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Per- and polyfluoroalkyl substances (PFAS) in the Hammarby groundwater reservoir

Evaluation of potential sources using particle tracking

Sabina Broström

Civilingenjörsprogrammet i miljö- och vattenteknik

Per- and polyfluoroalkyl substances (PFAS) in the Hammarby groundwater reservoir - Evaluation of potential sources using particle tracking

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Abstract

High levels of per- and polyfluoroalkyl substances (PFAS) have been detected in the Hammarby aquifer in Norra Stockholmsåsen. These levels exceed the new regulations concencering drinking water from the Swedish National Food Agency (LVSFS 2022:22) that will become mandatory on January 1, 2026. The cause of these high levels is unknown. PFAS is an artificially made substance that is difficult to break down and therefore remains in the environment and in humans for a long time, where it has been shown to have harmful health effects.

The purpose of this report is to evaluate the occurrence and potential sources of PFAS in the Hammarby groundwater reservoir in the Northern Stockholm Esker. The questions posed are: What sources contribute to the elevated PFAS concentrations observed in the groundwater reservoir? What additional information and data would be needed to confidently identify the primary sources responsible for PFAS contamination in the reservoir?

To investigate this, groundwater analyses have been conducted, a literature review on activities that release PFAS has been performed, and the distribution of PFAS was evaluated using particle tracking from potential sources with the help of a groundwater model developed in FEFLOW. This information has then been compiled into a scoring system for the potential sources.

The results indicate that it is difficult to definitively determine what contributes to the elevated levels of PFAS in the groundwater. A fire station and a landfill site located on the groundwater reservoir are important sources of PFAS. In particle tracking from these activities, the particles moved quickly to the groundwater reservoir and passed several of the observation wells where PFAS has been measured. The PFAS found in the groundwater can be connected to both landfill sites and fire stations in other studies.

There are several other activities that are positioned such that the particles in the particle tracking quickly reach the groundwater reservoir and pass several of the locations where PFAS has been detected. These activities include engineering industries, metal surface treatment, electrical engineering industry, and intermediate storage and sorting stations for waste. However, there is a lack of information on what exact PFAS these activities release and in what quantities. It may also be historical usage that spreads further from soil contamination. Furthermore, the use and handling of PFAS in all these industries would need to be investigated to ensure whether they contribute to PFAS emissions to the groundwater.

Teknisk-naturvetenskapliga fakulteten

Uppsala universitet, Utgivningsort Uppsala

Handledare: Fritjof Fagerlund Ämnesgranskare: Georgios Niarchos

Examinator: Fritjof Fagerlund

REFERAT

Per- och polyfluoralkylsubstanser (PFAS) i Hammarby grundvattenmagasin - Utvärdering av potentiella källor med hjälp av partikelspårning

Sabina Broström

I grundvattentäkten Hammarby i Norra Stockholmsåsen har höga halter av per- och polyflourerade alkylsubstanser (PFAS) uppmätts. Dessa halter överskrider de nya föreskrifterna från Livsmedelsverket som berör gränsvärden för dricksvatten (LVSFS 2022:22) som blir krav 1 januari 2026. Vad som orsakar dessa höga halter är okänt. PFAS är ett ämne som är svårt att bryta ned och stannar därför länge i naturen och i människan, där ämnet har visat sig ha skadliga hälsoeffekter.

Syftet med denna rapport är att utvärdera förekomst och potentiella källor till PFAS i Hammarby grundvattenmagasin i Norra Stockholmsåsen. De frågor som ställs är; vilka källor bidrar till de förhöjda PFAS-koncentrationerna som observerats i grundvattenmagasinet? Vilken ytterligare information och data skulle behövas för att med säkerhet kunna identifiera de huvudsakliga källorna som är ansvariga för PFAS-föroreningarna i magasinet?

För att undersöka syftet har analyser av grundvattnet gjorts, en litteraturstudie på vilka verksamheter som släpper ut PFAS samt partikelspårningar från de potentiella källorna i grundvattenmagasinets modell i FEFLOW. Denna information har sedan sammanställts i ett poängsystem för de potentiella källorna.

Denna uppsats pekar på att det är svårt att med säkerhet avgöra vad det är som bidrar till de förhöjda halterna av PFAS i grundvattnet. En brandstation och en avfallsdeponi placerade på grundvattenmagasinet är troliga källor till PFAS. I partikelspårningen från dessa verksamheter rörde sig partiklarna snabbt till grundvattenmagasinet och tog sig förbi flertalet av de punkter där PFAS har uppmätts. Andra studier har hittat PFAS ämnen kring dessa typer av verksamheter som även hittats i grundvattenmagasinet Hammarby.

Det finns flera andra verksamheter som är placerade så att partiklarna i partikelspårningen snabbt når till grundvattenmagasinet och passerar flera av platserna där PFAS detekterats. Dessa verksamheter är verkstadsindustrier, ytbehandling av metaller, elektroteknisk industri och mellanlagring och sorteringsstation av avfall. Det saknas däremot information om vilka PFAS ämnen dessa verksamheter släpper ut samt mängd. Det kan även vara historisk användning som sprids vidare från markföroreningar. Vidare skulle användningen och hanteringen av PFAS på alla industrierna behöva undersökas för att säkerställa om de bidrar med utsläpp av PFAS till grundvattnet.

Nyckelord: PFAS, grundvatten, FEFLOW

Sveriges Lantbruksuniversitet, SLU, Lennart Hjelms väg 8, 756 51 Uppsala

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POPULÄRVETENSKAPLIG SAMMANFATTNING

Denna studie har undersökt höga halter av per- och polyfluorerade alkylsubstanser (PFAS) i grundvattenmagasinet vid Hammarby i Stockholmsåsen samt utvärderat vilka verksamheter som bidrar till dessa förhöjda halter. PFAS är ett syntetiskt framställt ämne som har olika egenskaper och finns i flertalet produkter som människor använder dagligen. PFAS-ämnen är svåra att bryta ner vilket gör att de stannar länge i naturen och kan stanna i kroppen upp till 15 år. Ämnet har starka vattenbindande egenskaper vilket har bidragit till att grundvattenmagasinet Hammarby i Stockholmsåsen har blivit kontaminerat.

Den 1 januari 2023 trädde Livsmedelsverkets nya föreskrifter i kraft, där gränsvärden för PFAS anges och börjar gälla den 1 januari 2026. Enligt dessa föreskrifter får dricksvatten inte innehålla mer än 4 ng/l av PFAS 4 och 100 ng/l av PFAS 21. I grundvattnet i Hammarby grundvattenmagasin i Norra Stockholmsåsen överskrids dessa gränsvärden på flertalet ställen. Grundvattnet från Hammarby används som reserv till dricksvattnet om problem skulle uppstå i det vanliga vattenverket eller sjön där vattnet extraheras ifrån. Grundvattnet förväntas vara drickbart när det tas ut och inte behöva rening.

För att undersöka källan till de höga halterna av PFAS i grundvattnet analyserades PFAS i grundvattnet samt kartlades vilka verksamheter som visat sig släppa ut PFAS. Partikelspårning från dessa verksamheter, som misstänks bidra till föroreningen, genomfördes också. PFAS-halter i grundvattnet mättes vid tre olika tillfällen åren 2019, 2022 och 2024. Därefter analyserades kompositionen och halterna för att koppla ämnena till specifika verksamheter.

För att identifiera potentiella föroreningskällor undersöktes verksamheter som listats med PFAS-föroreningar i Naturvårdsverkets Branschlista. En litteraturstudie genomfördes för att fastställa vilka specifika PFAS-ämnen som dessa verksamheter släpper ut. Med hjälp av en modell över Hammarby grundvattenmagasin i FEFLOW utfördes partikelspårning från de misstänkta källorna. Detta innebar att partiklar släpptes vid verksamhetens placering och deras flödesvägar i den modellerade åsen analyserades. Utifrån dessa analyser drogs slutsatser om vilka verksamheter som sannolikt bidrar mest till de förhöjda PFAS-halterna i grundvattnet.

Baserat på resultaten visade det sig att de verksamheter som bedömdes ha störst inverkan var en brandstation och en avfallsdeponi, vilka båda är belägna ovanför grundvattenmagasinet. Däremot finns det idag ingen vetskap om dessa verksamheter släpper ut PFAS från deras anläggningar och därför kan inga säkra slutsatser dras om att de bidrar till de förhöjda halterna av PFAS i grundvattnet. Andra källor som verkstadsindustrier, ytbehandling av metaller, elektroteknisk industri och mellanlagring och sorteringsstation av avfall kan också vara bidragande då flertalet av de ligger placerade på grundvattenmagasinet men inga utsläpp från dessa har kunnat kopplas ihop med de uppmätta PFAS halterna i grundvattnet vilket gör att det inte är en stor säkerhet i att de påverkar. För att mer säkert kunna avgöra vad som bidrar till de förhöja halterna av PFAS skulle verksamheter behöva undersökas djupare och se vad de använder för PFAS och om det finns risk att de släpps ut till grundvattnet.

CONTENT

1. INTRODUCTION

Per- and polyfluoroalkyl substances (PFAS) have been used in a wide range of applications since the 1950s (OECD 2015). The unique physicochemical properties of PFAS that contributed to their widespread use are also linked to environmental and human health concerns. These substances are found to be persistent, toxic, and bioaccumulative. People globally can be exposed to PFAS through the environment, food items, and biota (OECD 2015). PFAS are found in products used in our everyday lives, for example, umbrellas, popcorn bags, sunscreen, and firefighting foam (Kemikalieinspektionen 2023). A lot of PFAS can be used for their grease, water, and dirt-repellant properties (Kemikalieinspektionen 2023). When people are exposed to PFAS, it can lead to various health effects, such as decreased fertility, developmental delays in children, several types of cancer, increased cholesterol, and a reduced ability of the body’s immune system (US EPA 2021). In Sweden, the largest emission source of PFAS is the firefighting foam used at training sites, which has contributed to high concentrations locally in groundwater, surface water, and drinking water (Kemikalieinspektionen 2023). But other sources could contribute to the high PFAS such as sewage plants, landfills, and incineration (Kemikalieinspektionen 2023).

Norrvatten, a municipal association, has discovered relatively high concentrations of PFAS in the aquifer used for groundwater production in Hammarby, Norra Stockholmsåsen[1]. The concentrations are relatively high for drinking water according to Livsmedelsverkets guidelines. It is unknown what has caused the high concentrations in the groundwater in Hammarby. The aquifer is not continuously pumped for large-scale groundwater production but is an important backup to drinking water used by the Norrvatten drinking water company (ibid). Norrvatten delivers their produced drinking water to 14 municipalities that are members (Norrvatten n.d.c), which is about 700,000 individuals (Norrvatten n.d.a). The drinking water extracted from Lake Mälaren is purified at Görvälnverket (Norrvatten n.d.a) and transported to the municipal water supply system (Norrvatten n.d.c). The municipalities that are members of Norrvatten are located in the north of Stockholms County, with the most northern municipality being Norrtälje followed by Knivsta and the most southern members are Solna and Sundbyberg (Norrvatten n.d.c). Norrvatten has Norra Stockholmsåsen groundwater as a reserve for the drinking water supply if any problem occurs at the water plant, Görvälnverket, or the lake, Mälaren, where they extract the water from (Norrvatten n.d.d). Norra Stockholmsåsen is an esker that extends from Sigtuna to Solna. An esker is an important ecosystem service that purifies the water naturally through its different layers, a process that cannot be re-created by humans (Norrvatten n.d.d).

The high concentrations of PFAS in Hammarby, Norra Stockholmsåsen, exceed the new regulations of PFAS in drinking water which goes into effect in January 2026 (LIVSFS 2022:12). Since January 2023 they are applied as guidance values (LIVSFS 2022:12). These regulations are 4 ng/l for the sum of four PFAS (PFOS, PFOA, PFNA, and PFHxS) called PFAS 4 and 100 ng/l for the sum of 21 PFAS called PFAS 21 (LIVSFS 2022:12). The substances included in PFAS 21 can be found in Appendix. The concentrations of PFAS 4 in the groundwater in Hammarby go from 0 to over 30 ng/l as seen in Figure 1. A majority of the measurements of PFAS 4 are above the regulation 4 ng/l. PFAS 21 has also been measured above the regulation, 100 ng/l, as seen in Figure 2. The esker’s ecosystem and the drinking water that it produces are vital to protect, therefore operations emitting PFAS must take action to minimize the leakage into the environment (Norrvatten n.d.b).

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[1] Helene Ejhed, environmental engineer, Norrvatten, meeting 2023-12-20

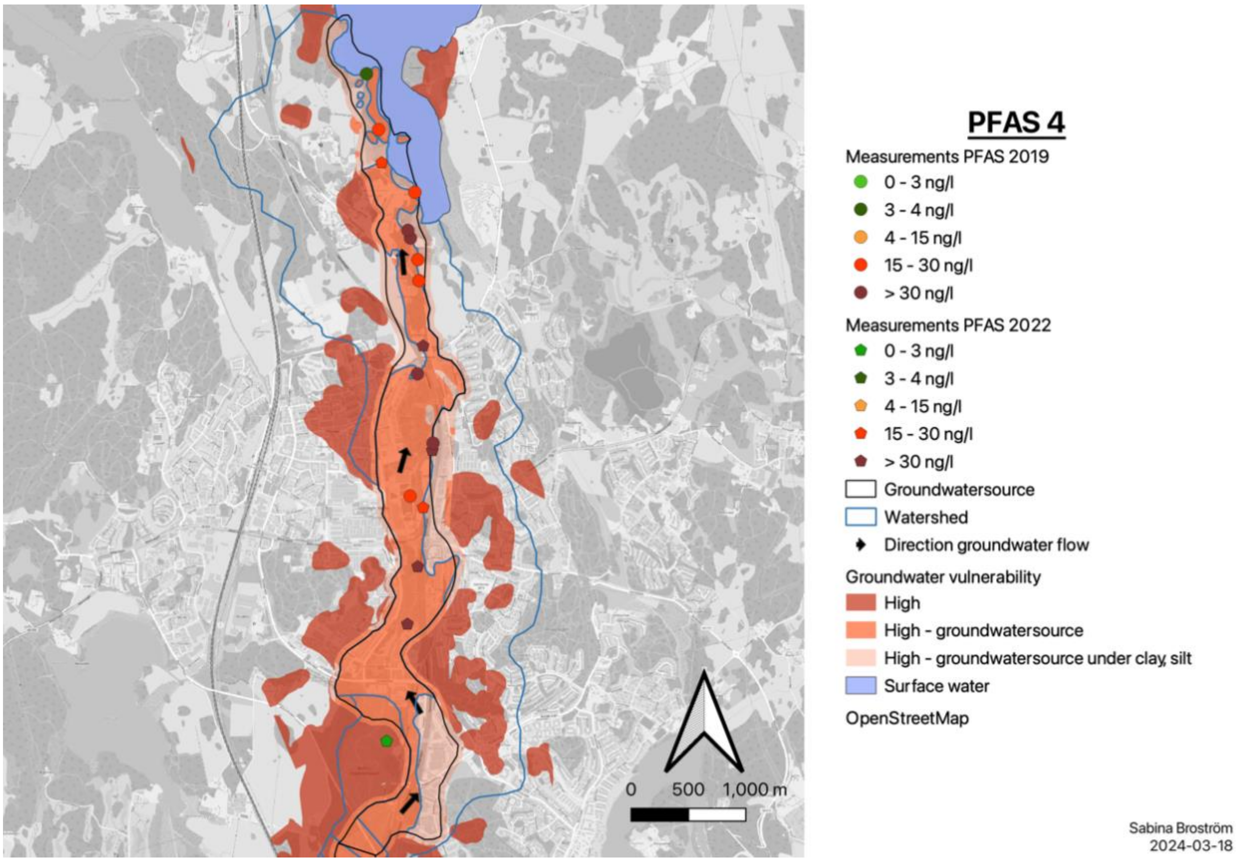

Figure 1: A map of Upplands Väsby and the esker located in the municipality. The concentrations of PFAS 4 from measurements done in 2019 and 2022 are presented together with the groundwater aquifer, its vulnerability, and flow direction.

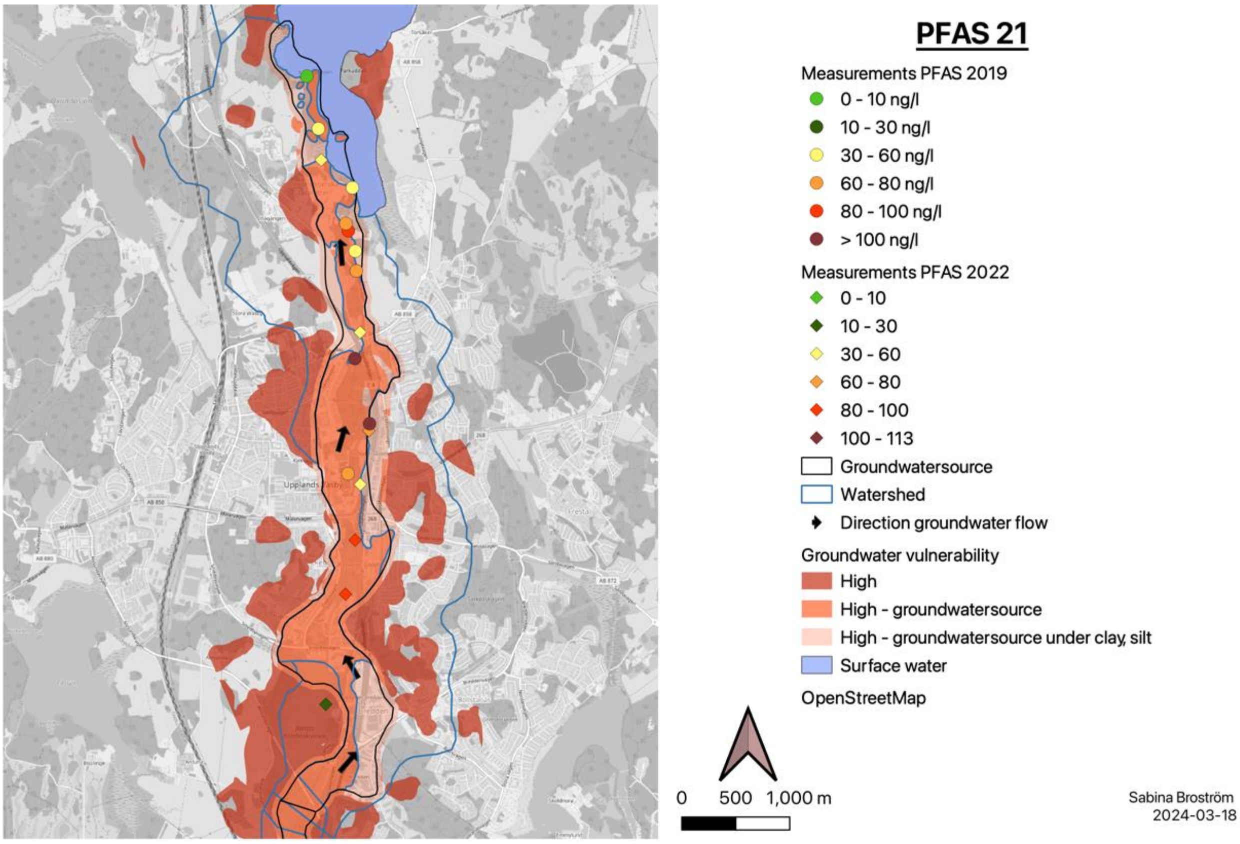

Figure 2: A map of Upplands Väsby and the esker located in the municipality. The concentrations of PFAS 21 from measurements done in 2019 and 2022 are presented together with the groundwater aquifer, its vulnerability, and flow direction.

1.1. Aim & research questions

The purpose of the thesis was to acquire knowledge about what potential sources are contributing to the load and distribution of PFAS in Hammarby's aquifer. This knowledge can be used to identify specific locations that should be further investigated and might require treatment to protect the groundwater aquifer from PFAS contamination. The researched questions addressed were:

- Which sources contribute to the elevated PFAS concentrations observed in the groundwater aquifer?
- What further information and data would be needed to confidently be able to identify the predominant sources responsible for PFAS contamination of the aquifer?

