proximity to Jonsvatnet such as the eastern part of the city, are estimated to have water mostly provided from VIVA whereas areas in close proximity to Kolstad pumping station have water mostly supplied from Benna treatment plant. This is however not confirmed and is only an educated guess work based on the study [32]. This hypothesis will be attempted to be uncovered in the upcoming MSc thesis. The degree of contribution is also likely to be changing depending on variations in water demand, system configurations and mode of operation. For instance, if Benna DWTP were to temporarily close down for maintenance, water supplied in Trondheim municipality and Melhus municipality will be exclusively provided by water from VIVA. The issues related to having several water sources will become more relevant in the future for Trondheim waterworks if connection between DWDS in Klæbu are made with rest of DWDS in Trondheim. In that case, there will be three water sources in Trondheim: Jonsvatnet, Benna and Fremo.

Rest of this chapter will focus on how a source trace analysis can be performed in Trondheim DWDS for the purpose of mapping where mixing occurs. Methods that can be used for calculating the degree of contribution from Jonsvatnet and Benna in the mixing areas will also be presented.

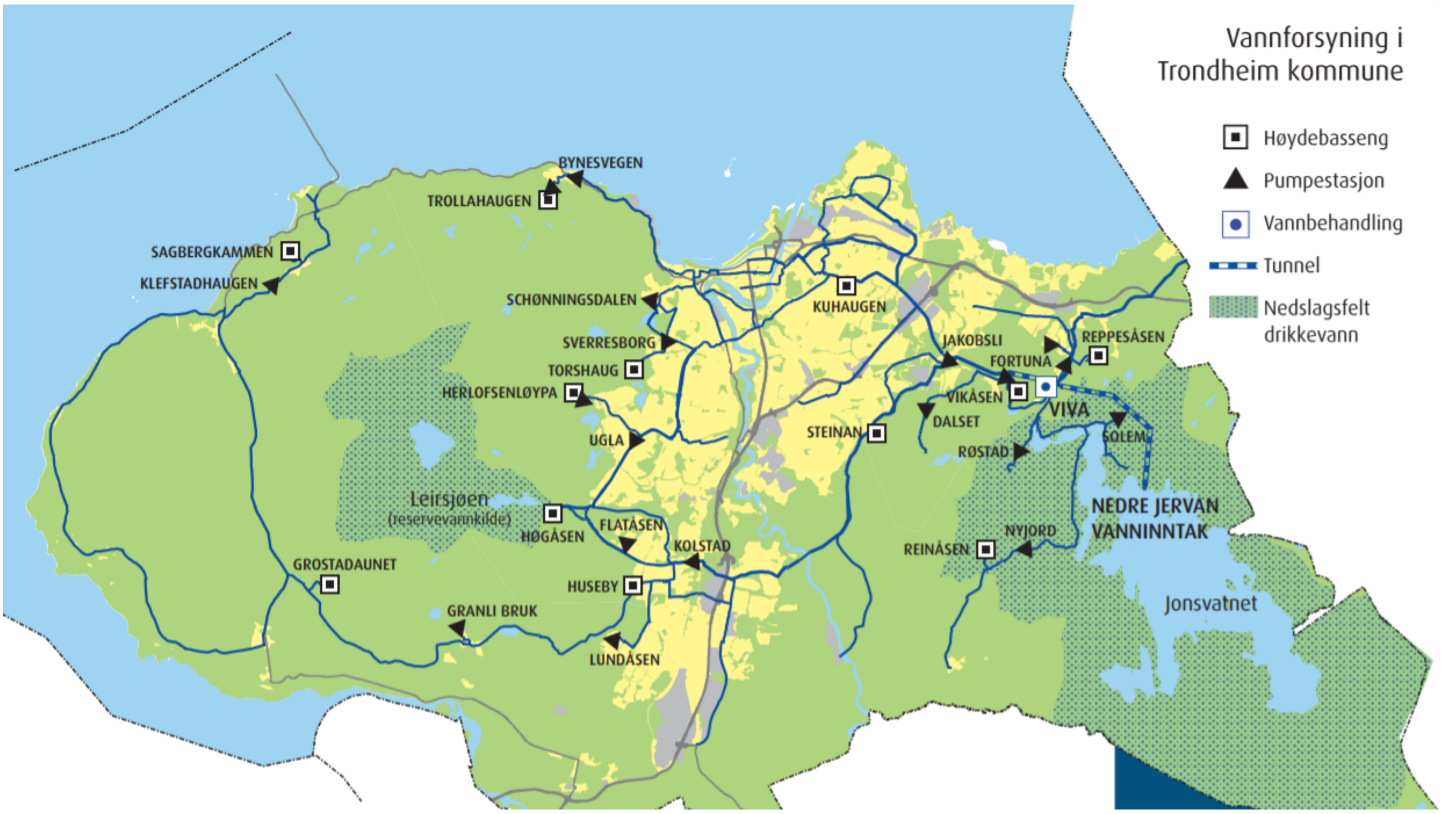


Figure 3. Map of water distribution in Trondheim. Screenshot from [31].

6.1 Parameters

In order for the fingerprint analysis to be possible, water quality from VIVA and Benna DWTP need to be different. If the water quality from the two sources are identical, tracer is then required to distinguish water from each source. Water quality from each source also have to be relatively stable during the experiment period as to make comparison of measured water quality in the area of interest and water source practicable. Subsequently, change or fluctuations in water quality during experiment period have to be taken into account in calculations.

Trondheim municipality regularly takes samples of water quality from its managing water sources. The content in water from the treated water are public available information provided by Trondheim municipality [22]. From municipality's website, contents in water from Jonsvantent and Benna in 2020 were able to be gathered [33]. With further inspection, water composition from Jonsvatnet and Benna was observed to be different. Following parameters were found to have been most different between Jonsvatent and Benna in 2020: copper, aluminum, nickel, color, iron, lead and nitrate. The observed average values of these parameters from each source are presented in *Table 3*. The differences in value and relative difference in percentage are also presented.