2. THEORY

2.1. PFAS

PFAS stands for per- and polyfluoroalkyl substances and are also known as highly fluorinated substances (Kemikalieinspektionen 2023). PFAS are defined as substances that are fluorinated and carry at least one fully fluorinated methyl, –CF3, or methylene carbon atom, –CF2–, without any bond to hydrogen, bromine, iodine, or chlorine atoms (OECD 2021). The general structure of PFAS consists of hydrocarbon backbones, where some or all hydrogen atoms have been replaced by fluorine (Kemikalieinspektionen 2023), as seen in Figure 3. A perfluorinated substance has a carbon chain in which the hydrogen atoms are completely replaced by fluorine, while in a polyfluorinated alkyl substance, the hydrogen atoms are partially replaced by fluorine. PFAS do not occur naturally; they are synthetically produced (Kemikalieinspektionen 2023).

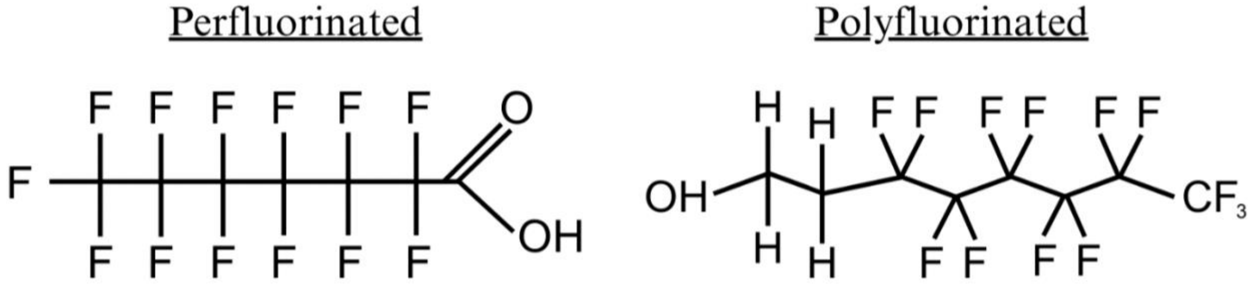

Figure 3: Example of the structure of a perfluoroalkyl substance to the left and the right shows an example of a polyfluoroalkyl substance. Made with inspiration from Swedish Chemicals Agency 2023.

The substances can be divided into two subgroups, non-polymeric and polymeric PFAS (Kemikalieinspektionen 2023). The non-polymeric group often has a functional group connected to the chain of carbon while the polymeric does not. The functional group can for example be a hydroxyl group, -*OH*, or a carboxyl group, -*COOH* (Kemikalieinspektionen 2023). The non-polymeric PFAS has four subgroups while the polymeric has three subgroups (OECD n.d.) as seen in Figure 4.

The length of the carbon chain in the PFAS creates other ways to categorize the substances (Kemikalieinspektionen 2023). Perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA) are long-chained PFAS since they have eight or more carbons in the chain. While perfluorohexanoic acid (PFHxA) and perfluorohexanesulfonic acid (PFHxS) are included in short-chain PFAS since they have 6 carbons (Kemikalieinspektionen 2023). For the subgroup perfluoroalkyl carboxylic acids (PFCA) the long-chain molecules have eight or more carbons and the short-chain ones have fewer than eight carbons (ITRC 2023). Perfluoroalkane sulfonic acids (PFSA) have five or fewer carbons if it is a short-chain, and the long-chain has six or more carbons (ITRC 2023). Both long and short-chained PFAS are manufactured but they can also be degraded from PFAS which are more complex, so-called precursors (AWWA 2019). Today the knowledge about PFAS has reduced the use of long-chain PFAS. Long-chain PFAS are known to bioaccumulate in the human body for a longer time than short-chain PFAS. The long-chain can stay up to 15 years in the human body compared with the short-chain which stays up to 5 years (AWWA 2019).

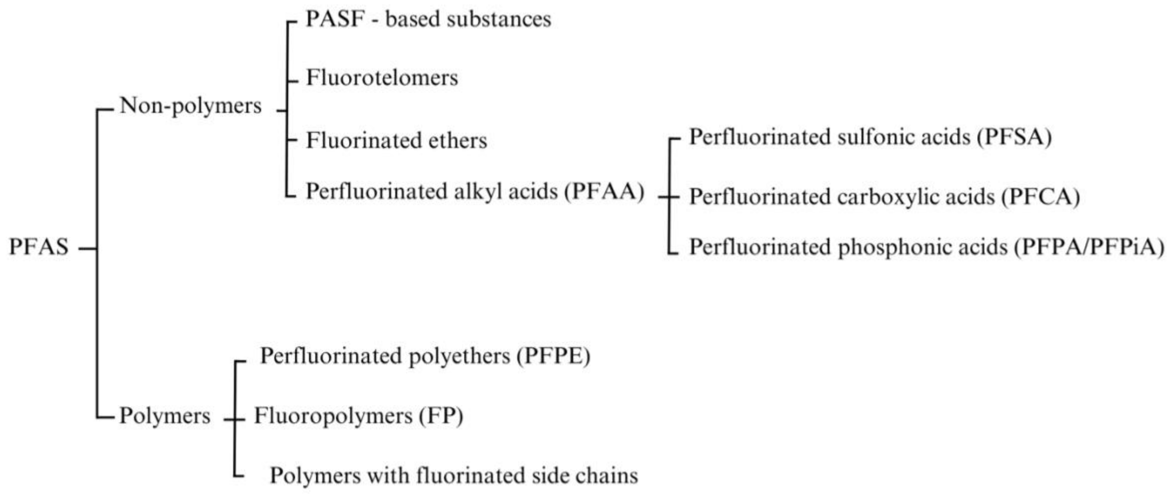

Figure 4: Visual representation of PFAS and its subgroups. Made with inspiration from OECD n.d.

Many PFAS are surfactants, a useful characteristic in cosmetics, ski wax, and detergents (Kemikalieinspektionen 2023). The substances have a distinctive characteristic of building a thin film between a liquid and a surface or two liquids (Kemikalieinspektionen 2023). This is caused by the molecule having one side, the long carbon chain, that is hydrophobic while the other side, the functional group, is hydrophilic. Some of the substances have a group between these two different parts contributing to even more possible variations of PFAS. The molecules are water soluble which together with their resistance to degradation poses a risk to drinking water sources (Kemikalieinspektionen 2023).

Although they can look different on molecule level, they are all difficult to decompose which is caused by the strong bond between carbon and fluorine (Kemikalieinspektionen 2023). Some of the substances can slowly decompose while others cannot be decomposed at all. The different structures of PFAS remain in nature since it has not been proven that it can be completely decomposed (Kemikalieinspektionen 2023). A chemical substance that can decompose into another substance is called a precursor (Kemikalieinspektionen 2021). Many PFAS, both non-polymeric and polymeric, decompose into perfluorinated alkyl acids (PFAA) meaning that PFAA has a lot of precursors. Some of these precursors are PFOSA and FTS which decompose into the PFAA substances PFOS and perfluorocarboxylic acids (PFCA). A contaminated site can often have more precursors than PFAA which makes it important to look for precursors in investigations (Kemikalieinspektionen 2021).

2.1.1. Transport of PFAS

PFAS can spread through different environmental mediums such as air, surface water, soil, groundwater, or stormwater (Kemikalieinspektionen 2021). It can be a complex process to map out how PFAS is transported from a source of emission. This is because of the site specifics and that the substances can have varying properties. Groundwater can be contaminated through soil contamination that is leaching. When soil contamination occurs the PFAS sorption in the soil is dependent on the emission properties and the soil characteristics, such as pH, soil type, grain size distribution, the content of organic material, and the length of the PFAS carbon chain. Usually, there is a higher content of longer PFAS molecules than shorter ones around the emission source (Kemikalieinspektionen 2021).

When the contamination reaches the groundwater through flooding, irrigation, or infiltration of precipitation it can be transported a long way due to its hydrophilic properties (Kemikalieinspektionen 2021). If there has been a long-term emission of PFAS, there can be great plumes in the groundwater. This can affect not only the groundwater long-term but also the surface water connected to it and the sediments that are downstream from the source of emission. How the groundwater affects the distribution of PFAS from the source is dependent on the chemical properties of the substance but also the site specifics. It is important to map out the geological and hydrogeological conditions to see the different possibilities at the site. Normally the plume of emission travels slower than the flow of the groundwater since the molecules of PFAS can stick and be delayed by particles in the soil (Kemikalieinspektionen 2021).

2.2. Legislation of PFAS

Regulation of individual PFAS occurs at different levels, such as globally, within the EU, and nationally, through various legislative frameworks (Kemikalieinspektionen 2023). There is no overarching legislation covering all PFAS; instead, various regulations govern specific PFAS. When new regulations are introduced for an individual PFAS, it is common for it to replace another regulated PFAS. This substitution often does not reduce the overall risk. The combination of these regulations, the extreme difficulty in degrading these substances, and the potential harm they pose, results in a greater overall risk. The Swedish Chemicals Agency and other EU Member States are working together to ensure that PFAS are assessed and regulated as a group, as individual assessments would take far too long (Kemikalieinspektionen 2023)

In the Water Framework Directive developed by the EU (2000/60/EG) water bodies assigned drinking water resources are included with specific regulations. Following the ministerial seminar on groundwater at The Hauge in 1991, the importance of introducing measures to protect groundwater from deterioration over time was presented (Directive 2000/60/EC of the European Parliament and of the Council).

According to the Swedish Food Agency’s regulation on drinking water (LIVSFS 2022:12), the PFAS included in PFAS 4 (PFOS, PFOA, PFNA, and PFHxS) should not exceed 4 ng/l for the water to be classified as clean and healthy. For PFAS 21 (see Appendix for the included substances), the limit is 100 ng/l. These regulations go into effect on January 1, 2026, and since January 1, 2023, they are applied as guidance values (LIVSFS 2022:12).

The drinking water directive (2020/2184) sets a parameter value of 100 ng/l for 20 different PFAS. All but one (6:2 FTS) of the PFAS listed in the new Swedish regulations for drinking water (LVSFS 2022:12) are included in the water directive (2020/2184). Sweden, along with other EU member states, is actively working to establish the lowest possible PFAS threshold value, considering the latest risk evaluation by the European Food Safety Authority (EFSA) for application in the drinking water directive. Sweden is a pioneering country regarding PFAS regulation (Naturvårdsverket 2022). In France, the French Parliament has collectively agreed to a bill that bans the manufacture, import, and sale of certain products containing PFAS, which will go into effect on January 1, 2026 (Amaru & Zarghamee 2024).

In Sweden, there has been a case in the Swedish Supreme Court concerning elevated concentrations of PFAS in groundwater. On December 5, 2023, in case no. T486-23, the Swedish Supreme Court ruled that Ronneby Miljö och Teknik AB is responsible for compensating the residents of Kallinge who sued for personal injury due to high concentrations of PFAS in their blood. The damages include the additional concentrations of PFAS in the blood, which deteriorate the physical characteristics of the body. T486-23 declares that Ronneby Miljö och Teknik AB is responsible for compensating each resident of Kallinge who participated in the proceedings, covering the costs of the litigation. The concentrations of PFAS in the blood of the residents who participated in the proceedings measured between 91 ng/ml and 1,800 ng/ml, which are some of the highest levels measured in populations around the world (T486-23). The levels in the drinking water were measured to very high levels, around ten thousand ng/l (Lagerstedt 2023).

2.3. Sources of PFAS

Potential sources of PFAS in the environment include airports, fire-training sites, fire stations, major fires and accidents involving firefighting foam, oil depots, various industrial operations, ski wax, landfills, treatment plants, and atmospheric deposition (Hansson et al. 2016). Although the composition of firefighting foam has been modified, due to the ban on PFOS in 2011, it remains the most significant source of PFAS in the Swedish environment. At fire-training sites, where firefighting foam has been used frequently for decades, PFAS continue to be released into the surrounding environment, making these sites likely significant sources of PFAS today. According to Hansson et al. (2016), wastewater treatment plants are likely major transport routes for PFAS from society into the environment. There are diffuse emissions from household products, industrial emissions, and leachate from landfills that accumulate in the WWTP (Hansson et al. 2016). In a study about the leakage of PFAS from landfills around Lake Mälaren PFAS was detected at all locations sampled (Hård af Segerstad 2023). The concentration varied with the size of the landfill and the human activity close to the landfills (Hård af Segerstad 2023).

Sources of PFAS can be categorized into three different classes, direct, secondary, and diffuse sources (Kemikalieinspektionen 2021). The direct sources are fire-fighting foam, both managing and storing and operations using PFAS in the manufacturing process. Secondary sources are treatment plants, landfills, and incinerators while the diffuse sources are atmospheric deposition and wear-and-tear of consumer products (Kemikalieinspektionen 2021).

2.3.1. Risk objects

The Swedish Environmental Protection Agency (1999) has developed a methodology for the inventory of contaminated sites (MIFO-objects). This methodology aims to assess not only the contamination that the risk object causes but also the risk that the identified or suspected contaminated site may pose to human health. In the first phase (Sw: Orienterande studier) hypotheses are created for what the risk object's possible pollutants can be, how they disperse from the site, and how the environment and humans can be exposed to the pollutants. In the second phase, called general studies, the hypotheses are tested and discarded or verified. Both phases are finished with a classification of the risks where the risk objects get placed in one of the four different classes of risks. The classification of risks can change between the two phases. The most reliable classification is created in the second phase. The classes tell how hazardous the risk objects are. If the risk object receives *Class 1* it has a very high risk while *Class 4* means a low risk. Responsible for these examinations is the County Administrative Board (Sw: Länsstyrelsen) with support from the municipalities, but other authorities can also perform the investigation (Naturvårdsverket 1999). The risk objects and their class of risk are presented in the EBH-map (EBH stands for remediation action in Swedish) which is found through the county administrative board (Länsstyrelserna n.d.). The risk objects are marked by how far it has come in the process (Statens geotekniska institut 2023). If they have already been classified, they are marked with their class of risk, if they are under the identification process, they are marked with an "*E*" and if a partial action or action has been initiated or completed at the site they are marked as sensitive land use or less sensitive land use. If a property is present on the map it means that it may have caused pollution but it does not mean that the property is contaminated (Statens geotekniska institut 2023).

The Swedish Environmental Protection Agency inventory initiative between year 1999 and 2015 did not include PFAS emissions due to it being recognized first after this initiative started (Naturvårdsverket 2023b). This means that in the EBH map, there may be some potential areas that could be contaminated by PFAS but are not recorded. The Swedish Environmental Protection Agency together with other authorities is commissioned by the government to get a better mapping and overview of how many areas are PFAS contaminated (Naturvårdsverket 2023b).

3. METHODOLOGY

3.1. Site description

The groundwater aquifer investigated in the study, Norra Stockholmsåsen – Hammarby, starts at a groundwater divide in a bedrock area about 1 km north of Edsån in Sollentuna and stretches north to Lake Fysingen north of Upplands Väsby, in a part called Hammarby (Eriksson 2009). The extent and location of the esker is seen in Figure 5. Along the shoreline of Fysingen, the esker forms a beach and then stretches under the water's surface. The length of the aquifer called Hammarby is about 7 km, and its width varies from 200 to 700 meters while the depth of the aquifer is between 10 to 30 meters. The groundwater flow starts in the south and moves towards Fysingen in the north where the groundwater discharges into the lake. Close to the lake, there is a spring which has an outflow of 10–15 l/s. The spring is located 250 meters north of the Hammarby church and is called Hammarby Spring (Eriksson 2009). The groundwater aquifer is used as a reserve for drinking water supply if problems occur at the drinking water treatment plant, Görvälnverket, or in the main source (Norrvatten n.d.d). Some of the water from the esker is used by the hospital Löwenströmska for cooling down the building during the summer (Eriksson 2009).

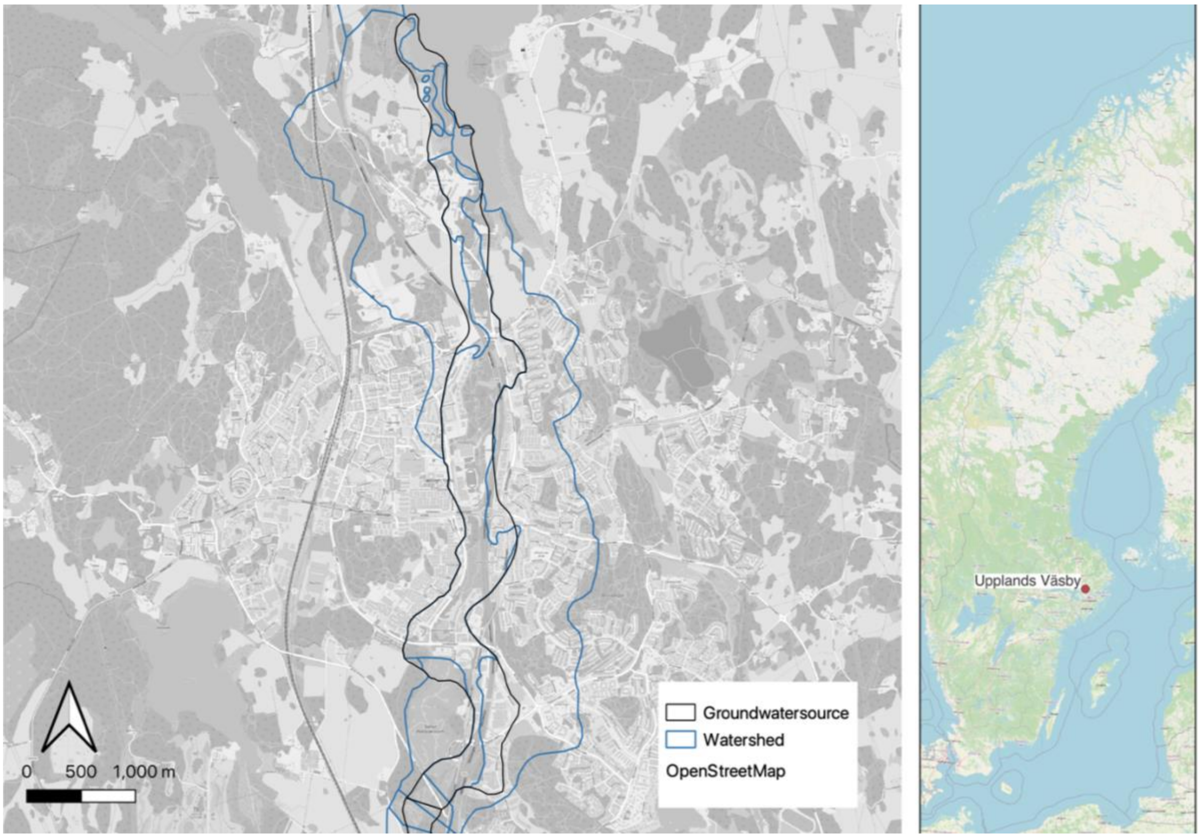

Figure 5: A map showing the extent and location of Norra Stockholmsåsen, Hammarby both on local and national scale.

3.2. Data

Norrvatten has provided three data sets, presented in Excel sheets, from the groundwater of Norra Stockholmsåsen, Hammarby. During 2019 sampling was performed at two occasions in May and September/October and in 2022 one sampling was performed in October/November. The third dataset are PFAS measurements from the groundwater drinking water plant. Here PFAS have been measured 7 different times between September 16, 2017, to February 2, 2024. The analysis of the samples was done by Eurofins. Some of the measured concentrations that are too low have been given the value "below this value" which is interpreted as a reporting limit. What the reporting limit is varies for different PFAS compounds, it can be 0.30, 1.00 or 2.00 ng/l. Values under reporting limit are evaluated to 0. What PFAS were measured in each measurement is available in the Appendix. Other data such as field documentation, measurements of pH, measurements of the esker's water level was also provided by Norrvatten.

3.2.1. Analysis of data

The data has been analyzed in Excel where the sum and the composition for each measurement was calculated and plotted. The composition was calculated by taking the concentration of each PFAS and dividing it with the sum of all detected PFAS in the sample. This made it possible to see how the composition changed throughout the esker and backtrack where it may come from. Graphs were made with the composition and the measurements distance from the most southern boundary.

3.3. Source identification

3.3.1. Groundwater sampling

To get more information and data on the PFAS in the esker more measurements of the PFAS concentrations in the groundwater were implemented. Measurements in the southern, up-stream part of the Hammarby esker aquifer were not available. To see if there were any changes in the upstream parts of the aquifer and if the concentration had changed in the esker more samples were needed. It was possible to take 8 samples in March from the esker and the containers for the measurements were provided by Eurofins. Before going out in field, 8 pipes were picked out which could be interesting for the result and that was not clogged up in earlier measurements. They were picked out using earlier inventory lists of the pipes in the esker.

With help from Emma at Blackthorn Science AB and Norrvatten it was possible to implement the groundwater sampling. The material used was sound solder, pump, pH-meter, conductivity meter, and oxygen meter. When getting to the location of the pipe the first thing was looking how much water there was in the pipe. For this the sound solder was lowered and the water level was found and annotated. Then the turnover time was tested through pumping the water and seeing how long it took until there was no more water at that depth. 5 minutes after the pumping the sound solder was lowered in the pipe again to see if the water level had recovered. If it had not recovered the turnover time was too long and it was not possible to take a sample in the pipe. When sampling was doable the water was filled up in four containers. For one of the containers the sample water needed to be filtered. In another separate container the pH, conductivity, and content oxygen were measured. The process was repeated for all pipes. Six of the pipes that was planned to analyze were dry or had been clogged, making it impossible to sample. In some cases where it was not possible to take samples another pipe was found nearby and sampled instead. In total sampling was done in five different pipes. When the sampling was done, the containers was sent to Eurofins for measurements. The result presented the uncertainty of measurement as ± 31% for all PFAS measurements.

3.3.2. Potential source identification

To determine what is contributing to the elevated PFAS concentrations in the esker's groundwater an investigation of the potential sources was executed. With help from the theory presented earlier about potential sources for PFAS emissions, information from Upplands Väsby's municipality, and the contaminated sites sector list (Sw: *branschlistan förorenade områden*) (Naturvårdsverket 2023a) some sources are picked out to investigate further with modelling. The contaminated sites sector list provides information on which hazardous activities and facilities contaminates with PFAS – all these are therefore picked out for further studies. PFAS is either considered as a *specific contamination of land from the industry, other related contamination of land, specific contamination of sediment from the industry,* or *other related contamination of sediment*. The *specific contamination from the industry* mentions contaminators that can be important to measure for the site since they are the most common primary contaminants around the hazardous activities and facilities according to the EBH-support. Being mentioned in the *other related contamination* means that the contaminant is known and related to the hazardous activities and facilities (Naturvårdsverket 2023a). Since not all sources could be further studied the hazardous activities and facilities having PFAS mentioned only as *other related* *contamination of land* or *other related contamination of sediment*, were excluded. If PFAS was mentioned as a *specific contamination from the industry*, or as more than one alternative, the hazardous activity/facility was further investigated. The hazardous activities and facilities also had to be located inside the boundaries of the model used in the particle tracking and found on the EBH-map or Google Maps to make it further in the study.

To find more information about how much PFAS and what types of PFAS profiles could be contributed from the potential sources a literature study was executed. The search words used to find information about each source were "*name of the source (e.g landfill)"* + *PFAS* and it was applied in the search feature on *sciencedirect.com*. If the reports that were read provided any interesting information on the subject referencing another report, that one was read also.

3.3.3. Particle Tracking

Particle tracking was used to see if the potential sources found in the literature study could contribute to the high concentrations in the esker. A pre-made model developed in FEFLOW was used. FEFLOW, short for Finite Element subsurface FLOW and transport system, is an all-in-one groundwater modelling solution by MIKE powered by DHI (DHI n.d.a). The program serves as an interactive system for modelling groundwater flow (DHI 2021). The groundwater model can be used for different purposes such as describing the spatial and temporal distribution and reactions of contaminants in the groundwater, modelling geothermal processes, estimating the duration and travel times of chemical species in aquifers and a lot more. FEFLOW was launched in 1979, and it has been improved and extended continuously since then by a team of experts at DHI WASY. The model is used worldwide for different purposes such as research institutes, universities, consulting companies and government agencies (DHI 2021).

In FEFLOW the framework used for creating a finite-element mesh is called Supermesh. The Supermesh contains all the basic geometrical information that is needed for the algorithm. The simplest version of Supermesh only defines the outline with a single polygon but the supermesh can also be applied as points, lines, polygons and also, 2D and 3D layers (DHI n.d.b).

FEFLOW has different methods for particle tracking – standard streamlines, and Random-Walk Particle-Tracking, RWPT (DHI n.d.b), in this study RWPT is used. In FEFLOW, particle-tracking involves solving the N_d-dimensional stochastic differential equation (SDE) (DHI n.d.b). SDE is aligned theoretically with the Fokker-Planck equation (FPE) for the transition probability $f(x, t)$,

$$\frac{\partial f(\boldsymbol{x},t)}{\partial t} = -\sum_{i}^{N_d} \frac{\partial A_i f(\boldsymbol{x},t)}{\partial x_i} + \frac{1}{2}\sum_{i,j}^{N_d} \frac{\partial}{\partial x_i}\frac{\partial}{\partial x_j} B_{i,j} f(\boldsymbol{x},t) \tag{1}$$

With the Îto formulation SDE can be written as,

$$\boldsymbol{X}_p(t+\Delta\mathrm{t}) = \boldsymbol{X}_p(t) + \boldsymbol{A}(\boldsymbol{X}_p,t)\Delta\mathrm{t} + \mathbf{B}(\boldsymbol{X}_p,t)\cdot\Delta\mathbf{w}(\Delta\mathrm{t}) \tag{2}$$

A is a vector commoly called the drift vector, and written as,

$$\boldsymbol{A} = \boldsymbol{v} + \nabla\cdot\boldsymbol{D} + \varepsilon^{-1}\boldsymbol{D}\cdot\nabla\varepsilon = \boldsymbol{v} + \nabla\cdot\boldsymbol{D} + \boldsymbol{D}\cdot\nabla\ln\varepsilon = \lim_{\Delta t\to 0}\frac{1}{\Delta t}\langle\boldsymbol{X}_p(t) - \boldsymbol{X}_p(\mathrm{t}_0)\rangle \tag{3}$$

The drift vector is describes the advective motion of a particle, which combines the fluid velocity with an additional velocity due to variations in the dispersion tensor, *D*, and porosity, *ε*. *D* can be written as,

$$2\boldsymbol{D} = \boldsymbol{B} \cdot \boldsymbol{B}^t = \lim_{\Delta t \to 0} \frac{1}{\Delta t} \langle [\boldsymbol{X}_p(t) - \boldsymbol{X}_p(\mathrm{t}_0)][\boldsymbol{X}_p(t) - \boldsymbol{X}_p(\mathrm{t}_0)]^t \rangle \tag{4}$$

The random component of the equation is called white noise and is described with the term $\boldsymbol{B} \cdot \Delta\mathbf{w}$. *B* is a diffusion matrix and $\triangle$w are the increments of independent Wiener processes. When the SDE is applied to a large number of particles the resulting particle ditributions replicate the Fokker-Planck Equation (FPE), effectively solving the Advection-Dispersion Equation (ADE). The matrices *A* and *B* are designed to align the ADE with the FPE. The divergence in the dispersion tensor term stems from differences between the FPE and the ADE. This term represents the conservation of particles due to dispersion in areas with varying flow velocities. Omitting this term would result in an unusual buildup of particles in areas with low dispersion. It is also worth noting that the porosity gradient term is often overlooked, and its physical significance is not well understood.

The RWPT uses Stratonovich as default integration method which can be written as,

$$\boldsymbol{X}_p(t + \Delta \mathrm{t}) = \boldsymbol{X}_p(t) + \left(\boldsymbol{v} + \frac{1}{2}\nabla \cdot \mathbf{D}\right)\Delta \mathrm{t} + \frac{1}{2}\left(\boldsymbol{B}(\boldsymbol{X}_p, t) + \boldsymbol{B}(\boldsymbol{X}_p + \boldsymbol{Y}_p(t), t)\right) \cdot \boldsymbol{\xi}(\mathrm{t})\sqrt{\Delta \mathrm{t}} \tag{5}$$

$$\boldsymbol{Y}_p(t) = \boldsymbol{B}(\boldsymbol{X}_p, t) \cdot \boldsymbol{\xi}(\mathrm{t})\sqrt{\Delta \mathrm{t}} \tag{6}$$

This equation is a Runge-Kutta method developed from the following formulation of SDE that is similar to a standard advective-tracking ODE with the modified velocity,

$$\boldsymbol{X}_p(t + \Delta \mathrm{t}) = \boldsymbol{X}_p(t) + \boldsymbol{u}(\boldsymbol{X}_p, t)\Delta \mathrm{t} \tag{7}$$

With,

$$\boldsymbol{u}(\boldsymbol{X}_p, t) = \boldsymbol{A}(\boldsymbol{X}_p, t) + \frac{1}{\sqrt{\Delta \mathrm{t}}}\boldsymbol{B}(\boldsymbol{X}_p, t) \cdot \boldsymbol{\xi}(\mathrm{t}) \tag{8}$$

Apart from Stratonovich, Backward Îto, Forward Îto and Runge-Kutta of order 4 can also be developed from Equation 8 (DHI n.d.b).

A model of the esker Norra Stockholmsåsen, Hammarby has been developed by Artesia and Akvanovum in FEFLOW (Johansson & Djurberg 2019). It is a conceptual model that has been developed for the groundwater conditions at the location. The model is based on an estimate of the recharge of the groundwater, the soil layers description and their hydraulic properties, the in- and outflow of the groundwater together with water balance and water quality. The model does have remaining uncertainties of major importance (Johansson & Djurberg 2019). The model has been provided by Norrvatten and will be used to see how the groundwater flows in the esker.

The first step of being able to track the particles was to create layers for all the potential sources. The tool *Create Layer* in QGIS to make each potential PFAS site their own layer. The industry was located by downloading them from the EBH-map and then taking the location for them to a new layer to be able to import it to FEFLOW. All the points where PFAS had been detected in 2019, 2022, and 2024 were added to one layer. The scenario used in FEFLOW was without any abstraction of water at the Hammarby groundwater plant. This is due to that the aquifer is used as a reserve for drinking water and not pumped regularly. The files that were created in QGIS were exported as .shp-files and then imported to the model in FEFLOW. The particle tracking was activated by clicking on the nearest node and the tool under *Data* in FEFLOW. When using RWPT the settings used was 1000 seeds per node and the seeds were released from a radius of 50 m around the node. The number of pipes that each potential source particle tracking touched was then calculated and summarized.

3.3.4. Scoring system

To be able to visualize the result better and tie together the different steps from the method a scoring system for the sources was implemented. This was based on the fingerprint for each potential sources and how many of the pipes that the particles in the particle tracking touched.

For the fingerprint, a point between 0 and 13 (the amount of PFAS detected in the groundwater) was given to the potential source. If the point was zero either none of the PFAS found in the groundwater could be connected to the potential source with help from the literature or no information was found of what PFAS may be emitted from the potential source. If the potential source was given the point 13 in the fingerprint, it means all the PFAS found in the groundwater could be connected to the potential source with literature.

For each of the pipe that the particle tracking from the potential source touched they were given one point. For example, if the particles from the Fire station touched 12 pipes, it got 12 points. The maximum score in this category is therefore 18 points. If the potential source was located further downstream it was not able to touch the pipes upstream from this point. The potential source could therefore not influence these parts of the aquifer and could not receive a full 18 points as the ones located further upstream could. This was done on purpose since there had been high concentrations measured in the upstream parts of the esker indicating that a source could be located nearby.

4. RESULTS

4.1. Groundwater sampling

The sample points where PFAS had been measured are presented in Figure 6 together with the name for each pipe. Number 17 is the location of *Hammarby källa* which lies closely located to *Hammarby water plant* (HWP) which is not presented in the map. The pipes are named 1-18 with number 1 being the pipe located most southern and number 18 located most northern. The actual names of the pipes are given in Appendix.

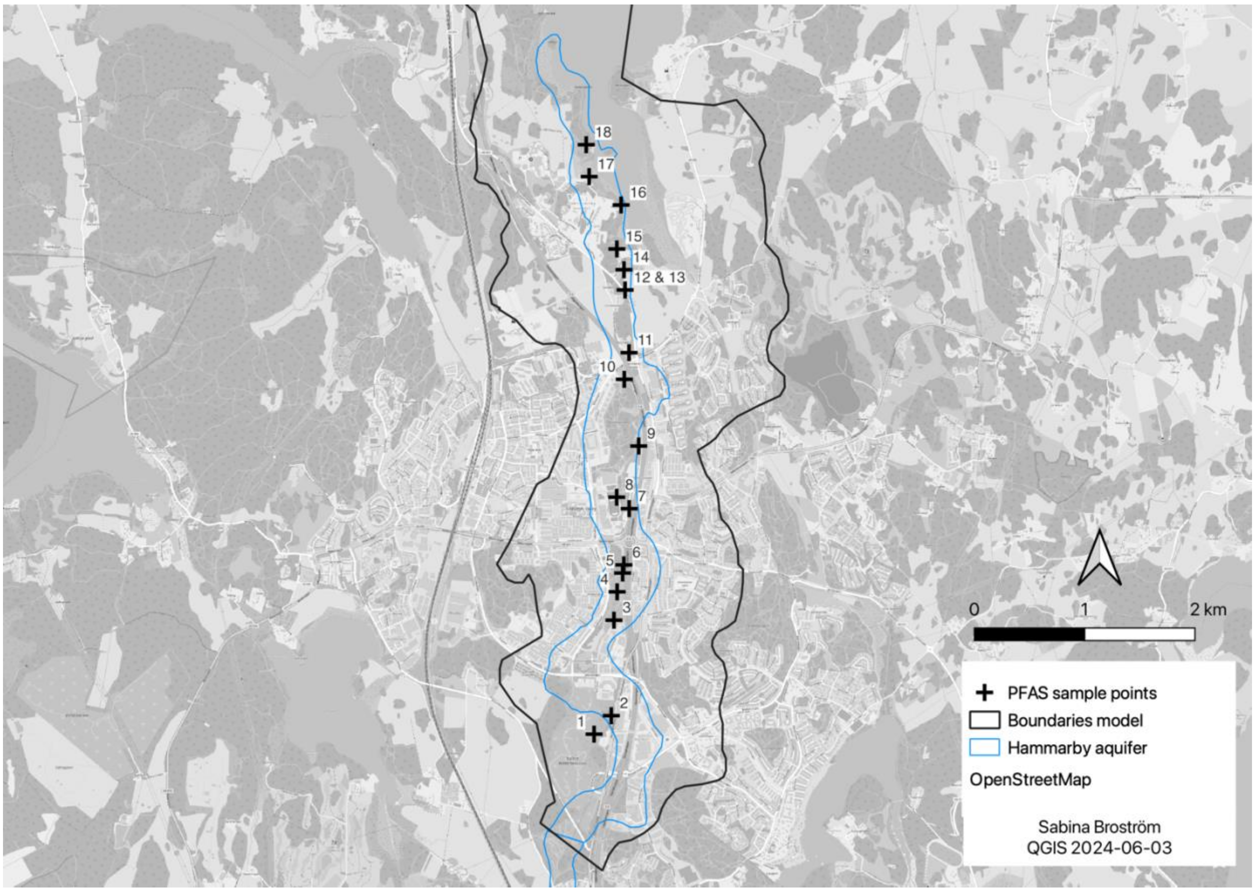

Figure 6: Location of the sample points where PFAS has been measured together with the groundwater aquifer and the outlines of the model.

In addition to the measured concentration presented under *1. INTRODUCTION*, the composition of PFAS in the groundwater of the esker has been analyzed to see if it can be traced back to a specific source. The measured PFAS from 2019 and 2022 in the esker are presented in Figure 7 and Figure 8. In both measurements the same 11 substances were found, PFHpA, PFHxA, PFBA, PFBS, PFHxS, PFOA, PFOS, PFPeA, PFPeS, PFNA, and PFHpS. Out of these 9 are PFAS 21 (PFHxS, PFOA, PFOS, PFNA (PFAS 4), PFHpA, PFHxA, PFBA, PFBS, and PFHpS) and two of them (PFPeA and PFPeS) are not found in the new regulations (LIVSFS 2022:12). In two measurements from 2019 6:2 FTS was also detected, which is included in PFAS 21. The measurements that detected 6:2 FTS were taken in the same groundwater pipe but at different levels.

The composition of the different samples measured in 2019 and 2022 follows a similar profile and does not differ much. The biggest difference is the measurements from pipe 1 taken in 2022 and the detection of 6:2 FTS in pipe 12 and 13 in 2019. Pipe 1 is located outside the groundwater aquifer which none of the other sample points are. The samples from 2022 inside the esker's boundaries are more similar to each other than the samples in 2019. In 2022 the composition of PFHxS is generally lower in all samples than in 2019. Some of the substances, PFHpS and PFNA, have been detected in very low concentrations (less than 1%) in both series. The substances with the highest percentage of the measurements seems to be PFHxS, PFOS and PFPeA (their lowest being 11%, 11%, and 14%). PFHxS is a substance that varies the most in its composition of the measurements, with variations from 11% to 25%.

In Figure 7 the concentration for each measured groundwater sample in 2019 is presented as a sum below the x-axis. These concentrations vary between 45.45 ng/l (pipe 12) to 105.46 ng/l (pipe 10) and there is no trend showing an increase or decrease along the esker. Although the two highest concentrations (pipe 9 and 10) are located more upstream. The lowest concentration is found in the sample taken closest downstream from the sample with the highest measured concentration, which are located 810 m from each other.

Figure 8 presents the concentration for each measured groundwater sample from 2022 as a sum below the x-axis. The lowest concentration is measured in pipe 1 (11.29 ng/l) which is located just outside the groundwater aquifer. For the samples inside the aquifer the concentration varies between 52.1 ng/l (pipe 17) and 130 ng/l (pipe 3). The two highest concentrations are the ones measured most upstream inside the aquifer and downstream from these the concentration decrease.

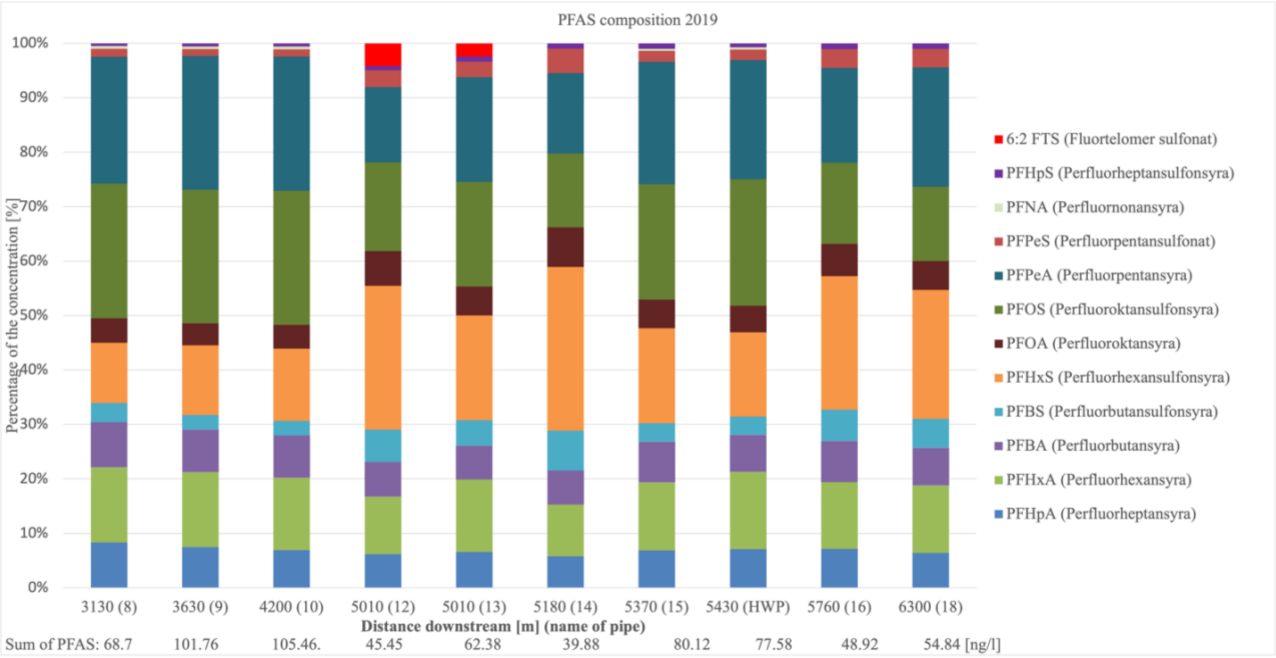

Figure 7: The composition of PFAS in measurements from 2019 of the groundwater in the esker together with the sum of the measured PFAS below the x-axis. Downstream distance is the distance groundwater divide at the South edge of Hammarby esker aquifer. Pipe numbers referring to Figure 6 are given in parenthesis after distance downstream.