Table 3. Average concentration of parameters that were most different in water from Jonsvatnet and Benna, and the differences in concentrations for each parameter

Parameter	Jonsvatnet	Benna	Delta (Δ)	Percentage difference relative to Jonsvatnet [%]
Copper [µg/l Cu]	44.7	0.8	43.9 [µg/l Cu]	98.2
Aluminum [µg/l Al]	82	5.1	76.9 [µg/l Al]	93.8
Nickel [µg/l Ni]	0.7	0.1	0.6 [µg/l Ni]	85.7
Color [mg/l Pt]	15.2	3.44	11.76 [mg/l Pt]	77.4
Iron [µg/l Fe]	7.1	1.7	5.4 [µg/l Fe]	76.1
Lead [µg/l Pb]	0.17	0.05	0.12 [µg/l Pb]	70.6
Nitrate [mg/l N]	0.24	0.084	0.156 [mg/l N]	65.0

Copper, aluminum, and nickel was calculated to be the top three parameters that had the biggest difference in terms of percentage. From the findings in *Table 3*, it can be concluded that water quality from Jonsvatnet and Benna have natural differences. However, if the differences in the parameters are significant enough to perform source trace analysis will depend on the available measuring method and its detection limit. To elaborate, in order to determine the water source that supplies e.g. a random junction in Trondheim DWDS, measuring method that can detect e.g. copper in water in the range of at least the average concentration value of copper from Jonsvatnet and Benna presented in *Table 3* are necessary. In addition, like tracer compounds, the parameters need to be chemically stable. Whether the concentration of copper, aluminum and nickel remains the same, as water travels through the network needs to be investigated. If the compounds are not stable, it will raise the difficulty to determine whether discrepancies in concentration from water sources and sampling points are due to mixing or reactions with substances in the network. To investigate this, an experiment could be conducted in parallel with tracer study and source trace analysis. The procedure would be to measure the concentration of e.g. copper at VIVA and then compare that value with concentration of copper in a sampling point that are confident to be only supplied by VIVA. Discrepancy in concentration from VIVA and the sampling point will reveal whether copper is stable or not. Discrepancy can then be related to hydraulic residence data from tracer study to make a function of concentration change of copper in relation to time.

Potential measuring method to determine concentration of copper, aluminum and nickel could be the Hach methods. These are water analysis methods developed by Hach Company that are designed to be simple and easy to perform, and are sold as test kits that include necessary chemicals and reagents with instructions on how to perform the relevant analysis [34]. It typically involves mixing the water sample with reagents and requires that instructions on the test kits are precisely followed. Test kits that are offered by Hach Company that can be used to determine concentration of nickel in the range 0.1 – 0.7µg/l Ni, does not exist according to guide for Hach methods in Hach Company's website [35]. For copper, there are a Hach method that exist that uses porphyrin as the reagent to detect copper in the range 1 – 210 µg/l Cu, and this can be a viable method to use to determine concentration of copper in our case [36]. For aluminum, there is a Hach method that can detect for concentration range 6 – 250,000 µg/l Al [37]. This method could therefore be used to determine concentration of aluminum in the water samples gathered from sampling points. Alternative option would be to use inductively coupled plasma mass spectrometry (ICP-MS) instrument t at department of chemistry at NTNU [38].

As mentioned in *5.1 Performing tracer study in Trondheim,* salt brine are produced in VIVA. Similar to tracer study, salt brine could be used as a tracer for source trace analysis. The additional salt in water from VIVA could be used to differentiate water from Benna. Additional salt brine in the water would increase the conductivity of the water and also increase the concentration of sodium and chlorine in the water from VIVA. Measuring these parameters in the areas of interest can be used to determine how much influence water produced from VIVA have on these areas. Use of tracers is not necessary to perform source trace analysis since there are natural differences in water from Jonsvatnet and Benna. Regardless, since tracer study with salt brine to find hydraulic residence time is already planned, investigating the possibility to perform source trace analysis simultaneously can be beneficial. The natural level of sodium, chlorine and conductivity in Jonsvatnet and Benna are similar, *Table 4*. Addition of salt brine in VIVA would increase sodium, chlorine and conductivity in water from Jonsvatnet, making it possible to determine areas where water is supplied by Jonsvatnet. This approach would eliminate the lab work that are related to measuring concentration of copper, aluminum, or nickel, and would thus reduce the workload.

Table 4. Average value of sodium, chlorine, and conductivity in water from Jonsvatnet and Benna

Parameter	Jonsvatnet	Benna
Sodium [mg/l Na]	4.34	3.73
Chlorine [mg/l Cl]	6.96	5.75
Conductivity [mS/m, 20°]	12.8	9.85

6.2 Calculation method

After gathering necessary information of concentration on parameters of interest, calculations have to be made to determine percentage contribution from the two water sources, Jonsvatnet and Benna. One simple approach to determine percentage contribution could be to use the same equation utilized in multi tracer study by DiGiano et al., 2005 [32]. In the study, tracer study was performed by manipulating concentration of three parameters in DWTPs: chloride, fluoride, and sulfate. The study area, the DWDS in Durham, North Carolina USA, had two water treatment plant that supplied the DWDS. The general principle of the equation used in the study to calculate percentage contribution from each of the two DWTP were as following:

Equation 1. Percentage contribution calculation [32]

$$\% \, contribtution\ from\ DWTP1 = \frac{[tracer]_{sampling\ point} - [tracer]_{DWTP2}}{[tracer]_{DWTP1} - [tracer]_{DWTP2}} \times 100$$

$[tracer]_{samplingpoint} = concentration\ of\ tracer\ at\ the\ sampling\ point$
$[tracer]_{DWTP1} = concentration\ of\ tracer\ at\ DWTP1$
$[traer]_{DWTP2} = concentration\ of\ tracer\ at\ DWTP2$

By the logic of the equation, if the concentration of the tracer at the sampling point is equal to concentration of the tracer in DWTP1, then the percentage of contribution from DWTP1 is 100%, meaning the water at the sampling point is exclusively supplied by DWTP1.