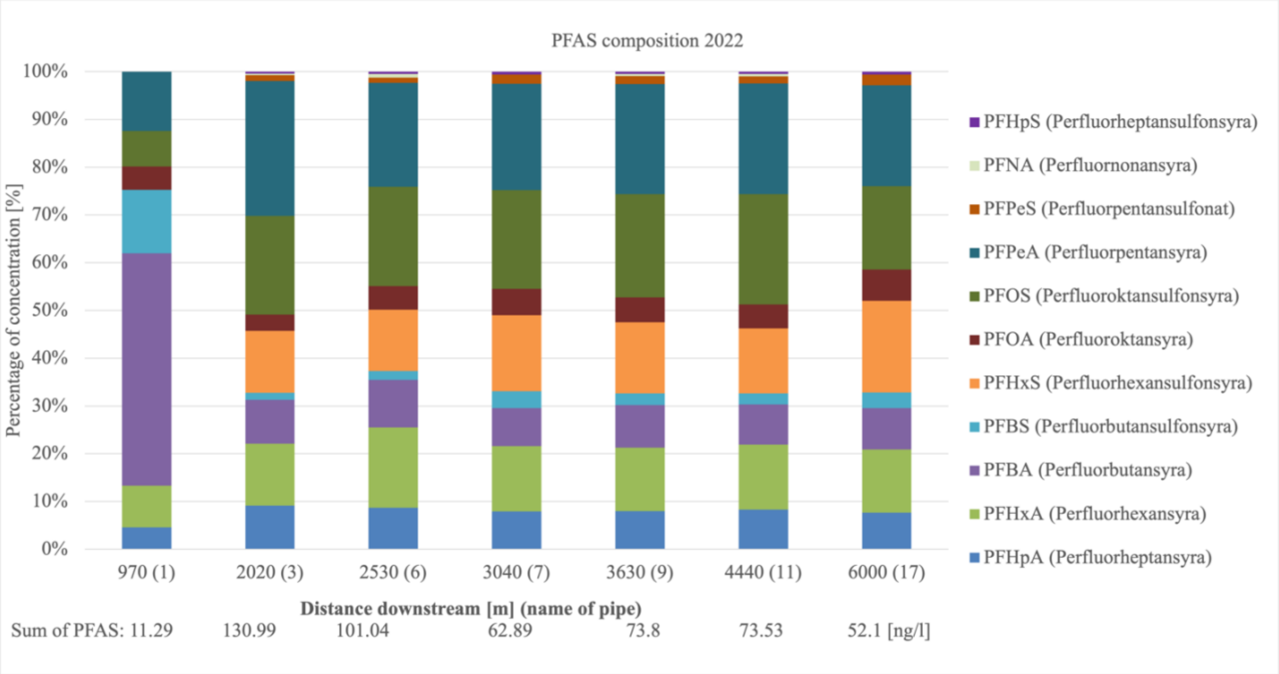

Figure 8: The composition of PFAS in measurements from 2022 of the groundwater connected to the esker. Downstream distance is the distance from the groundwater divide at the South edge of Hammarby esker aquifer. Pipe numbers referring to Figure 6 are given in parenthesis after distance downstream.

In Figure 9 the percentage of the concentration of PFAS from Hammarby water plant is presented from September 2017 to February 2024. The same substances that have been detected in the measurements from 2019 and 2022 have also been detected in the different measurements from the water plant. The composition in all measurement is constant and the variation is small. IN the first measurement, 26/9 2017, PFPeS, was not measured, therefore it may still have been present at the time. What PFAS has been measured in the last three years at Hammarby water plant is available in Appendix, what substances before that differs slightly. All data for the measurements can be found in Appendix. PFHxS, PFOS, and PFPeA (their lowest being 13%, 19%, and 19%) are the substances that has the highest percentage of the substances that have been measured in the dataset.

The concentration of the measurements from Hammarby water plant is presented in Figure 9 below the x-axis. The concentration is varying between 83.16 ng/l and 65.07 ng/l. The highest concentration was measured in the first sample (26/9 2017) and the lowest was measured in 2021. The latest concentration measured (6/2 2024) was 68.7 ng/l.

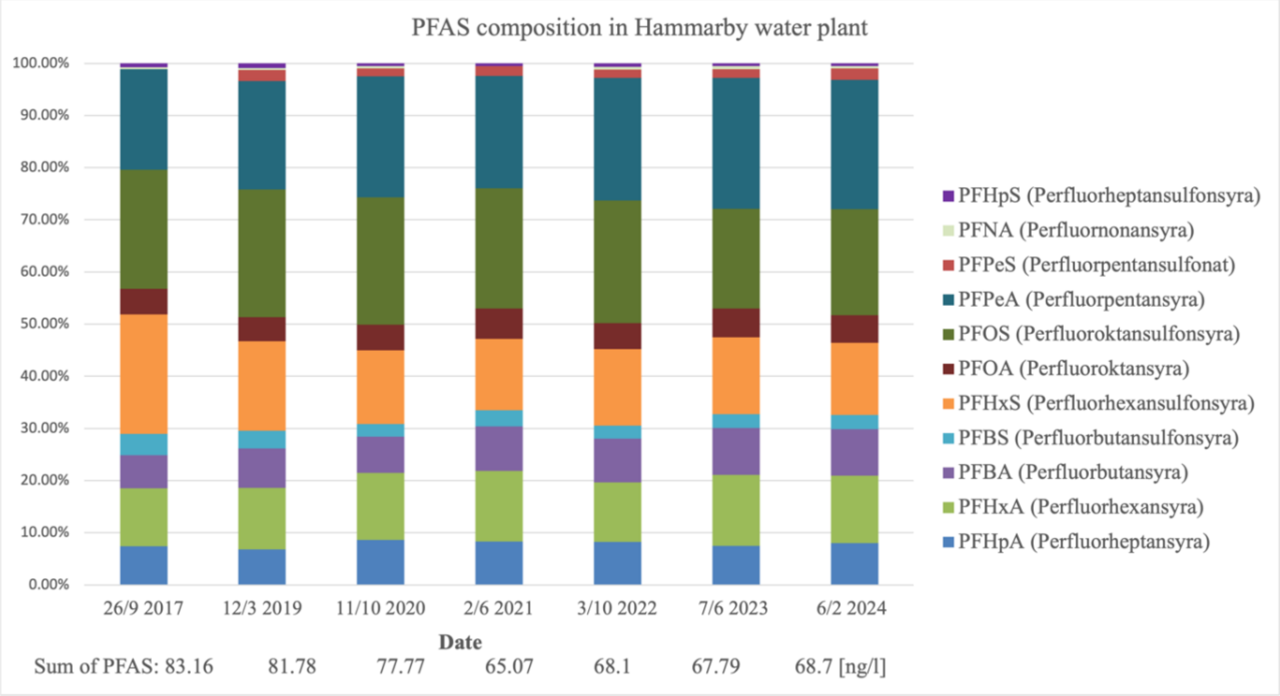

Figure 9: The composition of PFAS in Hammarby water plant on different dates from 2017 to 2024.

Concentration of the measurements done on the groundwater of Norra Stockholmsåsen is presented in Figure 10. The total concentration varies from 28.65 ng/l to 147.73 ng/l. The pipe that is located furthest upstream in the esker (pipe 2) has the highest concentration of the samples from 2024. The lowest concentration is instead found in the pipe located 2450 m (pipe 5) downstream in the esker. This pipe is located 160 m downstream from pipe 4 that measured a concentration of 113.43 ng/l. 80 m downstream from pipe 5, pipe 6 measured a concentration of 78.64 ng/l. There seems to be no trend of increase or decrease along the esker.

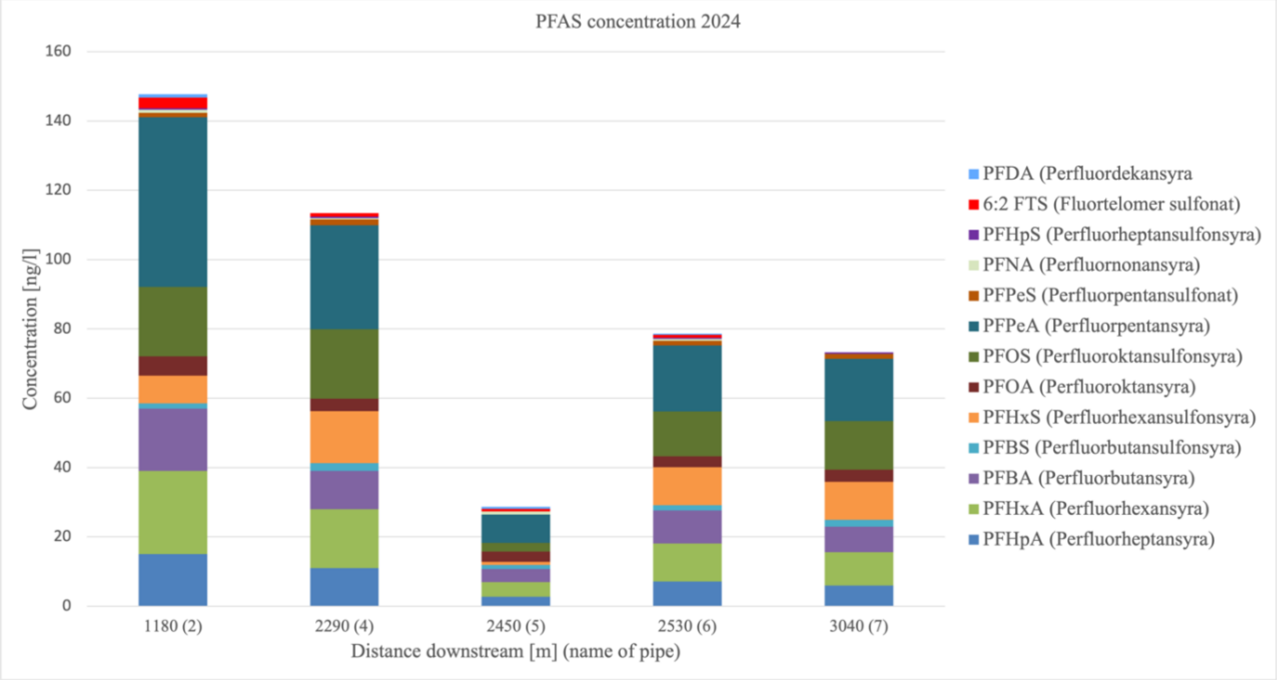

Figure 10: Concentration of PFAS in the groundwater from Hammarby aquifer from measurements taken in 2024 from five different pipes. Downstream distance is the distance from the groundwater divide at the South edge of Hammarby esker aquifer. Pipe numbers referring to Figure 6 are given in parenthesis after distance downstream.

In the measurements executed in 2024 there is variation in the composition of each measured sample as seen in Figure 11. The samples have detected the same 11 PFAS as in the other measurements, as well as 6:2 FTS and PFDA. To see what PFAS was analyzed in the test see Appendix. The sample that differs the most from the others was taken in pipe 5 at 2450 m downstream in the esker, a pipe that there were no previous measurements from. The biggest difference between pipe 5 and the others is that PFHxS has been detected in a lower percentage while PFNA, PFOA and PFDA has a higher percentage than in the others. Except pipe 5 the others follow a similar pattern where PFPeA and PFOS has the three highest percentages. PFHxS has a quite low percentage on pipe 2, but the substance has a higher percentage in pipe 4, 6 and 7.

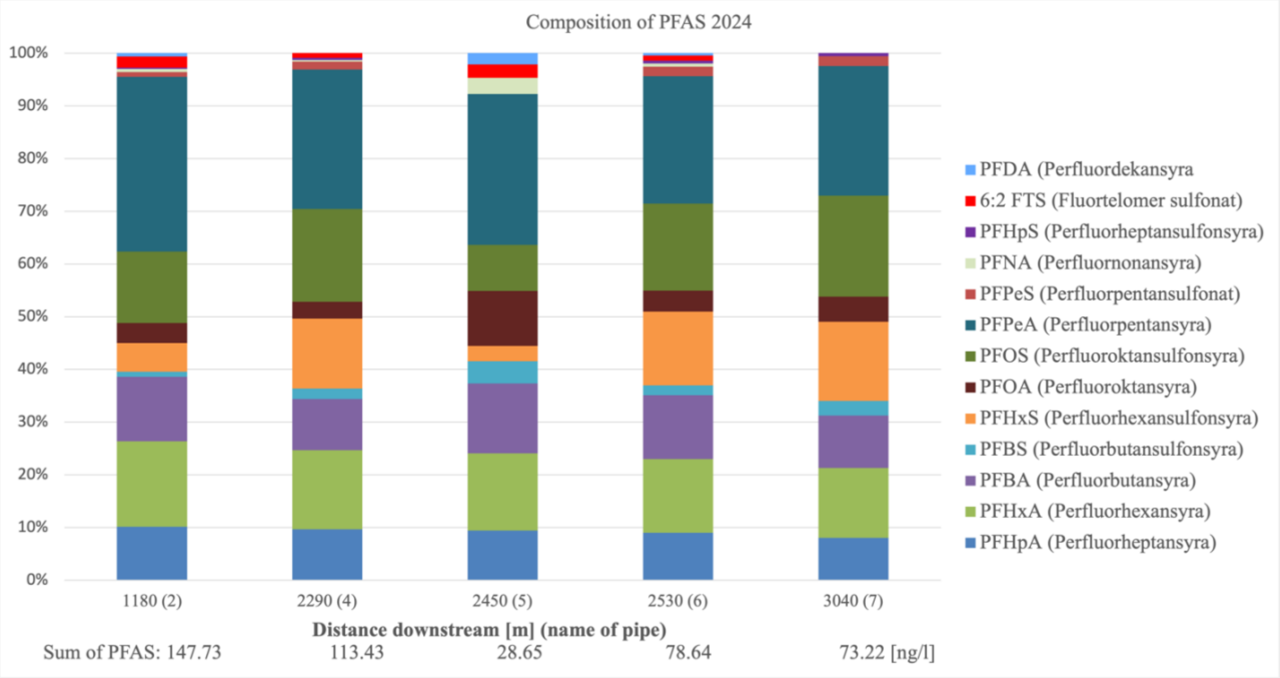

Figure 11: The composition of PFAS in the groundwater of Norra Stockholmsåsen from measurements taken in 2024 from five different pipes. Downstream distance is the distance from the groundwater divide at the South edge of Hammarby esker aquifer. Pipe numbers referring to Figure 6 are given in parenthesis after distance downstream.

4.2. Potential PFAS sources

According to the EBH map, showing the potentially contaminated sites, most of the sites located around the groundwater aquifer have not been classified yet and are still in the identification process (Länsstyrelserna n.d.). Several possible contaminated sites around the groundwater aquifer could contribute to the increased concentrations of PFAS as seen in Figure 12. Due to these not being classified with their risk yet; it is hard to say to what extent the possible contamination can occur. Not a lot of the objects are classified with risk class 1, *very high risk*. Out of the ones classified in the area, most have class 2 or 3, meaning *high risk* and *moderate risk*. Class 4 indicates *low risk* (Länsstyrelserna n.d.). Some objects have been classified with MKM, *less sensitive use of land*, or KM, *sensitive use of land* (Pettersson et al. 2015). The class: *sensitive use of land* means that the land can be used for schools, housing, or other similar things while *less sensitive use of land* indicates less extensive protection of the environment and humans. The land can be used for industries, traffic facilities, offices, or other similar uses (Pettersson et al. 2015). It was not until 2023 that the Swedish government had implemented a special initiative for county administrative boards to inventory areas that have been contaminated by PFAS (Naturvårdsverket 2023b). Therefore there may be many potential sources to PFAS that have not been registered in the EBH map (Naturvårdsverket 2023b).

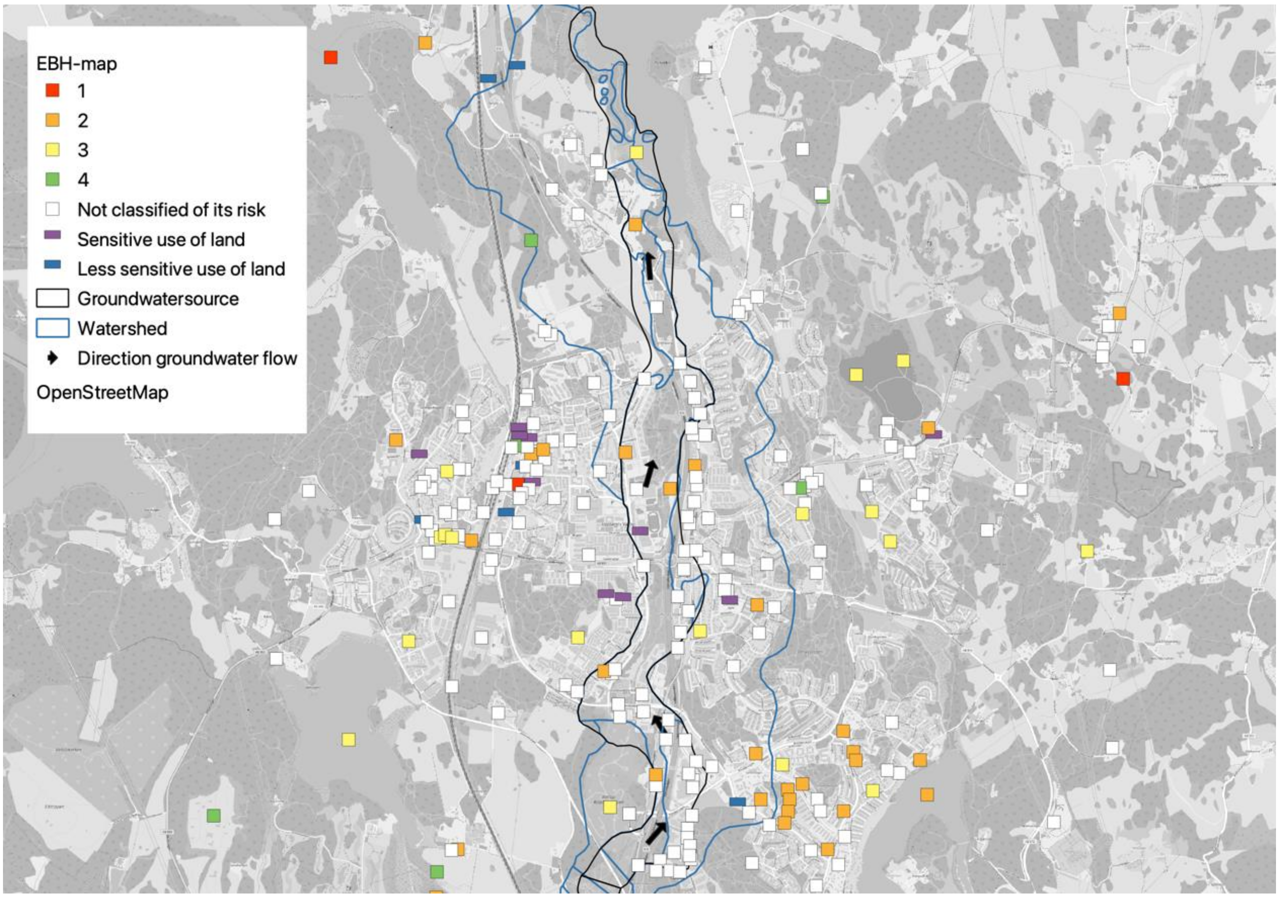

Figure 12: Map showing objects from the EBH-map with its risk class (Länsstyrelserna n.d.).

Some of the identified EBH objects have been chosen to investigate further and their location is presented in Figure 13. They have been chosen with from the methodology presented under *3.3.2 Potential source identification*. Some hazardous activities and facilities that were detected for PFAS contamination in the Swedish Environmental Protection Agency's industry list (Sw: *Naturvårdsverkets Branchlistan*) lack information on the specific substances that it may emit, meaning that no information was found about how the industry may contaminate with PFAS.

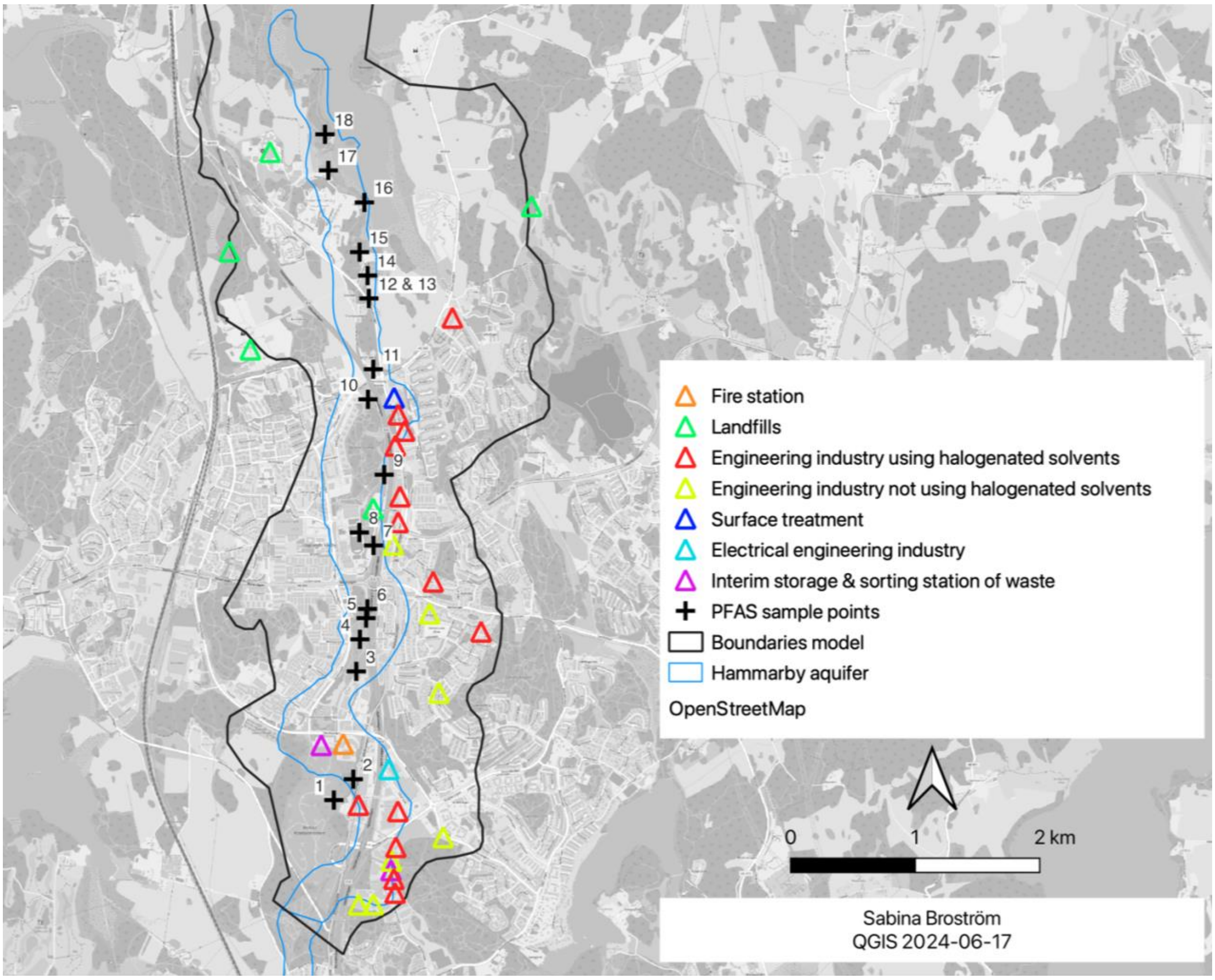

Figure 13: Map showing the operations that has been further investigated in the thesis.

4.2.1. Fire station

While researching the area above the esker one fire station was noticed. Fire stations are mentioned as a source contributing to PFAS emissions (Hansson et al. 2016). In the past, it was not unusual to have firefighting exercises at the fire station and afterwards wash the equipment with water, without collecting the water that may have been contaminated. The water used for cleaning the tools did either go to sewage, rainwater system, or directly to the recipient. Since fire stations stored firefighting foam and it is an expensive product it was standard to practice firefighting with foam that had passed its best days. After being emptied, the tanks were taken to landfills for deposition. Both historical and fire stations that are in service could be further investigated since contaminated soil around the location could contribute to PFAS emissions (Hansson et al. 2016). The fire station in Upplands Väsby was not included in the EBH map, it was discovered by searching Google Maps for a Fire station in the area. In a meeting with Upplands Väsby municipality, it became known that the fire station had been at the location since 1992[2]. Information about fire training exercises at the site historically is not known, but at the station today there is no firefighting foam used (ibid). According to Länsstyrelserna (2018), it is unclear if fire stations are contaminated, without them being close to fire training facilities. Investigations at fire training sites have shown that PFOS and PFHxS are the most dominating PFAS. Other PFAS found at fire training sites were PFPeA, PFHxA, PFOA, PFBS, PFHpA, and 6:2 FTS (Länsstyrelserna 2018).

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[2] Maria Wallström, environmental inspector, Upplands Väsby Municipality, meeting 2024-02-24

The fire station in Upplands Väsby, part of the Attunda fire department, now only uses firefighting foam that does not contain PFAS and has actively been working to phase out foam containing PFAS[3]. When PFAS were used in extinguishing agents, the risks were not yet known, but today there are bans on some of the substances. PFOS was banned in 2008, and in 2020, PFOA was also banned. Not all firefighting foams contain PFAS, even historically. The ones that do contain PFAS are mostly used for extinguishing liquid fires because of their film-forming properties, while the agents used for extinguishing fibrous fires do not contain PFAS (ibid).

4.2.2. Landfills

Landfills categorized as *Landfills - non-hazardous, hazardous waste* have been found to have PFAS as a specific contamination of sediment from the industry (Naturvårdsverket 2023a). Landfills are seen as one of the main PFAS reservoirs since it is the place where products containing PFAS are disposed (Chen et al. 2020). The leachate from landfills is a known source of PFAS contamination (Benskin et al. 2012). In an examination of PFAS contamination from legacy landfills in Australia, groundwater around old landfills was researched and all samples detected PFAS (Currell et al. 2024). 17 different substances were detected out of the 38 different substances that were analyzed. The most common substances detected were long-chained ‘legacy’ PFAS like PFOS, PFHxS, PFHxA and PFOA. Out of the short-chained compounds only 3:3 FTCA and 6:2 FTSA were detected – and in small concentrations (Currell et al. 2024). No other PFAS than PFOS and PFOA are usually analyzed around landfills (Länsstyrelserna 2018). However, for some investigations, PFAS 11 is analyzed which has given the result that other PFAS are detected. There is probably a large variation of the PFAS that occur at the site – therefore it is important to analyze as many different substances as possible (Länsstyrelserna 2018). It is a complex process to summarize the specific contaminations from landfills since the contents of the landfill varies a lot depending on what operation has disposed their waste at the location (Naturvårdsverket 2023a). What emission that might disperse depends on how the leachate has been treated and what waste has been collected (Naturvårdsverket 2023a).

There are two landfills inside the outline of the model and two just outside the model. Due to the two landfills outside the model being very close to the outline, the nearest node is applied to them as well. Out of the two landfills inside the model, one is not classified while the other one has class 2, *high risk*. While the two landfills outside the model one have not been classified and the other one has class 4*, low risk.*

4.2.3. Engineering industry

At locations called engineering industry welding, blasting, cutting, and assembly are executed (Naturvårdsverket 2023a). There is one type of engineering industry where halogenated solvents are used and one type where it is not used. Both have been found to have PFAS as a contaminant (Naturvårdsverket 2023a).

There are 13 sites inside the model that have an engineering industry that uses halogenated solvents and 7 other engineering industries where halogenated solvents are not used. Out of the ones using halogenated solvents there is one being classified with risk class 2 and the other 12 sites have not yet been classified. For the ones not using halogenated solvents, one site has received the classification MKM, less sensitive use of land and the others have not been classified. Unfortunately, there is not much data and information on engineering industries. It seems to be quite a wide use of the word that includes a lot of engineering industries and there is no information of what PFAS that could be emitted from the hazardous activities and facilities.

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[3] Elina Edin, District Manager, Brandkåren Attunda, E-mail 2024-07-02

4.2.4. Surface treatment of metals electrolytic/chemical processes

Hazardous activities and facilities having surface treatment of metals with electrolytic/chemical processes are considered to contribute to the contamination of PFAS (Naturvårdsverket 2023a). There is one located inside the model although which has not yet been classified. No studies about how these hazardous activities and facilities contribute to PFAS contamination have been found, therefore it is difficult to say what substances may come from the source and to what extent it may contaminate.

4.2.5. Electrical engineering industry

There is one electrical engineering industry located inside the model and it has not been classified based on its risk. This is another industry that does not have that many studies about its possible contamination of PFAS, it is therefore difficult to see how this industry may have influenced the elevated concentrations of PFAS in the esker.

4.2.6. Interim storage and sorting station of waste

The two interim storage and sorting stations of waste that are located inside the model have not yet been classified based on their risk. No information has been found about how the industry is contaminated with PFAS, it is therefore difficult to predict how the industry can have affected the elevated levels of PFAS in the esker's groundwater.

4.3. Particle tracking

In Figure 14A the particle tracking from *Engineering industry not using halogenated solvents 1* (EIWOHS 1) is presented. The particles just around the node is purple but quickly changes to blue and then green. This indicates a slow beginning for the plume that the particles move in. Some of the particles reaches the lake but to the most northern sample point there are only a few still being transported and reaching the point after 65 years (23741 days). The particles touch 11 of the groundwater pipes that have measured PFAS.

In Figure 14B the particle tracking of *Interim sources and sorting station of waste 2* (IS&SS 2) is presented. In the figure the plume divides in two after a few meters. The plume touch 9 of the crosses, 2 of them are before the plume divides and then the western plume touch most of the others before the plumes merge. The particles seem to move quick through the esker due to the color being purple and blue on most of the particles. All particles seem to touch the most northern cross in 65 years, but most of them get there in 25 years. The rest of the particle tracking from the potential sources is available in the Appendix.

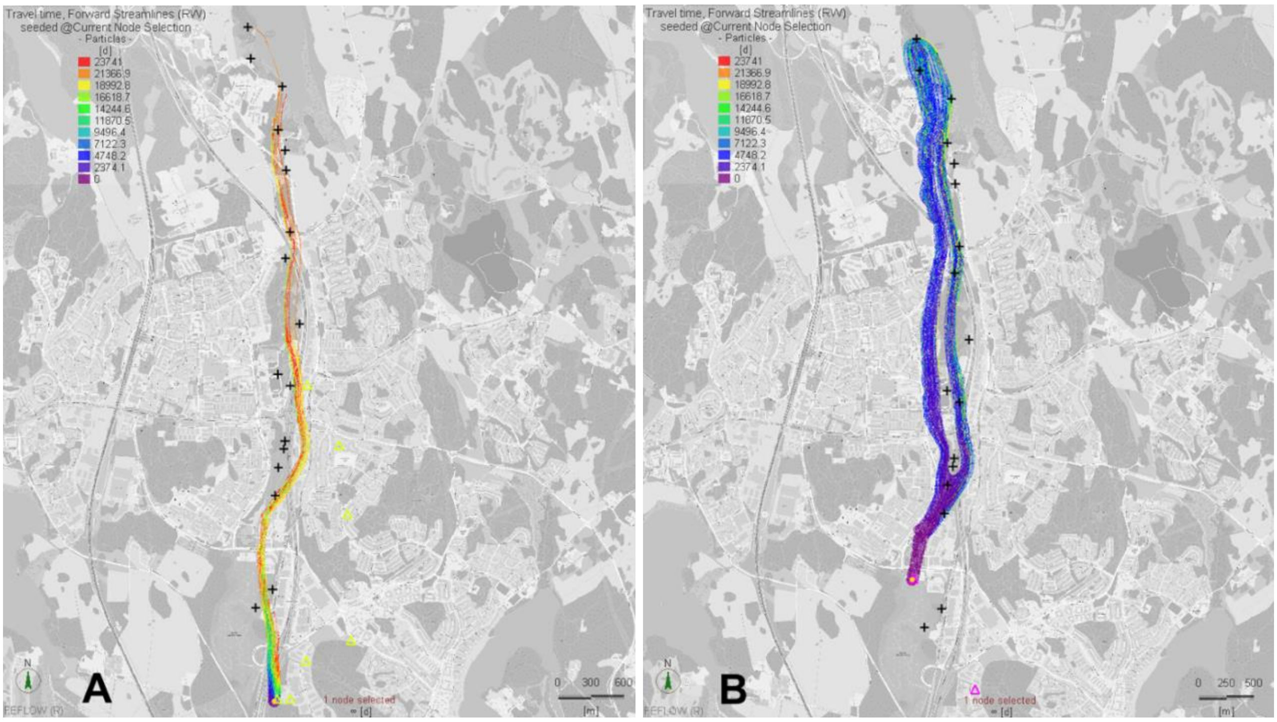

Figure 14: Particle tracking from Engineering industry not using halogenated solvents 1 (EIWOHS 1) presented in A and Interim storage and sorting station of waste 2 (IS&SS 2) presented in B. The yellow dots are the nearest node, the lime green- and magenta-colored triangles are locations of the hazardous activities and facilities, and the black crosses are points were PFAS have been measured 2019, 2022 or 2024.

Table 1 shows the number of pipes touched by the particle tracking from all potential sources are presented. There is one of the potential sources touching 11 of the pipes in total which is Engineering industries not using halogenated solvents 1 (EIWOHS 1) but as seen in the particle tracking in Appendix, there are only a few reaching the most northern cross in the 65 years it's been displayed. The Fire station and Engineering industry using halogenated solvents 5 (EIWHS 5) touch 10 pipes each which is the second most touched ones. The particles from these sources reach the most northern point in about 45 years, but the Fire station seems to have a bigger plume moving in the groundwater than EIWHS 5. EIWHS 5 and EIWOHS 1 are the only two particle trackings that touches pipe 2. The whole plume from EIWHS 5 touches pipe 2, while EIWOHS 1 slighlty touches it. Interim storage & sorting station of waste 2 (IS&SS 2) that is presented above touches 9 of the crosses in its particle tracking in a quite short time. Most of the potential sources touch between 1-6 out of the total 18 crosses. For example, the Surface treatment of metals electrolytic/chemical processes (ST) and Electrical engineering industry (EEI) touch 5 and 6 of the crosses. There are 10 of the potential sources that has particle tracking not touching any of the crosses, which are 4 of the landfills, 4 of the Engineering industries using halogenated solvents, IS&SS 1 and EIWOHS 5.

Table 1: The pipes touched by the particle tracking from the potential sources are marked as 1, while the ones not touched by the particles are marked as 0. The potential sources are sorted from the most touched pipes to the least.

Pipe	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12, 13**	**14**	**15**	**16**	**17**	**18**	**sum**
EIWOHS 1	0	1	1	0	0	0	1	0	1	1	1	1	1	1	1	0	1	11
firestation	0	0	1	0	0	0	1	0	1	1	1	1	1	1	1	0	1	10
EIWHS 5	0	1	0	0	0	0	1	0	1	1	1	1	1	1	1	0	1	10
IS&SS 2	0	0	1	1	0	0	1	0	0	1	1	0	0	1	1	1	1	9
EIWOHS 7	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	1	6
EEI	0	0	0	0	0	0	0	0	1	0	0	1	1	1	1	0	1	6
EIWHS 8	0	0	0	0	0	0	0	0	1	0	0	1	1	1	1	0	1	6

EIWHS 7	0	0	0	0	0	0	0	0	1	0	0	1	1	1	1	0	1	6
EIWHS 9	0	0	0	0	0	0	0	0	1	0	0	1	1	1	1	0	1	6
Landfill 1	0	0	0	0	0	0	0	0	0	1	1	0	0	1	1	0	1	5
ST	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	5
EIWHS 12	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	5
EIWHS 10	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	5
EIWHS 11	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	5
EIWOHS 6	0	0	0	0	0	0	0	0	1	0	0	1	1	1	0	0	1	5
EIWOHS 2	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	3
EIWHS 3	0	0	0	0	0	0	0	0	1	0	0	1	0	1	0	0	0	3
EIWOHS 3	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	2
EIWHS 4	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1
EIWOHS 4	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1
IS&SS 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EIWHS 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EIWHS 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Landfill 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Landfill 3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Landfill 4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Landfill 5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EIWHS 6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EIWHS 13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EIWOHS 5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

4.4. Point system

In Table 2 the result from the point system is presented. The Fire station got the highest score, 18 points, it touched 10 pipes and had 8 PFAS that could be connected to the activity. The Fire station was followed by *Engineering industry not using halogenated solvents 1*, EIWOHS 1, that got 11 points, which was all provided by the number of pipes that its particle tracking touched. Landfill 1 and EIWHS 5 ended with 10 points each where half of Landfills 1 points were from the fingerprint while no information of what PFAS could be used at an Engineering industry using halogenated solvents was found. *Interim storage and sorting station of waste 2*, IS&SS 2, got a score of 9 points which were all provided by the pipes that its particle tracking touched.

Table 2: Result of the point system presented for each potential source with the categories Pipes touched, Fingerprint and then the total score presented under the column Score.

Potential Source	Pipes touched	Fingerprint	Score
Fire station	10	8	18
EIWOHS 1	11	0	11
EIWHS 5	10	0	10
Landfill 1	5	5	10
IS&SS 2	9	0	9
EIWOHS 7	6	0	6
EEI	6	0	6
EIWHS 8	6	0	6
EIWHS 7	6	0	6

EIWHS 9	6	0	6
ST	5	0	5
EIWHS 12	5	0	5
EIWHS 10	5	0	5
EIWHS 11	5	0	5
EIWOHS 6	5	0	5
Landfill 2	0	5	5
Landfill 3	0	5	5
Landfill 4	0	5	5
Landfill 5	0	5	5
EIWOHS 2	3	0	3
EIWHS 3	3	0	3
EIWOHS 3	2	0	2
EIWHS 4	1	0	1
EIWOHS 4	1	0	1
IS&SS 1	0	0	0
EIWHS 2	0	0	0
EIWHS 1	0	0	0
EIWHS 6	0	0	0
EIWHS 13	0	0	0
EIWOHS 5	0	0	0

5. DISCUSSION

The composition of the PFAS in the measured pipes inside the aquifer does not differ a lot in the samples from 2019, 2022, and the water plant, which could mean that the reason for the elevated PFAS is located at the beginning of the esker and has an emission that has been constant since atleast 2019. There could also be more than just one source, contributing to the contamination of PFAS in the aquifer. The same composition has also reached the water plant at the beginning of 2024, which provides more evidence that the emission of PFAS happens continually. The biggest difference in the composition is found in the samples from 2024.

The composition of PFAS in measurements from 2024 has samples that differ from the pattern that has been shown in the other samples. There are two groundwater samples (2 and 5), that stand out from the rest. Pipe 2 is the furthest upstream out of all the sampled pipes and located inside the outlines of the groundwater aquifer. The pipe is also located upstream from the fire station. The goal of sampling in 2024 was to get a sample as far upstream in the esker as it was possible to see if there was a background concentration and what it could be. Sample from pipe 2 was expected to be lower due to being further upstream and the first suspicion of a potential source was the fire station. The fact that it measured a very high concentration (147.73 ng/l) could mean that it is close to a source with PFAS emissions. The groundwater pipe, pipe 2, is located close to an EBH-object with the primary industry "*Other BKL 3*" (Länsstyrelserna n.d.). This category does not have any contaminants given in any of the categories due to it being a class for industries that cannot be categorized (Naturvårdsverket 2023a) therefore the contaminants from the sites can vary a lot and are very dependent on the location and the operations executed at the site. A MIFO-form has been provided by Upplands Väsby municipality of the industry from 2023 where it says that the operations at the time were a crushing and sorting plant. This form provided information on the analyses of the water from the site, which did not detect aliphatic, aromatics, or PAHs.

The groundwater pipe 5 is located in the middle of the groundwater aquifer and was therefore not expected to measure such low concentration (28.65 ng/l). In 2022 pipe 5 was dry, and no sample could therefore be taken in the pipe, there is no information about the pipe from 2019. Pipe 6, located 80 m downstream from pipe 5, was measured in both 2022 and 2024 and had a total PFAS concentration of 100 ng/l in 2022 and 78 ng/l in 2024. A few meters upstream from this pipe, there is an infiltration dam where stormwater infiltrates the groundwater (Johansson 2021). Stormwater has been proven to contain PFAA-precursors and short-chain PFCA (Chen et al. 2023). This means that the stormwater could be another source of PFAS, and the infiltration would not create groundwater that is free from PFAS. The groundwater level in pipe 5 was at a depth of 2.23 m from the pipe's upper edge while pipe 6 was at a depth of 5.23 m when sampling in 2024. The water in pipe 5 could be more influenced by the rainwater and does not reflect the groundwater as well as pipe 6 does.