The equation offers a simple method to calculate amount of contribution from each sources given a point in the DWDS, but there are several conditions that have to be met to utilize *Equation 1.* First, concentration of the measured tracers has to be relatively constant. Second, concentration of the tracer at the DWTPs and concentration of tracer in the package of the water that arrives in the sampling point are assumed to be same, meaning the compound have to be chemically stable in water. It also has to be assumed that water from the sources in the sampling point are perfectly mixed. In real life, how much a given location in DWDS is supplied by a DWTP is not constant but fluctuating or changing depending on the demand and system operation settings. Thus, the result from *Equation 1* only gives a value for a specific demand and system operation settings. In order to have an overview of a general condition, many samples are required for a broad period to calculate for various demand and system operation. This is not deemed practicable in the time scope of next year's master thesis as it requires extensive work in sampling and lab work. But if the equation is paired with a calibrated hydraulic model, the equation can prove to be a simple and useful method to calculate water source for a given point in DWDS. Hydraulic model can then be used to estimate source contribution of each water sources in various settings.

Alternatively, classifiers could be used to identify the origin of water in the sampling points. More specifically, classifiers that exist in Scikit-learn, open source machine learning library for programming language Python could be utilized to complete origin-identification of water in nodes within Trondheim DWDS [39]. As there are numerous classifiers that exist in the scikit library, future work should test several of these to investigate which ones are best suited given the input data that are at hand after the tracer study experiment. The advantage of classifiers would be that it could be used to identify and take into account for correlations that exists between substituents in water. A disadvantage of using classifiers is that it will require more data as machine learning algorithms are generally data hungry [40].

6.3 Contingency Plan

Like the situation for last year's MSc thesis, there is a possibility that Benna might be out of service during the period of next year's MSc thesis. If this event occurs, VIVA would be the only water source that supplies Trondheim municipality. This condition would make it unfeasible to perform source trace analysis, as well as tracer study from Benna DWTP. In consequence, other objectives have to be made. The MSc thesis could then shift its focus on investigating parameters that are suited for source trace analysis. Chemical stability of compounds presented in *Table* 3, could be investigated to prepare for a future source trace analysis. Tracer study from VIVA could still be performed, but like last year's MSc thesis, only water age from VIVA would be revealed from the experiment. Although the result would give water age from VIVA at a specified condition, it could still be of use, getting better estimates of water age from VIVA. Eastern part of Trondheim is presumed to be supplied mainly by VIVA even when both Benna DWTP and VIVA is in operation. Results that show high water age in eastern Trondheim would for instance indicate that there are high water age even when Benna is in service.

Even when Benna is in service, it might not be feasible to conduct tracer study from Benna DWTP due to the issue of finding and get approval of suitable tracer that can be used by Trondheim waterworks. In the event when both Benna DWTP and VIVA is in operation, but tracer study can only be performed from VIVA, water age from VIVA can still be determined but water age from Benna DWTP cannot be determined. Source trace analysis would however still be possible, and the thesis could therefore shift its focus more on source trace analysis by using fingerprint analysis approach as well as utilizing NaCl as tracer from VIVA to distinguish water from VIVA and Benna DWTP.

7. Conclusion

This paper has looked at the feasibility of performing source trace analysis and determining water age in Trondheim DWDS. The positive correlation that exists between hydraulic residence time and water quality in DWDS raises incentives for Trondheim municipality to investigate water age in Trondheim DWDS. Similar to last year's MSc, *Modeling of Water Age in the Drinking Water Distribution System of Trondheim Kommune* [10], it is deemed that the best solution to determine water age in Trondheim DWDS is to perform tracer study. However, last year's MSc only performed tracer study from VIVA due to circumstances and field measurements of water age from Benna DWTP was not obtained. Future MSc thesis therefore aims to perform tracer study from both VIVA and Benna DWTP. The easiest method to perform tracer study from VIVA is to inject NaCl, the same approach as last year's MSc thesis. The reason is because of existing onsite equipment at VIVA are able to produce necessary quantity of salt brine that can be used as the tracer compound. In addition, since this approach have been performed once already, it makes it easier to perform and reduces the uncertainty of whether this method is feasible. For Benna DWTP however, there are limited option of onsite production of tracers, which forces tracer compounds to be brought from offsite. One of the challenges of performing tracer study from Benna is the approval of offsite produced tracer compound that can be injected into drinking water of Trondheim municipality. The feasibility of this process needs to be investigated further through communication with Trondheim waterworks. If it proves to be unfeasible, more focus could then put in performing source trace analysis.

The feasibility of conducting source trace analysis in Trondheim DWDS are good because of the two primary water sources that are present in Trondheim municipality, Jonsvantnet and Benna, have natural differences in water quality. This circumstance makes it possible to conduct source trace analysis without any additional injection of tracers to distinguish the water from each source. Water quality parameter that was most different between Jonsvatnet and Benna was found to be copper, aluminum and nickel. To measure the concentration of these metals, Hach method or ICP-MS was suggested. Source trace analysis can also be performed by injecting NaCl, identically as the tracer study. Therefore, work to measure concentrations of copper, aluminum and nickel might not be needed if the data obtained from tracer study could also be utilized for source trace analysis. Calculation for identifying and determining the origin of water in a location within Trondheim DWDS can be done through by using the simple *Equation 1*. Alternatively, machine learning classifiers that exists in Scikit-learning library could be utilized. The benefit would be that potential correlations that exist between different substituents in water that affects the concentration of the measured parameters may be considered. Whether the required effort to use this method is justifiable will have to be questioned for future work.