The concentration of PFAS throughout the groundwater of the aquifer varies. The highest concentrations (above 100 ng/l) are detected in the upstream parts of the aquifer, but there are no indications on a significant decreasing trend downstream, instead concentrations vary. These high concentrations indicate that there is a source close to these pipes (2, 3, 4, 6, 9, and 10). In the measurements from 2024 the concentrations are high in the upper parts of the esker and then decrease before increasing again. The concentrations of PFAS in Hammarby water plant have not varied a lot during the time it has been measured. This indicates that there could be a constant flow of PFAS reaching the water plant.

A reason for unexpected concentrations could be the measurement uncertainty which is important to have in mind when analyzing these results. The measurement uncertainty is ± 31% for each measured PFAS, meaning that the results could differ a lot from the actual value in all samples. With another value for all the PFAS, the result may have looked different. The PFAS composition may have looked different with more precise measurements.

Some of the detected PFAS can be traced back to fire stations. In other investigations of fire stations, PFOS, PFHxS, PFPeA, PFHxA, PFOA, and PFHpA have been identified as emissions (Länsstyrelserna 2018). PFOS, PFHxS, PFPeA, and PFHxA have been detected above 10% in all measurements, while PFOA and PFHpA have a lower percentage (above 3%) in all samples. It is not known if there have been any historical firefighting exercises at the fire station, but there are no firefighting exercises at the site currently[4]. The fire station is a possible source of the elevated PFAS levels in the esker, but to draw more confident conclusions about it, both current and historical usage of PFAS at the site needs to be investigated to see how much PFAS may emit from the site. Another aspect to consider when drawing conclusions about the fire station is to investigate the site using MIFO and measure the PFAS concentrations in the ground and water around the site. More groundwater pipes could be placed upstream and downstream of the site, along with multiple tests for increased reliability. The fire station is likely not the sole contributor to the elevated levels in the Hammarby aquifer.

Another possible source is the landfills. The leachate from landfills has been shown in other studies to have the following emissions of PFAS; PFOS, PFHxS, PFHxA, and PFOA as the most common long-chained 'legacy' PFAS and out of the short-chained substances only 3:3 FTCA and 6:2 FTS

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[4] Maria Wallström, environmental inspector, Upplands Väsby Municipality, meeting 2024-02-24

have been detected (Currell et al. 2024). All the long-chained PFAS mentioned has been detected in all measurements of the esker's groundwater and 6:2 FTS has been detected in a few measurements while 3:3 FTCA has not been measured in any of the measurements. Since most of the substances that have been detected in other studies on landfills have also been detected in Norra Stockholmsåsen, Hammarby, landfills are a possible source of the PFAS contamination in the esker. Landfills had other studies that had investigated the problem, which was not found for some of the other hazardous activities and facilities in the study.

In the literature study no information was found on what PFAS could be connected to engineering industries, surface treatment of metals, electrical engineering industries, and interim storage and sorting station of waste. This has aggravated the possibility of connecting the composition from the sampling to these hazardous activities and facilities. Some of these objects did show an interesting particle tracking in FEFLOW meaning that if they have PFAS emissions to the groundwater they could contribute to the elevated concentrations.

The particles that reached the primary groundwater flow with the Random-Walk Particle-Tracking method all went around some of the points where PFAS had measured high concentrations. The reason for the turn around pipe 5 and 6 is an infiltration in the esker (Johansson 2021). The stormwater infiltrates through a dam at a rate of 5.5 L/s and is led from an area of 0,99 km^2 (Johansson 2021). The infiltration makes the particles move around sample points 5 and 6, and none of the particles touch these pipes. These pipes could therefore be influenced by the stormwater that infiltrates through the dam. There are also other infiltration dams downstream from these dams in the esker (Johansson 2021). These have a much smaller infiltration rate (Johansson 2021) and does not seem to affect the particles as much. The infiltration of stormwater could be a source for PFAS (Chen et al. 2023), but upstream from these, other hazardous activities and facilities such as the fire station may have more influence.

The particle tracking from the fire station touched the second most pipes in the particle tracking. Looking at the particle tracking in the Appendix the particles from the source travel far in a short time. If the fire station has emissions of PFAS the particles would reach far in a short time due to the industry being located right on top of the groundwater flow. This reinforces the fact that the fire station is a possible source for contaminating the groundwater in the esker. The particle tracking does not seem to touch all the pipes where PFAS has been measured, indicating that there is a high possibility of other sources contributing as well. It is very likely that the groundwater flow in the aquifer is not constant over the year or in the infiltration dams, which the model assumes. This can contribute to the particles moving in other paths and patterns like a wider plume. The number of pipes that the particle tracking may be underestimated because of this. The location of the Fire station is located close to the groundwater aquifer which is not the case for all the objects investigated.

Out of five landfills that were particle tracked, four of them did not reach any of the pipes and did not move far from the node they were released. These four landfills are therefore not likely to affect the groundwater short-term but may contaminate the groundwater with its emissions after a long time. The particles were tracked for 65 years and how the particles move after that is unknown. Only one of the particle tracking's from the landfills touched some pipes, in total 5 pipes, making this object a possible contaminator for PFAS in the groundwater. There were other particle trackings from other objects that touched more pipes than this landfill.

The most southern engineering industry, not using halogenated solvents touched most pipes (11) in the particle tracking from its site. One of them being pipe 2, which is only touched from this site and one other. The concentration measured in pipe 2 is the highest measured concentration in Hammarby aquifer. Since this pipe is only touched in two particle trackings (EIWOHS 1 and EIWHS 5), these seem to be the only ones investigated that influences this pipe. They are therefore very likely to be the sources that contributes to the high concentrations. The plume in the particle tracking from EIWHS 5 is the only plume moving through this pipe while the particles released from EIWOHS 1 slightly touches these. The location of this engineering industry (EIWOHS 1) is placed in a position where an emission would affect the groundwater aquifer. However, the particles do not reach far in a short time, the last cross that the particles touch takes 65 years for them to reach.

The particles released from one of the interim storage and sorting station of waste move a lot faster and reaches the last cross in 25 years. The particle tracking from this site touch 9 pipes which is the third most pipes touched. The particles seem to move passed some of the pipes due to the plume dividing in to two after the infiltration dams. Since the particle seem to move faster from this site, this might be a more considerable potential source.

The fifth most southern engineering industry that uses halogenated solvents touches more pipes than the interim storage and sorting station of waste mentioned above. In total it touches 10 pipes, where one of them is the second pipe, that is only touched by this source and one other. Otherwise, the pipes touched by this plume is mainly the same as the others that touches the most pipes.

In the point system the highest score went to the fire station. This is because the location of the groundwater in a high extent and there have been several of the PFAS found in the groundwater that has also been found around fire stations in other studies. Next is the most southern engineering industry not using halogenated solvents which received all its points from the number of pipes that its particle tracking touched. There was no information found about what PFAS was used in these operations. Information of what PFAS had been found around landfills was found in other studies and there were 5 of the ones found that had also been found in the groundwater of Hammarby aquifer. Although 4 of the 5 landfills located around the aquifer was placed in a way where an emission would not affect the groundwater in less than 65 years. But since one of them is located a bit downstream in the esker and the particle tracking shows that there may be 5 pipes touched by emissions from the site, this one could contribute to the high concentrations in the downstream parts of the esker. In these parts the concentration is generally lower than in the beginning, which could indicate that there are no big emissions in this part.

Since there is a lot of information missing on what PFAS are used at the engineering industries, interim storage and sorting stations of waste and surface treatment of metals it is hard to say if these could be potential sources. Investigations about this would be needed to say if these affect the groundwater.

There are several factors that could have affected the result of the study. One is that the particle tracking uses a model of the esker, and the real trajectory of the particles may differ. The model assumes an inflow from dams along E4, which may not be constant and therefore the particles could move in another way. The particle tracking was executed in the model with no extractions from the extraction well and when developing the model some trial pumpings were implemented (Johansson & Djurberg 2019) which can have affected particles to move differently in the last 65 years. The particles in the particle tracking do not have any properties indicating that they are PFAS particles, meaning that the transport of PFAS in the groundwater could differ. PFAS can stick and get delayed by particles in the soil and therefore the plume of emission would travel slower than the flow of groundwater (Kemikalieinspektionen 2021). The particle tracking may not be a real representation of how PFAS moves in the esker. Another factor influencing the result is the analytical uncertainty of the measurements from Eurofins.

6. CONCLUSIONS

The reason for the elevated levels in Norra Stockholmsåsen, Hammarby seems to be more than one single source. Although, since variations in the groundwater flow have not been considered, the possibility of there being only one source cannot be ruled out. The fire station in Upplands Väsby, the most southern engineering industry not using halogenated solvents and the fifth most southern engineering industry using halogenated solvents seems to be reasonable candidates for the upstream parts of the aquifer, where the highest concentrations have been measured. The use of PFAS at these sites should be further investigated. Some of the detected PFAS from the measurements are substances that typically have been found in connection with fire stations and landfills. This could mean that the reason for these PFAS in the groundwater is the fire station or the landfill. The landfill above the aquifer is located further downstream and does not influence the pipes upstream, the ones that have measured the higher concentrations. To be more secure if these sites contribute to the PFAS levels in the groundwater more investigations around them needs to be done. These investigations would need to sample the groundwater closer to the sites and see what PFAS are used at the sites. To more confidently say what sources are responsible for the elevated levels of PFAS in the groundwater some of the sources need to be further investigated. The investigation needs to examine the hazardous activities and facilities use of PFAS at the sites and if the PFAS used is collected.

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8. Appendix

8.1. Substances included in PFAS 4 and PFAS 21

Table 3: Showing which substances are included in the groups PFAS 4 and PFAS 21

PFAS 21	PFAS 4	Perfluoroktansyra (PFOA)
		Perfluornonansyra (PFNA)
		Perfluorhexansulfonsyra (PFHxS)
		Perfluoroktansulfonsyra (PFOS)
		Perfluorbutansyra (PFBA)
		Perfluorpentansyra (PFPA)
		Perfluorhexansyra (PFHxA)
		Perfluorheptansyra (PFHpA)
		Perfluordekansyra (PFDA)
		Perfluorundekansyra (PFUnDA)
		Perfluordodekansyra (PFDoDA)
		Perfluortridekansyra (PFTrDA)
		Perfluorbutansulfonsyra (PFBS)
		Perfluorpentansulfonsyra (PFPS)
		Perfluorheptansulfonsyra (PFHpS)
		Perfluornonansulfonsyra (PFNS)
		Perfluordekansulfonsyra (PFDS)
		Perfluorundekansulfonsyra (PFUnDS)
		Perfluordodekansulfonsyra (PFDoDS)
		Perfluortridekansulfonsyra (PFTrDS)
		Fluortelomersulfonsyra (6:2 FTS)

8.2. ID for pipes

Table 4: The name that the pipes had in the report and their actual ID given by Norrvatten.

name in report	ID
1	rb2109
2	Rb2113
3	u6, rödtopp
4	nr2 (norra)
5	9101
6	8302
7	17SW03GW
8	9203_2
9	9202
10	1401
11	0109
12	1403_a
13	1403_b
14	1405
15	Hammarby källa
HWP	Hammarby vattenverk
16	1407 - B
17	1408
18	Löwenströmska

8.3. Measurements of PFAS in Upplands Väsby – Hammarby in 2019

Table 5: PFAS measurements executed in 2019 on the groundwater from Norra Stockholmsåsen, Hammarby.

Provets märkning	**9203_2**	**9202_2**	**1401**	**1403_b**	**1403_a**	**1405**
Provtagningsdag	2019-09-27	2019-09-27	2019-09-27	2019-09-23	2019-09-23	2019-09-23
PFBA (Perfluorbutansyra)	5.7	8	8.2	2.9	3.9	2.5
PFPeA (Perfluorpentansyra)	16	25	26	6.3	12	5.9
PFHxA (Perfluorhexansyra)	9.5	14	14	4.8	8.3	3.8
PFHpA (Perfluorheptansyra)	5.7	7.6	7.3	2.8	4.1	2.3
PFOA (Perfluoroktansyra)	3.1	4.1	4.6	2.9	3.3	2.9
PFNA (Perfluornonansyra)	0.37	0.46	0.56	<0,30	<0,30	<0,30
PFDA (Perfluordekansyra)	<0,30	<0,30	<0,30	<0,30	<0,30	<0,30
PFUdA (Perfluorundekansyra)	<0,30	<0,30	<0,30	<0,30	<0,30	<0,30
PFDoA (Perfluordodekansyra)	<0,30	<0,30	<0,30	<0,30	<0,30	<0,30
PFTeDA (Perfluortetradekansyra)	<0,30	<0,30	<0,30	<< 1,0	<< 1,0	<< 1,0
PFHxDA (Perfluorhexadekansyra)	<0,30	<0,30	<0,30	<0,30	<0,30	<0,30
HPFHpA (7H-Perfluorheptansyra)	<0,30	<0,30	<0,30	<0,30	<0,30	<0,30
P37DMOA (Perfluor-3,7-dimetyloktansyra)	<0,30	<0,30	<0,30	<< 2,0	<< 2,0	<< 2,0
PFBS (Perfluorbutansulfonsyra)	2.4	2.7	2.8	2.7	2.9	2.9
PFHxS (Perfluorhexansulfonsyra)	7.6	13	14	12	12	12
PFHpS (Perfluorheptansulfonsyra)	0.33	0.6	0.6	0.35	0.58	0.38
PFOS (Perfluoroktansulfonsyra)	17	25	26	7.4	12	5.4
PFDS (Perfluordekansulfonsyra)	<0,30	<0,30	<0,30	<0,30	<0,30	<0,30
4:2 FTS (Fluortelomer sulfonat)	<0,30	<0,30	<0,30	<0,30	<0,30	<0,30
6:2 FTS (Fluortelomer sulfonat)	<0,30	<0,30	<0,30	1.9	1.5	<0,30
8:2 FTS (Fluortelomer sulfonat)	<0,30	<0,30	<0,30	<0,30	<0,30	<0,30
PFOSA (Perfluoroktansulfonamid)	<0,30	<0,30	<0,30	<0,30	<0,30	<0,30
EtFOSA (N-etylperfluoroktansulfonamid)	<20	<20	<20	<20	<20	<20
EtFOSAA (N-etylperfluoroktansulfonamid-ättiksyra)	<0,30	<0,30	<0,30	<0,30	<0,30	<0,30
EtFOSE (N-etylperfluoroktansulfonamid-etanol)	<10	<10	<10	<10	<10	<10
FOSAA (Perfluoroktansulfonamid-ättiksyra)	<0,30	<0,30	<0,30	<0,30	<0,30	<0,30
MeFOSA (N-metylperfluoroktansulfonamid)	<10	<10	<10	<10	<10	<10
MeFOSAA (N-metylperfluoroktansulfonamid-ättiksyra)	<0,30	<0,30	<0,30	<0,30	<0,30	<0,30
MeFOSE (N-metylperfluoroktansulfonamid-etanol)	<10	<10	<10	<10	<10	<10
PFDoS (Perfluordodekansulfonat)	<1,0	<1,0	<1,0	<1,0	<1,0	<1,0
PFNS (Perfluornonansulfonat)	<0,30	<0,30	<0,30	<0,30	<0,30	<0,30

PFODA (Perfluoroktadekansyra)	<1,0	<1,0	<1,0	<1,0	<1,0	<1,0
PFPeS (Perfluorpentansulfonat)	1	1.3	1.4	1.4	1.8	1.8
PFTrDA (Perfluortridekansyra)	<1,0	<1,0	<1,0	<1,0	<1,0	<1,0

Provets märkning	**Hammarby källa**	**Hammarby vv**	**1407 - B**	**Löwenströmska**	**1409_b**
Provtagningsdag	2019-09-23	2019-09-23	2019-09-23	2019-09-23	2019-09-23
PFBA (Perfluorbutansyra)	6	5.3	3.7	3.8	<0,60
PFPeA (Perfluorpentansyra)	18	17	8.5	12	<0,30
PFHxA (Perfluorhexansyra)	10	11	6	6.8	0.46
PFHpA (Perfluorheptansyra)	5.5	5.5	3.5	3.5	<0,30
PFOA (Perfluoroktansyra)	4.2	3.8	2.9	2.9	0.35
PFNA (Perfluornonansyra)	0.33	0.3	<0,30	<0,30	<0,30
PFDA (Perfluordekansyra)	<0,30	<0,30	<0,30	<0,30	<0,30
PFUdA (Perfluorundekansyra)	<0,30	<0,30	<0,30	<0,30	<0,30
PFDoA (Perfluordodekansyra)	<0,30	<0,30	<0,30	<0,30	<0,30
PFTeDA (Perfluortetradekansyra)	<< 1,0	<0,30	<0,30	<< 1,0	<< 1,0
PFHxDA (Perfluorhexadekansyra)	<0,30	<0,30	<0,30	<0,30	<0,30
HPFHpA (7H-Perfluorheptansyra)	<0,30	<0,30	<0,30	<0,30	<0,30
P37DMOA (Perfluor-3,7-dimetyloktansyra)	<< 2,0	<0,30	<0,30	<< 2,0	<< 2,0
PFBS (Perfluorbutansulfonsyra)	2.7	2.6	2.8	2.9	1
PFHxS (Perfluorhexansulfonsyra)	14	12	12	13	2.5
PFHpS (Perfluorheptansulfonsyra)	0.79	0.58	0.52	0.54	<0,30
PFOS (Perfluoroktansulfonsyra)	17	18	7.3	7.5	0.6
PFDS (Perfluordekansulfonsyra)	<0,30	<0,30	<0,30	<0,30	<0,30
4:2 FTS (Fluortelomer sulfonat)	<0,30	<0,30	<0,30	<0,30	<0,30
6:2 FTS (Fluortelomer sulfonat)	<0,30	<0,30	<0,30	<0,30	<0,30
8:2 FTS (Fluortelomer sulfonat)	<0,30	<0,30	<0,30	<0,30	<0,30
PFOSA (Perfluoroktansulfonamid)	<0,30	<0,30	<0,30	<0,30	<0,30
EtFOSA (N-etylperfluoroktansulfonamid)	<20	<20	<20	<20	<20
EtFOSAA (N-etylperfluoroktansulfonamid-ättiksyra)	<0,30	<0,30	<0,30	<0,30	<0,30
EtFOSE (N-etylperfluoroktansulfonamid-etanol)	<10	<10	<10	<10	<10
FOSAA (Perfluoroktansulfonamid-ättiksyra)	<0,30	<0,30	<0,30	<0,30	<0,30
MeFOSA (N-metylperfluoroktansulfonamid)	<10	<10	<10	<10	<10
MeFOSAA (N-metylperfluoroktansulfonamid-ättiksyra)	<0,30	<0,30	<0,30	<0,30	<0,30
MeFOSE (N-metylperfluoroktansulfonamid-etanol)	<10	<10	<10	<10	<10

PFDoS (Perfluordodekansulfonat)	<1,0	<1,0	<1,0	<1,0	<1,0
PFNS (Perfluornonansulfonat)	<0,30	<0,30	<0,30	<0,30	<0,30
PFODA (Perfluoroktadekansyra)	<1,0	<1,0	<1,0	<1,0	<1,0
PFPeS (Perfluorpentansulfonat)	1.6	1.5	1.7	1.9	0.51
PFTrDA (Perfluortridekansyra)	<1,0	<1,0	<1,0	<1,0	<1,0

8.4.Measurements of PFAS in Upplands Väsby – Hammarby in 2022

Table 6: pH and PFAS data for measurements executed in 2022 in groundwater pipes Norra Stockholmsåsen, Hammarby 2022.