Reference

1. UN General Assembly, *UN General Assembly, Transforming our world : the 2030 Agenda for Sustainable Development, 21 October 2015, A/RES/70/1*. 2015.
2. World Health Organization, *Guidelines for drinking-water quality: fourth edition incorporating first addendum*. 4th ed + 1st add ed. 2017, Geneva: World Health Organization.
3. Folkehelseinstituttet, *Vannrapport 127: Vannforsyning og helse. Veiledning i drikkevannshygiene* 2016.
4. Haestad, M., et al., *Advanced Water Distribution Modeling and Management*. 2004.
5. US Environmental Protection Agency, *Effects of Water Age on Distribution System Water Quality.* 2002.
6. US Environmental Protection Agency, *Health Risks from Microbial Growth and Biofilms in Drinking Water Distribution Systems.* 2002.
7. Blokker, E.J.M., et al., *Relating Water Quality and Age in Drinking Water Distribution Systems Using Self-Organising Maps.* Environments, 2016. **3**(2): p. 10.
8. Shamsaei, H., O. Jaafar, and N. Basri, *Effects Residence Time to Water Quality in Large Water Distribution Systems.* Engineering, 2013. **05**: p. 449-457.
9. Jon Kristian Rakstang, M.B.W., Marius Møller Rokstad, Cynthia Halle,, *Demonstrating the potential of salt tracer studies to improve Norwegian drinking water network models and water age estimates.* Vann, 2021. **56**(01): p. 61-69.
10. Rakstang, J.K., *Modeling of Water Age in the Drinking Water Distribution System of Trondheim Kommune*, in *Department of Civil and Environmental Engineering*. 2020, Norwegian University of Science and Technology.
11. Statistisk Sentralbyrå. *Kommunefakta Trondheim*. 2021 [cited 26.10.2021; Available from: https://www.ssb.no/kommunefakta/trondheim.
12. Statistisk Sentralyrå. *Norges 100 mest folkerike kommuner*. 2021 [cited 26.10.2021; Available from: https://www.ssb.no/befolkning/artikler-og-publikasjoner/norges-100-mest-folkerike-kommuner?tabell=446939.
13. Trondheim Kommune, *Kommunedelplan for vannforsyning 2017 - 2028*. 2017.
14. Statistisk Sentralbyrå. *Kommunefakta Melhus*. 2021 [cited 26.10.2021; Available from: https://www.ssb.no/kommunefakta/melhus.
15. Statistisk Sentralbyrå. *Kommunefakta Malvik*. 2021 [cited 26.102021; Available from: https://www.ssb.no/kommunefakta/malvik.
16. Lovdata, *Forskrift om sammenslåing av Klæbu kommune og Trondheim kommune til Trondheim kommune, Sør-Trøndelag*. 2017.
17. Statistisk Sentralbyrå. *Population*. 2021 [cited 27.10.2021; Available from: https://www.ssb.no/en/statbank/table/06913/.
18. Norges Geologiske Undersøkelse (NGU), *Grunnvannsundersøkelser for Klæbu nye vannverk på Fremo i Melhus kommune.* 2000.
19. VVSakutuelt. *NORGES BESTE DRIKKEVANN*. 2006 [cited 27.10.2021; Available from: https://www.vvsaktuelt.no/norges-beste-drikkevann-70598/nyhet.html.
20. Trondheim kommune, *METROVANN-PROSJEKT TEKNISK BESKRIVELSE.*
21. Trondheim Kommune, *VIKELVDALEN VANNBEHANDLINGSANLEGG VIVA*. 2007.
22. Trondheim Kommune. *Drikkevannskvalitet*. 2021 [cited 26.10.2021; Available from: https://www.trondheim.kommune.no/tema/veg-vann-og-avlop/vann-og-avlop/om-vann-og-avlop/drikkevannskvalitet/.
23. Susanne Hyllestad, *Drinking water in Norway*. 2017, Norwegian Institue of Public Health.
24. VA-Norm, *VA-Norm Trondheim Kommune*, VA-Norm, Editor.
25. Standard Norge, *Norsk Standard NS-EN 805. Vannforsyning. Krav til systemer og komponenter utenfor bygninger (Water supply. Requirements for systems and components outside buildings)*. 2000, Standard Norge.
26. Flemming, H.-C., S.L. Percival, and J.T. Walker, *Contamination potential of biofilms in water distribution systems.* Water Supply, 2002. **2**(1): p. 271-280.
27. Waak, M.B., et al., *Occurrence of Legionella spp. in Water-Main Biofilms from Two Drinking Water Distribution Systems.* Environmental Science & Technology, 2018. **52**(14): p. 7630-7639.