Provmärkning	**rb2109**	**u6**	**8302**	**17SW03GW**	**9202 2**	**109**	**1408**
Ankomstdatum	2022-12-01	2022-11-02	2022-10-21	2022-10-19	2022-10-19	2022-10-06	2022-10-06
pH	7.00	7.40	7.50	7.40	-	7.60	7.60
P37DMOA - Perfluor-3,7-dimetyloktansyra	<2,0	<2,0	<2,0	<2,0	<2,0	<2,0	<2,0
PFBA - Perfluorbutansyra	5.5	12	10	5	6.6	6.2	4.5
PFBS - Perfluorbutansulfonsyra	1.5	1.9	1.9	2.2	1.8	1.7	1.7
PFDA - Perfluordekansyra	<0,30	<0,30	<0,30	<0,30	<0,30	<0,30	<0,30
PFDoA - Perfluordodekansyra	<0,30	<0,30	<0,30	<0,30	<0,30	<0,30	<0,30
PFDoS - Perfluordodekansulfonat	<1,0	<1,0	<1,0	<1,0	<1,0	<1,0	<1,0
PFDS - Perfluordekansulfonsyra	<0,30	<0,30	<0,30	<0,30	<0,30	<0,30	<0,30
PFHpA - Perfluorheptansyra	0.52	12	8.8	5	5.9	6.1	4
PFHpS - Perfluorheptansulfonsyra	<0,30	0.55	0.47	0.39	0.35	0.34	0.3
PFHxA - Perfluorhexansyra	0.98	17	17	8.6	9.8	10	6.9
PFHxDA - Perfluorhexadekansyra	<0,30	<0,30	<0,30	<0,30	<0,30	<0,30	<0,30
PFHxS - Perfluorhexansulfonsyra	<0,30	17	13	10	11	10	10
PFNA - Perfluornonansyra	<0,30	0.44	0.77	<0,30	0.35	0.39	<0,30
PFNS - Perfluornonansulfonat	<0,30	<0,30	<0,30	<0,30	<0,30	<0,30	<0,30
PFOA - Perfluoroktansyra	0.55	4.5	5	3.5	3.8	3.7	3.4
PFODA - Perfluoroktadekansyra	<0,30	<0,30	<0,30	<0,30	<0,30	<0,30	<0,30
PFOS - Perfluoroktansulfonsyra	0.84	27	21	13	16	17	9.1
PFOS - Perfluoroktansulfonsyra	0.84	27	21	13	16	17	9.1
PFOSA - Perfluoroktansulfonamid	<0,30	0.95	<0,30	<0,30	<0,30	<0,30	<0,30
PFPeA - Perfluorpentansyra	1.4	37	22	14	17	17	11
PFPeS - Perfluorpentansulfonat	<0,30	1.6	1.1	1.2	1.2	1.1	1.2
PFTeDA - Perfluortetradekansyra	<1,0	<1,0	<1,0	<1,0	<1,0	<1,0	<1,0
PFTrDA - Perfluortridekansyra	<1,0	<1,0	<1,0	<1,0	<1,0	<1,0	<1,0
PFTrDS - Perfluortridekansulfonsyra	<1,0	<1,0	<1,0	<1,0	<1,0	<1,0	<1,0
PFUdA - Perfluorundekansyra	<0,30	<0,30	<0,30	<0,30	<0,30	<0,30	<0,30
PFUnDS - Perfluorundekansulfonsyra	<1,0	<1,0	<1,0	<1,0	<1,0	<1,0	<1,0

8.5. Measurements of PFAS in Upplands Väsby – Hammarby in 2024

Table 7: pH and PFAS data for measurements executed in 2024 in groundwater pipes Norra Stockholmsåsen, Hammarby 2022.

Provanmärkning	**Rb2113**	**nr2 (norra)**	**9101**	**8302**	**17SW03GW**
Ankomstdatum	2024-03-23	2024-03-23	2024-03-23	2024-03-23	2024-03-23
pH	7.4	7.6	7.3	7.6	7.7
PFBA (Perfluorbutansyra)	18	11	3.8	9.5	7.30
PFPeA (Perfluorpentansyra)	49	30	8.2	19	18.00
PFHxA (Perfluorhexansyra)	24	17	4.2	11	9.70
PFHpA (Perfluorheptansyra)	15	11	2.7	7.1	5.90
PFOA (Perfluoroktansyra)	5.6	3.6	3	3.1	3.50
PFNA (Perfluornonansyra)	0.88	0.36	0.88	0.51	<0.30
PFDA (Perfluordekansyra	0.93	<0.30	0.62	0.36	<0.30
PFUdA (Perfluorundekansyra)	<0.30	<0.30	<0.30	<0.30	<0.30
PFDoA (Perfluordodekansyra)	<0.30	<0.30	<0.30	<0.30	<0.30
PFTeDA (Perfluortetradekansyra)	<1.0	<1.0	<1.0	<1.0	<1.0
PFHxDA (Perfluorhexadekansyra)	<0.30	<0.30	<0.30	<0.30	<0.30
HPFHpA (7H-Perfluorheptansyra)	<0.30	<0.30	<0.30	<0.30	<0.30
P37DMOA (Perfluor-3,7-dimetyloktansyra)	<2.0	<2.0	<2.0	<2.0	<2.0
PFBS (Perfluorbutansulfonsyra)	1.5	2.3	1.2	1.5	2.00
PFHxS (Perfluorhexansulfonsyra)	8	15	0.83	11	11.00
PFHpS (Perfluorheptansulfonsyra)	0.42	0.48	<0.30	0.4	0.42
PFOS (Perfluoroktansulfonsyra)	20	20	2.5	13	14.00
PFDS (Perfluordekansulfonsyra)	<0.30	<0.30	<0.30	<0.30	<0.30
4:2 FTS (Fluortelomer sulfonat)	<0.30	<0.30	<0.30	<0.30	<0.30
6:2 FTS (Fluortelomer sulfonat)	3.1	0.99	0.72	0.77	<0.30
8:2 FTS (Fluortelomer sulfonat)	<0.30	<0.30	<0.30	<0.30	<0.30
PFOSA (Perfluoroktansulfonamid)	<0.30	<0.30	<0.30	<0.30	<0.30
PFTrDA (Perfluortridekansyra)	<1.0	<1.0	<1.0	<1.0	<1.0
PFDoS (Perfluordodekansulfonat)	<1.0	<1.0	<1.0	<1.0	<1.0
PFNS (Perfluornonansulfonat)	<0.30	<0.30	<0.30	<0.30	<0.30
PFPeS (Perfluorpentansulfonat)	1.3	1.7	<0.30	1.4	1.40
PFTrDS (Perfluortridekansulfonsyra)	<0.30	<0.30	<0.30	<0.30	<0.30
PFUnDS (Perfluorundekansulfonsyra)	<0.30	<0.30	<0.30	<0.30	<0.30
EtFOSA (N-etylperfluoroktansulfonamid)	<1.0	<1.0	<1.0	<1.0	<1.0

EtFOSAA (N-etylperfluoroktansulfonamid-ättiksyra)	<0.30	<0.30	<0.30	<0.30	<0.30
EtFOSE (N-etylperfluoroktansulfonamid-etanol)	<1.0	<1.0	<1.0	<1.0	<1.0
FOSAA (Perfluoroktansulfonamid-ättiksyra)	<0.30	<0.30	<0.30	<0.30	<0.30
MeFOSA (N-metylperfluoroktansulfonamid)	<1.0	<1.0	<1.0	<1.0	<1.0
MeFOSAA (N-metylperfluoroktansulfonamid-ättiksyra)	<0.30	<0.30	<0.30	<0.30	<0.30
MeFOSE (N-metylperfluoroktansulfonamid-etanol)	<1.0	<1.0	<1.0	<1.0	<1.0
PFODA (Perfluoroktadekansyra)	<0.30	<0.30	<0.30	<0.30	<0.30

8.6. The measured PFAS in 2019, 2022, 2024 and Hammarby water plant

Table 8: The PFAS measured in samples from 2019, 2022, 2024 and the last three measurements from the water plant in Hammarby(HWP). TRUE means that the substance was measured while FALSE means it was not.

PFAS	2019	2022	2024	HWP
4:2 FTS (Fluortelomer sulfonat)	TRUE	TRUE	TRUE	TRUE
6:2 FTS (Fluortelomer sulfonat)	TRUE	TRUE	TRUE	TRUE
8:2 FTS (Fluortelomer sulfonat)	TRUE	TRUE	TRUE	TRUE
EtFOSA (N-etylperfluoroktansulfonamid)	TRUE	TRUE	TRUE	TRUE
EtFOSAA (N-etylperfluoroktansulfonamid-ättiksyra)	TRUE	TRUE	TRUE	TRUE
EtFOSE (N-etylperfluoroktansulfonamid-etanol)	TRUE	TRUE	TRUE	TRUE
FOSAA (Perfluoroktansulfonamid-ättiksyra)	TRUE	TRUE	TRUE	TRUE
HPFHpA (7H-Perfluorheptansyra)	TRUE	TRUE	TRUE	TRUE
MeFOSA (N-metylperfluoroktansulfonamid)	TRUE	TRUE	TRUE	TRUE
MeFOSAA (N-metylperfluoroktansulfonamid-ättiksyra)	TRUE	TRUE	TRUE	TRUE
MeFOSE (N-metylperfluoroktansulfonamid-etanol)	TRUE	TRUE	TRUE	TRUE
P37DMOA (Perfluor-3,7-dimetyloktansyra)	TRUE	TRUE	TRUE	TRUE
PFBA (Perfluorbutansyra)	TRUE	TRUE	TRUE	TRUE
PFBS (Perfluorbutansulfonsyra)	TRUE	TRUE	TRUE	TRUE
PFDA (Perfluordekansyra)	TRUE	TRUE	TRUE	TRUE
PFDoA (Perfluordodekansyra)	TRUE	TRUE	TRUE	TRUE
PFDoS (Perfluordodekansulfonat)	TRUE	TRUE	TRUE	TRUE
PFDS (Perfluordekansulfonsyra)	TRUE	TRUE	TRUE	TRUE
PFHpA (Perfluorheptansyra)	TRUE	TRUE	TRUE	TRUE
PFHpS (Perfluorheptansulfonsyra)	TRUE	TRUE	TRUE	TRUE
PFHxA (Perfluorhexansyra)	TRUE	TRUE	TRUE	TRUE
PFHxDA (Perfluorhexadekansyra)	TRUE	TRUE	TRUE	TRUE
PFHxS (Perfluorhexansulfonsyra)	TRUE	TRUE	TRUE	TRUE
PFNA (Perfluornonansyra)	TRUE	TRUE	TRUE	TRUE
PFNS (Perfluornonansulfonat)	TRUE	TRUE	TRUE	TRUE
PFOA (Perfluoroktansyra)	TRUE	TRUE	TRUE	TRUE
PFODA (Perfluoroktadekansyra)	TRUE	TRUE	TRUE	FALSE
PFOS (Perfluoroktansulfonsyra)	TRUE	TRUE	TRUE	TRUE
PFOSA (Perfluoroktansulfonamid)	TRUE	TRUE	TRUE	TRUE
PFPeA (Perfluorpentansyra)	TRUE	TRUE	TRUE	TRUE
PFPeS (Perfluorpentansulfonat)	TRUE	TRUE	TRUE	TRUE
PFTeDA (Perfluortetradekansyra)	TRUE	TRUE	TRUE	TRUE

PFTrDA (Perfluortridekansyra)	TRUE	TRUE	TRUE	TRUE
PFTrDS (Perfluortridekansulfonsyra)	FALSE	TRUE	TRUE	TRUE
PFUdA (Perfluorundekansyra)	TRUE	TRUE	TRUE	TRUE
PFUnDS (Perfluorundekansulfonsyra)	FALSE	TRUE	TRUE	TRUE

8.7. Particle Tracking

8.7.1. Fire station

In Figure 15 the particle tracking from the fire station is presented. Purple and blue are the colors that are primarily occurring in the particles, which indicates that it has taken the particle less than 40 years to reach those points. There are some green and orange particles corresponding to a transport time of 70 and 90 years. At the most northern cross there are particles of different colors, such as purple, blue and green. Particles can therefore reach this cross in different times depending on the trajectory they take. The particles move in a plume that does not change its width excessively in the groundwater. The particles touch 11 sample points before reaching the one most downstream, while others are not even near the route the particles are taking.

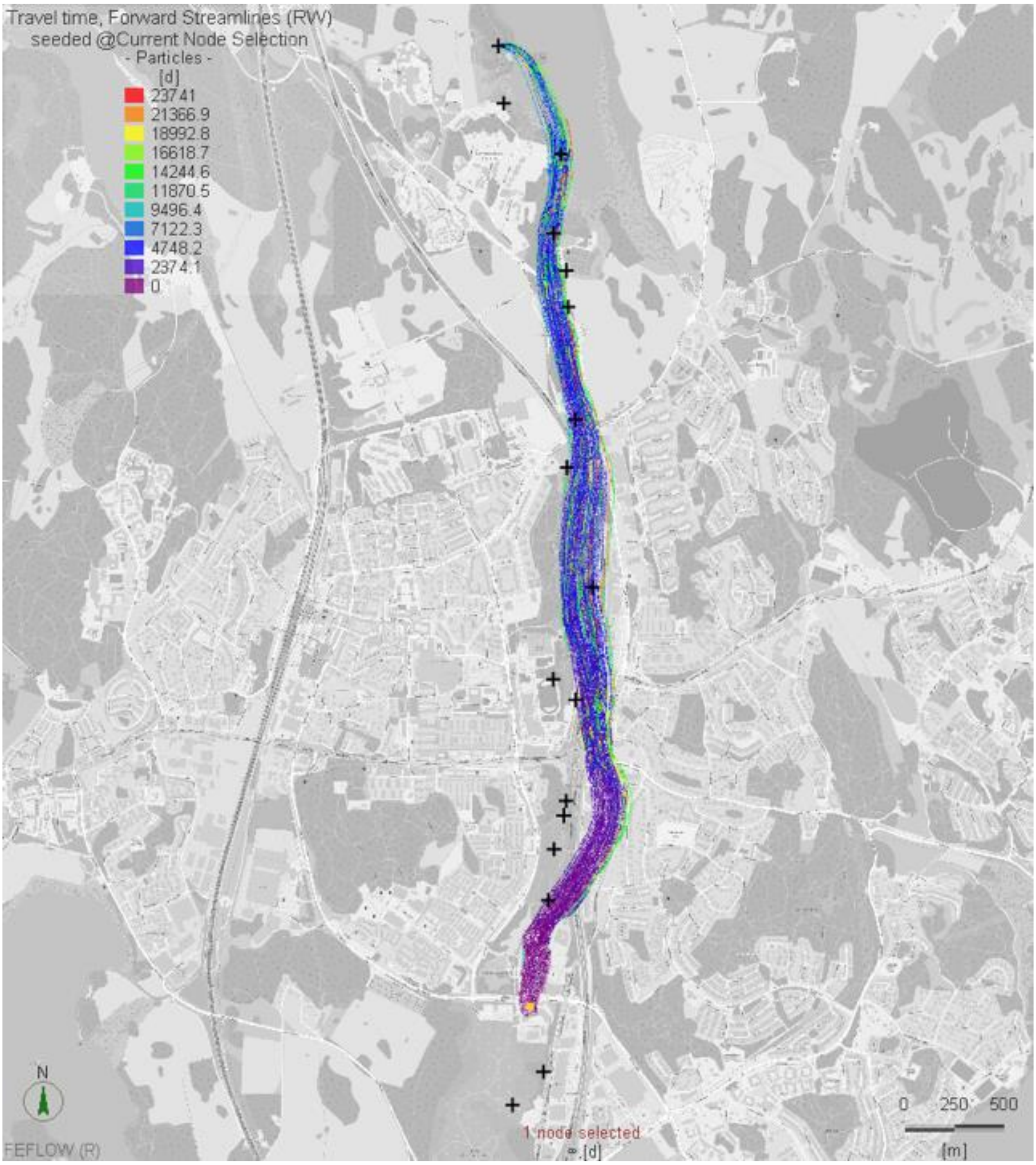

Figure 15: Particle tracking from the fire station located on the esker. The black crosses are where the measurements are located. The yellow dot is the nearest node in the model to the fire station.

8.7.2. Landfills

One of the five landfills that were particle tracked from had a result where the particles reached further than 200 m and into the groundwater aquifer. When particles are released from the landfill located most upstream, *Landfill 1*, in the esker it takes about 10 years for them to reach the most northern sample point as seen in Figure 16. There are some particles colored blue, that has a transport time to its destination for less than 40 years. The plume has a constant width from the starting node to the last sample point. Out of the 10 sample points that the plume passes more than half of them are touched by the plume.

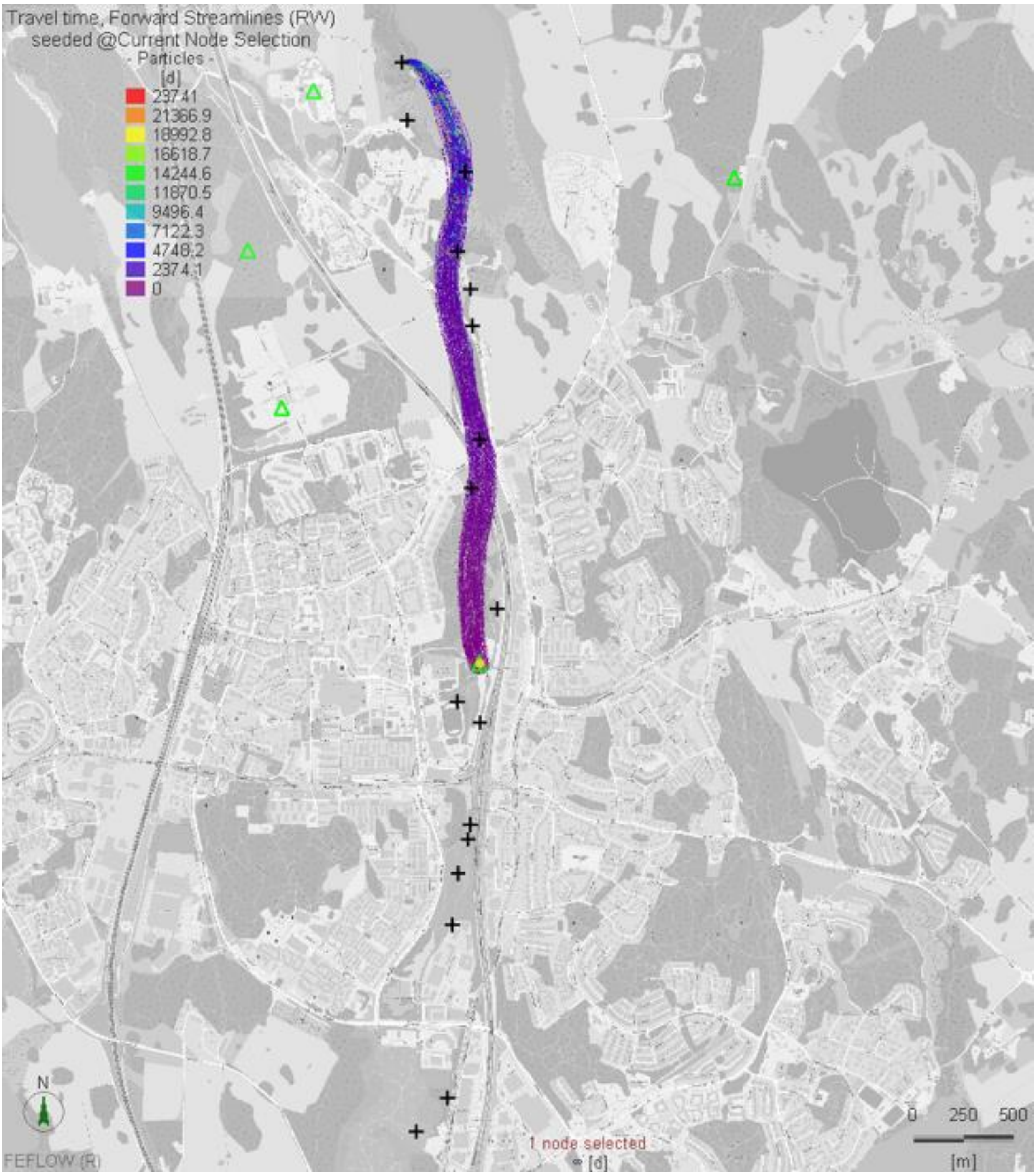

Figure 16: Particle tracking from one of the landfills. The yellow dot is the nearest node, the green triangle is the location of the landfill, and the black crosses are points were PFAS have been measured 2019, 2022 or 2024.

The next landfill, *Landfill 2*, was located just outside the outlines of the model. The nearest node was selected, but as seen to the left in Figure 17 the particles from the particle tracking does not travel that far. The particles did not move far from the radius they were released from, barely 100 m, and did therefore not cross any of the points that measured PFAS. The next particle tracking of a landfill, *Landfill 3*, presented to the right in Figure 17 barely moved from the node it was released, not even 100 m. This landfill is located outside the outline of the model but still having the nearest node selected. The particles do not cross any of the sample points. The next particle trackings from, *Landfill 4* (left side) and *Landfill 5* (right side), moves a few meters from the released node as seen in Figure 18. The particles do not touch any of the black crosses where PFAS have been measured. *Landfill 4* is located slightly outside the model outlines.