28. van der Kooij, D., et al., *Distributing drinking water without disinfectant: highest achievement or height of folly?* Journal of Water Supply: Research and Technology-Aqua, 1999. **48**(1): p. 31-37.
29. United States Environemental Protection Agency. *Our Mission and What We Do*. 02.07.2021 [cited 03.11.2021; Available from: https://www.epa.gov/aboutepa/our-mission-and-what-we-do.
30. NRK, *Forurenset drikkevann og sykdomsutbrudd på Askøy*, in *NRK*. 2019: ww.nrk.no.
31. Trondheim Kommune, *Drikkevann – en livsviktig ressurs. Om vannforsyningen i Trondheim kommune.*
32. DiGiano, F.A., W. Zhang, and A. Travaglia, *Calculation of the mean residence time in distribution systems from tracer studies and models.* Journal of Water Supply: Research and Technology-Aqua, 2005. **54**(1): p. 1-14.
33. Trondheim Kommune. *Drikkevannskvalitet 2020*. 2020 [cited 07.11.2021; Available from: https://docs.google.com/spreadsheets/d/e/2PACX-1vQ_I9PksZTy13PIUmkhwtlVsw8e4w_i7g2h2rb6kWpSANDjt870ncDOInlDnvcwQmDI3LROyxIynuRH/pubhtml.
34. Hach Company. *Hach Company*. [cited 04.12.2021; Available from: https://www.hach.com/about.
35. Hach Company. *Hach Methods Quick Reference Guide*. 2020 [cited 04.12.2021; Available from: https://www.hach.com/quick.search-download.search-en.jsa?keywords=quick+reference+guide.
36. Hach Company. *Copper Porphyrin Method 8143, Powder Pillows, DOC316.53.01038*. 2014 [cited 04.12.2021; Available from: https://www.hach.com/quick.search-quick.search.jsa?keywords=DOC316.53.01038.
37. Hach Company. *Aluminum, Eriochrome Cyanine R Method 8326 Powder Pillows, DOC316.53.01003*. 2021 [cited 04.12.2021; Available from: https://www.hach.com/quick.search-quick.search.jsa?keywords=DOC316.53.01003.
38. Norwegian University of Science and Technology. *ICP-HR-MS Lab*. [cited 04.12.2021; Available from: https://www.ntnu.edu/chemistry/research/icp-hr-ms.
39. Scikit-learn. *Scikit-learn*. [cited 05.12.2021; Available from: https://scikit-learn.org/stable/index.html.
40. Brownlee, J. *How Much Training Data is Required for Machine Learning?* 2017 [cited 19.12.2021; Available from: https://machinelearningmastery.com/much-training-data-required-machine-learning/.

NTNU
Norwegian University of
Science and Technology

Appendix 1

Term Paper

Tracer Study to Determine Hydraulic Residence Time in Drinking Water Distribution Systems – a Review

TVM4141 - Water and Wastewater Systems, Advanced Course

Department of Civil and Environmental Engineering

November 2021

Sang Munn Kim

Tracer Study, Drinking Water Distribution System, Hydraulic Residence Time, Water Age, Water Quality

Abstract

In the context of asset management in drinking water distribution systems, it is important that the utilities have sufficient information concerning water quality. Hydraulic residence time, also known as water age, is therefore of interest as water degradation in distribution systems have positive correlation with hydraulic residence time. For this reason, the utilities need a method that can be used to gain accurate information about water age in distribution systems. In addition, accurate data about water age is also required to assemble calibrated hydraulic models with regards to water age. However, there are limited information on how to investigate water age in distribution systems. For this paper, a method using tracer/s in drinking water distribution systems to track the flow and age of the water, commonly called tracer study, have been investigated to explore how the method can be utilized to find hydraulic residence time in distribution systems. Three different tracer studies performed in various drinking water distribution systems in North America have been investigated and reviewed. All of the three studies performed tracer study for the purpose to investigate hydraulic residence time in the distribution system. Although no standards exist for performing tracers study in distribution systems, a similar methodology were observed between the three studies. Different approaches utilized in the three studies were compared with each other and assessment on which approach is preferable was made. With basis on the three studies, a general guide on how to perform tracer study in drinking water distribution systems is suggested in this paper. Typical challenges when performing a tracer study and limitations of tracer studies is also presented.

Table of Contents

1. Introduction

Tracer study in the context of drinking water distribution systems (DWDS) involves the process of adding one or several conservative substances to the water in DWDS for a given period to measure changes in concentrations of the tracer/tracers in the locations of interest within the DWDS (Haestad et al., 2004). The purpose of a tracer study is to gather data regarding hydraulic residence time, flow path or identifying water source in the DWDS. The gathered data can then be furthered utilized to calibrate water distribution models (WDMs). WDMs are often used by water utilities, and it is regarded as an important tool in asset management. One of the main applications of WDMs is to simulate the behavior of the real DWDS to assess an aspect of the system that are of interest. The benefit is that the simulations can be used to foresee any reactions of the system to various events without disturbing real operation of DWDS (Haestad et al., 2004). It also makes it possible to test for scenarios or events that are not practicable or feasible to perform in the real DWDS. For the WDMs to have any value however, the results that are produced from the simulations have to be assumed correct. WDMs are essentially mathematical representation of fluid dynamics that occurs in a system such as a DWDS. Therefore, the accuracy and the confidence of WDMs relies on the accuracy of the inputs. To confirm the validity of the model, comparison of model predicted vs. field measures are often used. Discrepancies then reveals how accurate the model is able to represent the dynamics in the real system. To improve the model, adjustments can be made so that any discrepancies are minimized between the predicted result and the field measurements. This process is called calibration and it is an important process to increase the confidence of any simulation results produced by WDMs (Haestad et al., 2004).

Water utilities have the important responsibility of ensuring safe water is provided to consumers and WDMs can be a viable tool for the utilities as it can be used for water quality modeling. Water quality modeling makes it possible for utilities to assess the state of water quality in DWDS for various conditions. However, typical WDMs are assembled for the purpose to run hydraulic simulations with pressure and flow data as the primary interest. Therefore, these models are typically calibrated by first gathering pressure and demand data from the real DWDS. Roughness coefficient of pipes in the model are then adjusted so that the pressure and demand data from the model matches with the observed data (Haestad et al., 2004). Although, this calibration process makes the model well suited to investigate pressure and flow behavior of the DWDS, it makes it less suitable to be used for water quality monitoring (Boccelli et al., 2004; Haestad et al., 2004). Hence, in order to assemble WDMs that are useful for water quality monitoring, an alternative calibration method have to be applied, where data that are more related to water quality are collected.

There are many parameters that can be assessed in the context of water quality in DWDS, but hydraulic residence time, also known as water age, gives an overall indication of the water quality. Various studies have shown that there are positive correlation between water age and degradation in water quality in DWDS (Blokker et al., 2016; US Environmental Protection Agency, 2002). Assessing water age gives a general picture of water quality in DWDS, offering a relatively simple method to control water quality for the utilities. Assembling WDMs that can give an accurate result of water age in the DWDS offers the utilities a method to assess the water quality with ease, allowing to e.g. locate areas where water age is high and have low disinfectant residuals (Digiano et al., 2005). For this purpose, tracer studies are relevant as it can be used to determine water age and flow path in DWDS that can further be used for the calibration step.

There exist limited amount of papers that have performed large scale tracer study in a DWDS for the purpose of finding hydraulic residence time. In this paper, three existing papers regarding this topic were selected and assessed. The main objective was to explore how a tracer study could be used to find water age in a DWDS. Following research questions was raised and attempted to be answered:

- How can tracer studies be used to determine hydraulic residence time?
- What are the typical steps and criteria in a tracer study?
- What are the typical challenges of performing a tracer study?

2. Tracer Study

As mentioned, there are limited amount of existing papers that have performed tracer study in DWDS to determine hydraulic residence time. Among the existing papers, degrading water quality in relation to time was a common motivation to perform tracer study. More specifically, formation of disinfectant by-product and deterioration of disinfectant residual in relation to time was a common concern and motivation to perform tracer study in DWDS. The three selected tracer studies that are reviewed in this chapter also listed water quality issue in relation to time as the main motivation.

To find the relevant academic papers, search was done in the topic with keywords such as tracer study, hydraulic residence time, water age and water quality. The search was done in the website Google Scholar and Web of Science (*Google Scholar*; *Web of Science,*). After examining several papers in the search results, following papers were deemed most relevant:

1. *Tracer Tests for Network Model Calibration* (Boccelli et al., 2004)
2. *Calculation of the mean residence time in distribution systems from tracer studies and models* (Digiano et al., 2005)
3. *Tracer study to verify hydraulic limits and determine water residence times in a distribution system: Part I* (Delisle et al., 2014)

The three papers differ in methodology, case description and purpose, but common theme for these papers is that tracer study have been performed to determine hydraulic residence time. A short summary of the case and methodology for the three papers are made in the following subchapters.

2.1 *Tracer Tests for Network Model Calibration* (Boccelli et al., 2004)

This study was a dual tracer study where two tracers were utilized. The main motivation behind the tracer study for this paper was to gather more relevant information to better calibrate hydraulic models in regard to hydraulic residence time. The location of the study area was not disclosed. The size of the distribution network or how many consumers the DWDS was providing were also not disclosed. The relevant DWDS was an independent system with no connection to other DWDS and consisted of one drinking water treatment plant. In the treatment plant, saturated NaCl solution was injected in several pulses and the existing fluoride feed was stopped for duration of 24hrs. This created a subsequent increase in conductivity in water as a result of increase in NaCl and drop of fluoride in the water. Throughout the DWDS, sampling points was established where continuous recording of conductivity and fluoride concentration was measured. When the expected conductivity pulse had arrived and had completely passed, the monitoring ceased. Based on the time from the initial injection/removal of NaCl/fluoride to the arrival of conductivity pulses/drop in fluoride concentration, hydraulic residence time was determined for sampling points throughout the DWDS. Afterwards, the results was used to manually calibrate the relevant WDM by adjusting user demand inputs.

2.2 *Calculation of the mean residence time in distribution from tracer studies and models* (Digiano et al., 2005)

The study's main purpose was to demonstrate that tracer studies can be a simple and cheap method to determine hydraulic residence time in DWDS so that hydraulic models can be better calibrated with regards to water age. To demonstrate, two tracer study was performed in the DWDS in Raleigh (serving 250,000) and Durham (serving 190,000), North Carolina, USA. The study also showcased the use of tracer study to calculate mean residence time. Mean residence time was presented as the average time ''water parcel'' takes to travel from water treatment plant (WTP) to sampling points.

The DWDS in Raleigh had one treatment plant where the fluoride feed was turned off for 5 days. Subsequent concentration drop in fluoride was measured in 20 sampling stations and mean residence time were calculated for the sampling points. A hydraulic model made by the utilities in Raleigh was used to predict water age. The result from field measurements were compared with the predicted water age to reveal any inaccuracies of the hydraulic model.

Two WTP were present in the Durham DWDS; Brown WTP and Williams WTP. During the experiment, Brown WTP switched chloride to alum as the coagulant. This decreased the concentration of CL^{-} and increased the concentration of SO_4^{-2}. The fluoride feed on both WTP was shut down for the experiment. This setting was maintained for 7 days. 10 sampling points was established and responses in the three tracers CL^{-}, SO_4^{-2} and F^{-} were measured. The measurements were then used to calculate mean residence time in the sampling points.

2.3 *Tracer study to verify hydraulic limits and determine water residence times in a distribution system: part I* (Delisle et al., 2014)

Similar to the studies mentioned above, the purpose of this study was to present a methodology to perform tracer study in DWDS to determine hydraulic residence time. For calculation of mean residence time, the authors utilized the same calculation method presented in the study (Digiano et al., 2005). The study was performed in the DWDS in Quebec City, Quebec, Canada. The DWDS was described to be supplied by one WTP. However, the DWDS was also interconnected with neighboring DWDS in Sainte-Foy, allowing for mixing of water in Quebec City from the two WTP to occur. This meant that while water from Quebec WTP might have low water age, water from adjacent WTP might have high water age, making it challenging to determine the overall water wage. To take this issue into account, an additional experiment was done to determine the limit of Quebec WTP and map where the mixing occurs. This was done by measuring conductivity of water in sampling points and determine the source of water depending on the measured conductivity. This was possible due to the natural difference of conductivity in water from WTP in Quebec City and Sainte-Foy.

For the experiment, fluorosilicic acid solution was injected at the WTP in Quebec City, which dissociated into the compounds tetrafluorosilane and hydrogen fluoride. The concentration of fluoride was then subsequently measured in the established sampling points throughout the DWDS to determine mean residence time. The injection of the tracer lasted for 26hrs and there were in total 60 sampling points totaling in 865 samples.

3. Results, Review and Discussion

The three presented studies showcased that tracer studies are feasible to perform in DWDS. Although there are no guidelines on how to perform a tracer study in DWDS, the three studies all used similar strategy and methodology. From examining the three studies, it can be concluded that a tracer study typically involves injecting one or several chemical substances into the water at WTP, but it can also involve stopping the injection of an existing substance. Fluoride was a common choice of tracer as it was an already utilized compound for water treatment in the relevant WTPs. This allowed the researchers to stop the fluoride feed and use the expected drop in concentration of the fluoride to determine hydraulic residence time. Whether the injection or removal of tracers are preferred, ultimately depends on the context (Delisle et al., 2014). The injection/removal of the tracers were performed in WTPs in all three studies. This was mainly because there was an interest to determine hydraulic residence time of water produced in WTPs. However, if the interest was to determine hydraulic residence time of water released from a storage tank, the same method used in the studies could have been applied.

As we have seen, the three chosen papers have used both injection and removal of tracers to achieve concentration changes. However, there seems to be an advantage to remove rather than inject a tracer, as injection of tracer makes the control of concentration of the tracer more challenging. Removing tracers such as stopping the fluoride feed at WTPs also allows for the research to skip the process of producing tracer to be injected. This makes the process considerably easier and cheaper as large quantity of the selected tracer are needed because injection is a continuous process that often takes place for long period of time. For instance, in the study by (Boccelli et al., 2004), approx. 2200 gallons of saturated NaCl solution had to be made for injection that lasted 24hrs. Whether the solution was produced at the WTP or produced offsite and then transported to the WTP was not disclosed in the study. If the injection of tracer is desired, due to large volume needed of the tracers, the process can be easier if the production of tracer that are to be injected can be produced in the WTP. The selection of the tracer also largely depends on the context. Aside from looking at the availability of compounds that can be used as a tracer, the tracers also have to be checked whether it is safe to be added to the drinking water. In addition, tracers that can cause a damage, deterioration or impairment of the system should be avoided. Tracer and the concentrations that are needed, have to be confirmed on whether it is expected to be above or below a threshold that are set by the utilities or other authorities.

The DWDS in the studies were fairly large, such as Raleigh DWDS serving 250,000 people and DWDS in Quebec City serving 540,000 people. From the result of the examined tracer studies, adding or removing tracers produced noticeable increase or decrease in concentrations, making it possible to calculate arrival time of the tracers in the sampling points throughout DWDS. This signifies that tracer studies can be performed in large DWDS. In Figure 1, concentration change of the tracers in the Brown WTP in Durham from the study (Digiano et al., 2005) are presented, whilst in Figure 2, measured concentration of tracers in a sampling point close to Brown WTP in Durham are presented. The patterns are the same, showing that same induced concentration change of tracers in WTPs are produced in the sampling point. This indicates that tracers do not dissipate along the way from WTP to sampling points, making it possible to observe and measure concentration of the tracers.

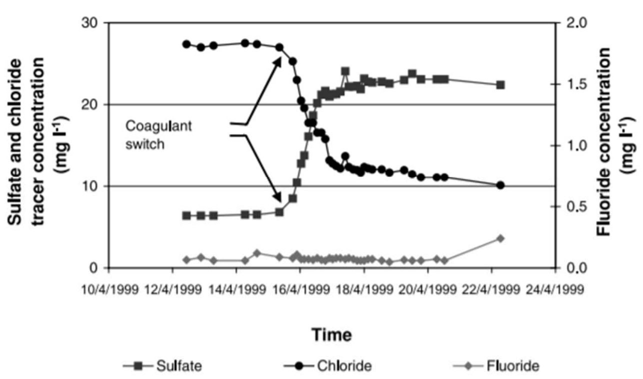


Figure 1. Tracer concentration in the finished water at the Brown WTP in Durham (Digiano et al., 2005).

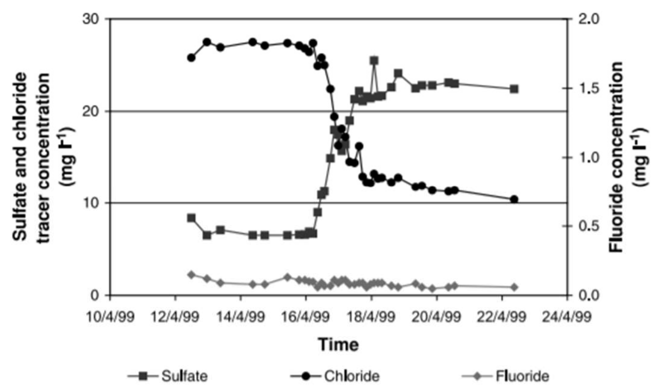


Figure 2. Tracer responses at sampling point nearby Brown WTP in Durham (Digiano et al., 2005).

However, the correspondence of pattern in Figure 1 and Figure 2 shows an extreme case, as the sampling point was fairly close to the WTP. Throughout the three studies, change in concentrations had the tendency to be less noticeable in areas where mixing occurred. Areas far away from the WTPs also had the tendency to produce patterns of concentration change that were less similar to the induced concentration change in the WTPs. Regardless, for all three studies, concentration changes in the sampling points were noticeable enough to determine hydraulic residence time.

From observing the methodology and the results presented in the three examined studies, summarization of answers to the research question that were made in the start of this paper are presented below.

1. How can tracer studies be used to determine hydraulic residence time?

Hydraulic residence time is determined by adding or removing a selected tracer compound in the drinking water, typically at the WTP. The purpose is to increase or decrease noticeable amount of concentration of the tracer compound in the water so that the change in the concentration can be detected and measured in the established sampling points. Hydraulic residence time is determined by measuring the time between addition/removal of tracer compounds at starting point and detection of concentration change in the sampling points.

2. What are the typical steps and criteria in a tracer study?

Typical steps consist of determining what compound to use as tracers, establishing sampling points where measurements of the tracers can be made and gather data from the measurements to calculate hydraulic residence time. The methods are highly contextual and can be limited by the condition or settings that are present in the DWDS and WTP. For instance, NaCl as a tracer might not be feasible in a DWDS that already has a high NaCl concentration if addition of NaCl can cause the concentration to be above a regulatory concentration limit. There are no standardized steps or criteria to follow when performing tracer studies as preexisting guidelines or standards does not exist. From the three studies, tracer study was performed by first establishing what compound/s to use as tracer/s and then establishing sampling points within the DWDS. The tracers was chosen on the criteria that:

- It is safe to consume
- It is conservative
- The concentration needed is within preexisting guidelines
- Does not damage materials in the DWDS.

Whether the tracers are injected or removed have to be determine based on the existing operation settings of the WTP and DWDS. It is easier to temporarily stop adding compounds that are used in water treatment such as fluoride for tracer study given that it is feasible, but this is contextual and has to be decided case to case

3. What are the typical challenges of performing a tracer study?

Typical challenges in tracer studies are production of tracers as a there is a need to inject large amount of tracers. Therefore, there are significant advantage if the tracers can be produced onsite at the WTP or if this process can be skipped all together by just stopping the feed of an existing compound that can be used as a tracer in the WTP. Tracer studies are more challenging in DWDS where there are more than one WTP. This is because water from the WTPs mixes with each other throughout DWDS, making it more challenging to determine the overall water age. In situations like this, several tracers can be utilized to differentiate ‘’water parcel’’ from one WTP to another. Limitation of tracer study is that it only gives a hydraulic residence time for the specific demand setting when the experiments are performed. This is due to hydraulic residence time in DWDS depends on user demands. Therefore, water age can vary between weekdays and weekends, and there can even be seasonal variations of water age. However, this is not a problem if the purpose of the tracer study is to gather more data to better calibrate a hydraulic model.

4. Conclusion

There are limited amount existing studies that have attempted tracer study in DWDS. The studies that have performed tracer study have demonstrated that a tracer study can be used to determine hydraulic residence time, even in large DWDS. The purpose to perform tracer study can be varied, but typical reason can be to get a better understanding of water age DWDS and gather data to calibrate and assemble a hydraulic model that can simulate more accurate water age and other water quality parameters that are dependent on reaction time in water. There are no specific methods to perform a tracer study in DWDS, but same general methodology were observed in the examined tracer studies. There seems to be an advantage of temporarily altering operation in WTP to create a tracer. From the studies, turning off the fluoride feed at WTP was commonly used, but switching coagulants at WTP to create a concentration change or injecting brine have also been observed. In general, decreasing concentration of the tracer by removing existing compound at WTP is preferred rather than injection of a new compound. Challenges regarding production of tracer and maintaining correct concentration level of tracers are some reasons. Sampling points where mixing of water from more than one WTP occurs can create a distorted picture of concentration change, making it harder to observe whether the tracer/s from WTP have arrived or not. This issue can however be solved if each WTPs uses unique tracer to distinguish their water from each other.

References

Blokker, E. J. M., Furnass, W. R., Machell, J., Mounce, S. R., Schaap, P. G., & Boxall, J. B. (2016). Relating Water Quality and Age in Drinking Water Distribution Systems Using Self-Organising Maps. *Environments*, *3*(2), 10. https://www.mdpi.com/2076-3298/3/2/10

Boccelli, D., Shang, F., Uber, J., A, O., D, M., S, H., M, M., J, S., Blount, B., & F, C. (2004). *Tracer Tests for Network Model Calibration*. https://doi.org/10.1061/40737(2004)449

Delisle, F.-J., Rochette, S., Pelletier, G., & Rodriguez, M. J. (2014). Tracer study to verify hydraulic limits and determine water residence times in a distribution system: Part I. *Journal of Water Supply: Research and Technology-Aqua*, *64*(3), 365-377. https://doi.org/10.2166/aqua.2014.050

Digiano, F., Zhang, W., & Travaglia, A. (2005). Calculation of the mean residence time in distribution systems from tracer studies and models. *Journal of Water Supply: Research and Technology - AQUA*, *54*. https://doi.org/10.2166/aqua.2005.0001

Google Scholar. https://scholar.google.com/

Haestad, M., Walski, T., Chase, D., Savic, D., Grayman, W., Backwith, S., & Koelle, E. (2004). Advanced Water Distribution Modeling and Management. In.

US Environmental Protection Agency. (2002). Effects of Water Age on Distribution System Water Quality. https://www.epa.gov/sites/default/files/2015-09/documents/2007_05_18_disinfection_tcr_whitepaper_tcr_waterdistribution.pdf

Web of Science,. https://www.webofscience.com/wos/woscc/basic-search

NTNU

Norwegian University of
Science and Technology