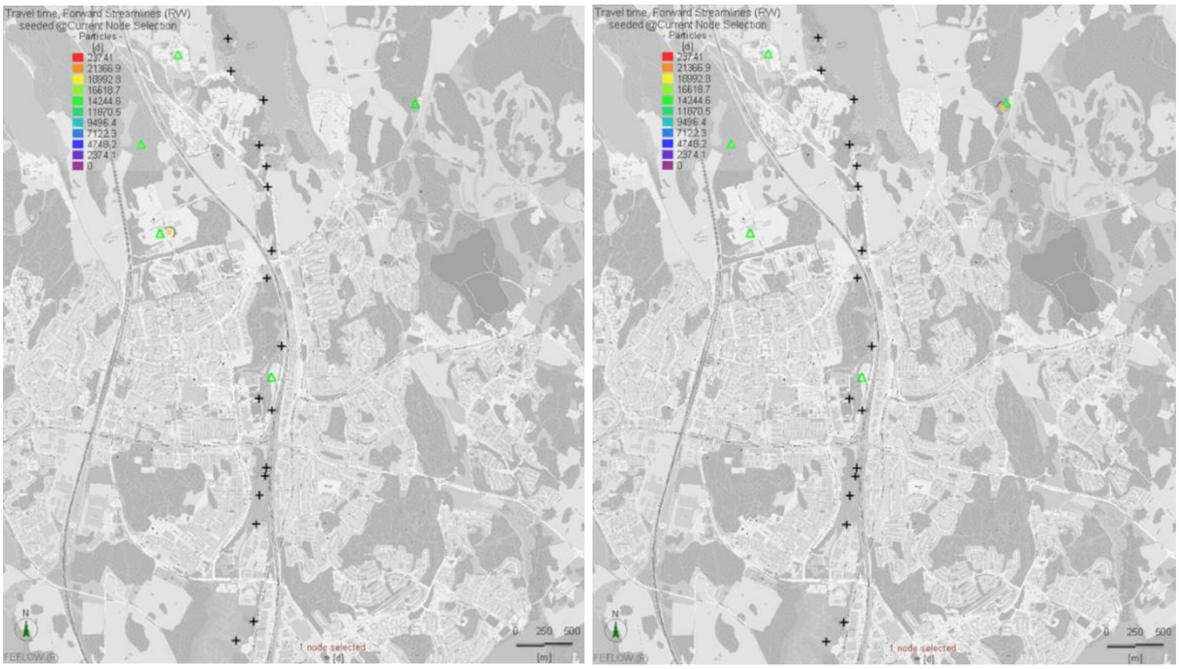

Figure 17: Particle tracking from two of the landfills, Landfill 2 to the left and Landfill 3 to the right. The yellow dot is the nearest node, the green triangle is the location of the landfill, and the black crosses are points were PFAS have been measured 2019, 2022 or 2024.

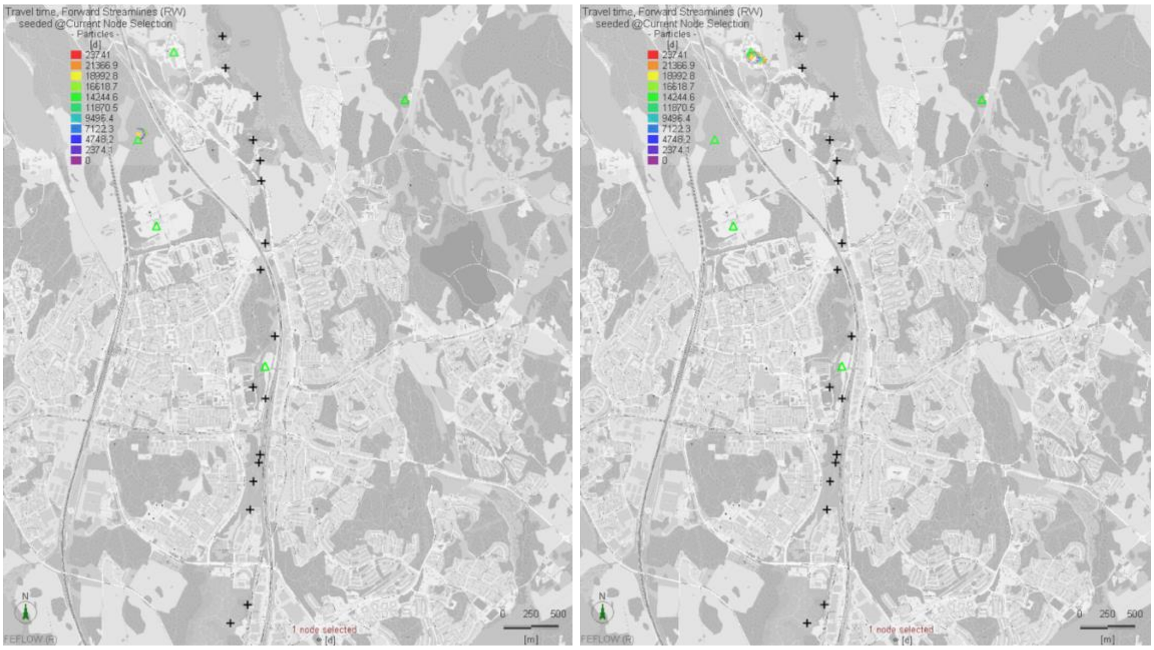

Figure 18: Particle tracking from two of the landfills, Landfill 4 (left side) and Landfill 5 (right side). The yellow dot is the nearest node, the green triangle is the location of the landfill, and the black crosses are points were PFAS have been measured 2019, 2022 or 2024.

8.7.3. Engineering industry

The engineering industries in the area are categorized as either an engineering industry using halogenated solvents or an engineering industry not using halogenated solvents. In the area there were 13 using halogenated solvents and 7 not using halogenated solvents.

With halogenated solvents

The particle tracking of *Engineering industry using halogenated solvents 1* (EIWHS 1, left) and EIWHS 2 (right) is presented in Figure 19. For EIWHS 1 the particles do not move far in 65 years and does not cross any of the sample points. The color on the particles quickly changes from purple to yellow/red, indicating a very slow start. The particles start moving in a wide plume but after a while the plume gets narrower. The particles from EIWHS 2 presented on the right side of Figure 19 touch none of the crosses and does not move half the distance to the lake. The particles change color quickly and distinctively indicating. The particles move in a plume that gets narrower quite fast.

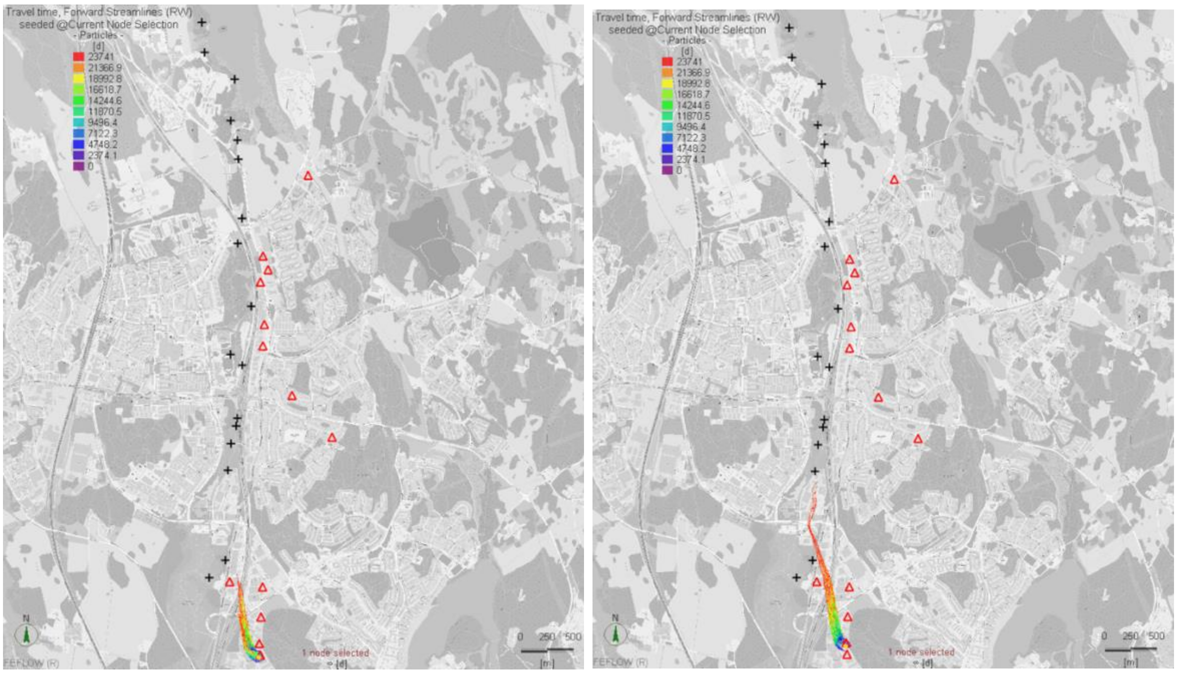

Figure 19: Particle tracking from two Engineering industry using halogenated solvents, EIWHS 1 (left) and EIWHS 2 (right). The yellow dot is the nearest node, the red triangles are the locations of the industries, and the black crosses are points were PFAS have been measured 2019, 2022 or 2024.

On the left side of Figure 20 the particle tracking from another engineering industry using halogenated solvents (EIWHS 3) is presented. It is seen that the colors quite quickly change to green and yellow. This means that the movement in the beginning is quite slow before speeding up when reaching the groundwater flow. The particles move in a narrow plume at the beginning. The particles touch 3 of the of the points where PFAS has been measured. On the right side of Figure 20 particle tracking from EIWHS 2 is presented. The particles reach into the lake and the most northern sample point. The transport is slow in the beginning but once reaching the groundwater flow the particles moves faster. In this case the particles are moving in a plume for a long distance but near the lake there are just single particles travelling alone. The particles touch 5 of the points where PFAS has been measured.

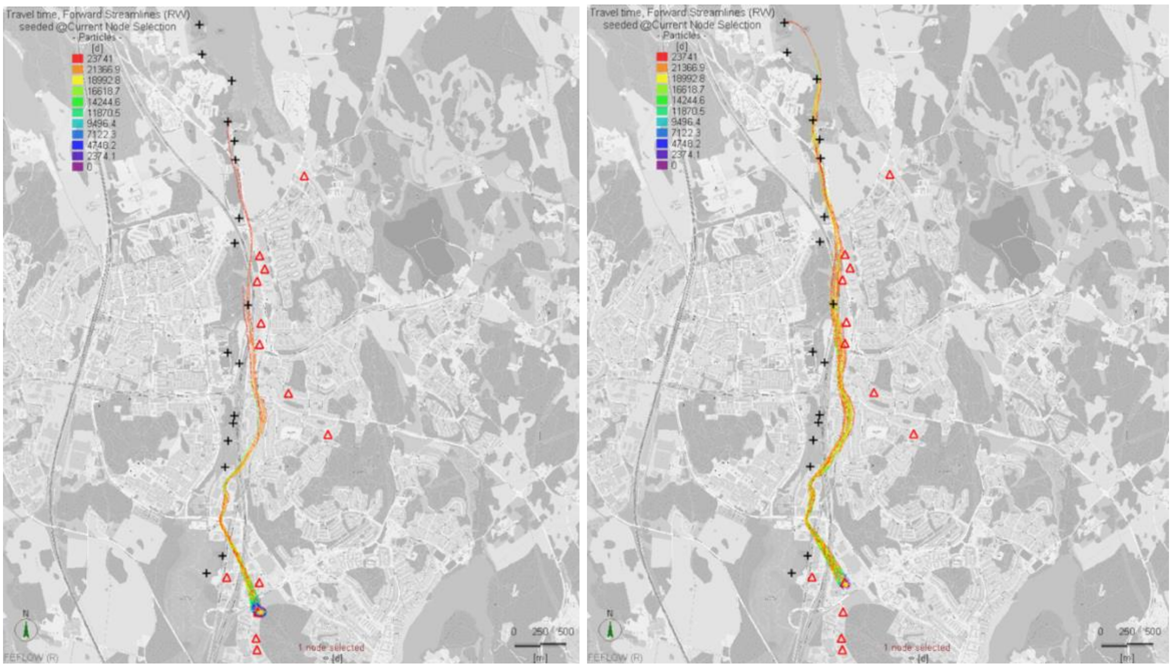

Figure 20: Particle tracking from two Engineering industries using halogenated solvents, EIWHS 3 (left) and EIWHS 4 (right). The yellow dot is the nearest node, the red triangles is the location of the industries, and the black crosses are points were PFAS have been measured 2019, 2022 or 2024.

On the left side of Figure 21 the particle tracking from EIWHS 5 is seen to move quite fast since there are a lot of blue and green particles along the whole way. Some of the particles gets to the most northern cross in 12 years while others take longer time, up to 65 years. The plume touch 10 of the crosses. In the beginning the plume moves right through the second visible cross. On the right side of Figure 21 the particle tracking from EIWHS 6 is presented. These particles do not move further than 250 m in 65 years and does therefore touch 0 of the sample points that have measured PFAS.

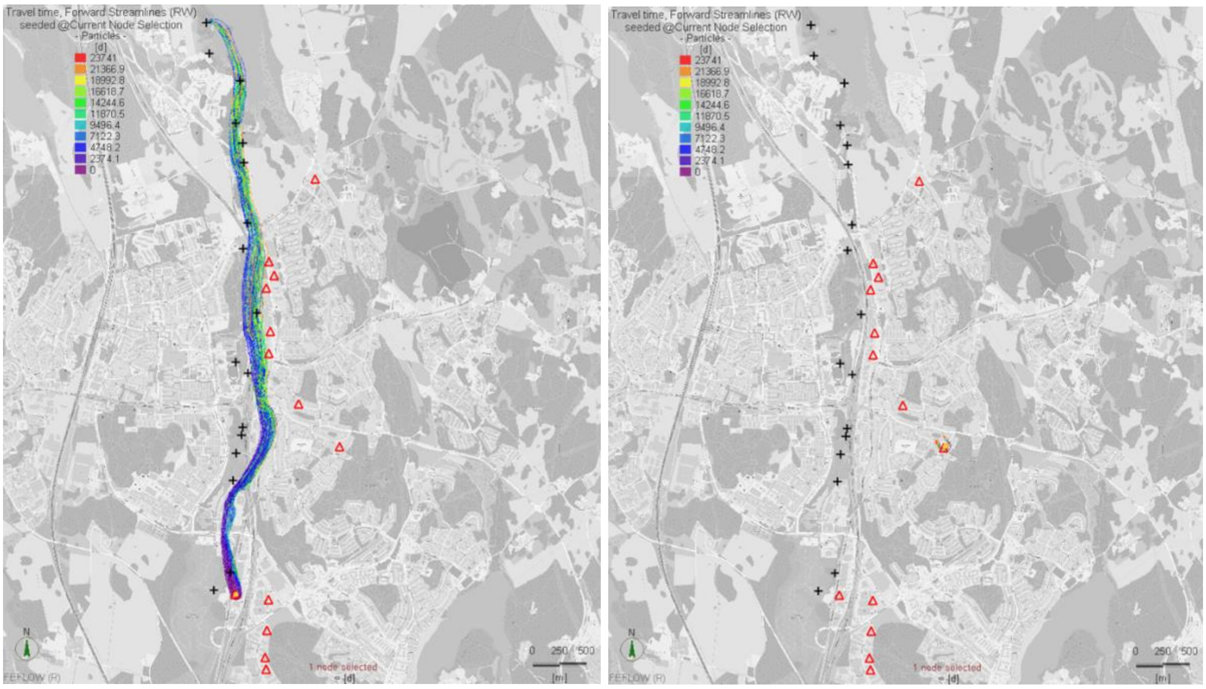

Figure 21: Particle tracking from two Engineering industries using halogenated solvents, EIWHS 5 (left) and EIWHS 6 (right). The yellow dot is the nearest node, the red triangles is the location of the industries, and the black crosses are points were PFAS have been measured 2019, 2022 or 2024.

In Figure 22 the particle tracking from EIWHS 7 (left) is presented. The particles are purple/blue in the beginning and abruptly changes to green and yellow at the same time as the plume narrows down.

In the beginning the particles move quite slow and then after a while they move even faster and get all the way to the most northern cross. The plume touch 6 crosses and reach all the way to the lake and the most northern cross in 65 years. To the right in Figure 22 presents EIWHS 8 and the particle tracking from it. Since the color of the particles are generally blue and green, it does not take longer than 40 years for the plume to reach the most northern cross. The plume touch 6 of the points that has measured PFAS.

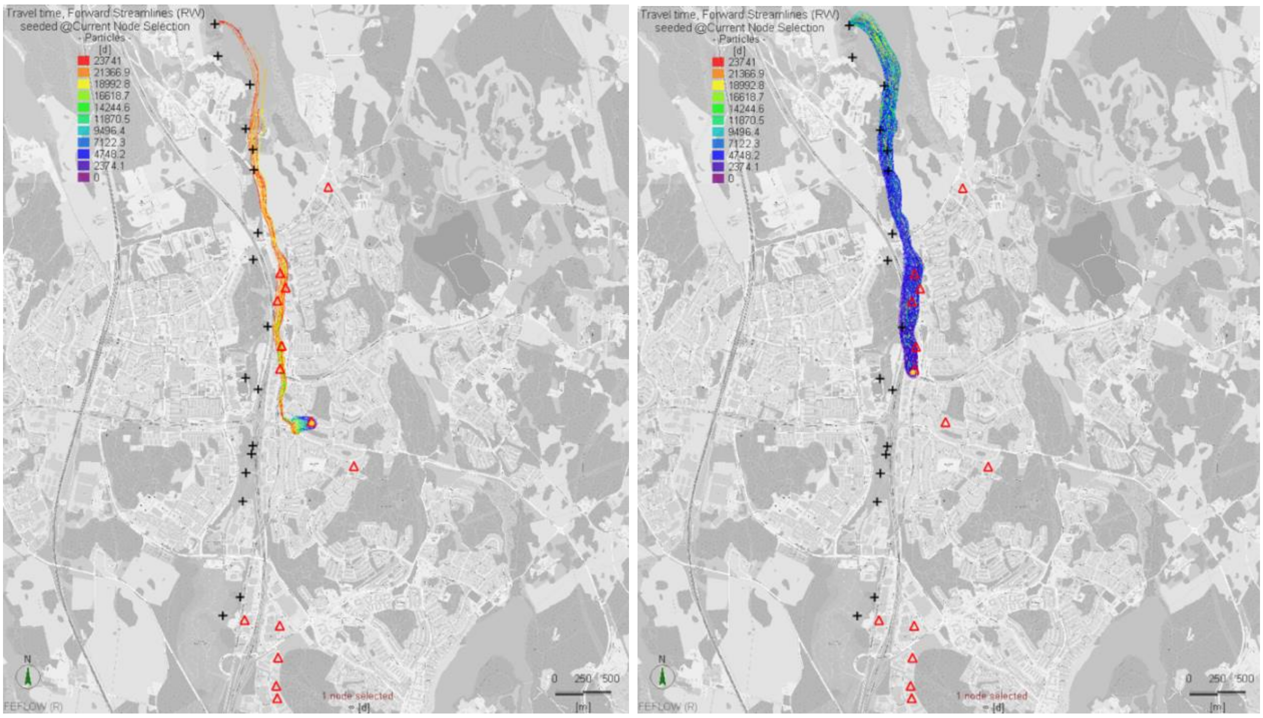

Figure 22: Particle tracking from two Engineering industries using halogenated solvents, EIWHS 7 (left) and EIWHS 8 (right). The yellow dot is the nearest node, the red triangles is the location of the industries, and the black crosses are points were PFAS have been measured 2019, 2022 or 2024.

In the particle tracking presented to the left in Figure 23, EIWHS 9, the particles move in a plume that starts narrow and then widens when getting closer to the lake. The particles go from purple to blue to green quickly. The slowest particles take 65 years to reach the most northern cross, but the majority gets there in 45 years. The particles touch 6 moves of the sample points for PFAS. On the right side of Figure 23 particle tracking from EIWHS 10 is presented. These particles reach the most northern cross in 25 years and touch 5 of the crosses.

Figure 24 presents the particle tracking from EIWHS 11 to the left and EIWHS 12 to the right. These two sites are located closely to each other and therefore has very similar particle tracking. The plume that the particles move in are mostly purple and blue and when the plume reaches the lake some particles turn green, meaning that it takes maximum 40 years to reach the most northern cross. The particles touch 5 crosses each.

Figure 25 presents the particle tracking from EIWHS 13 which does not reach long from the node they have been released from, therefore none of the crosses are touched by the plume.

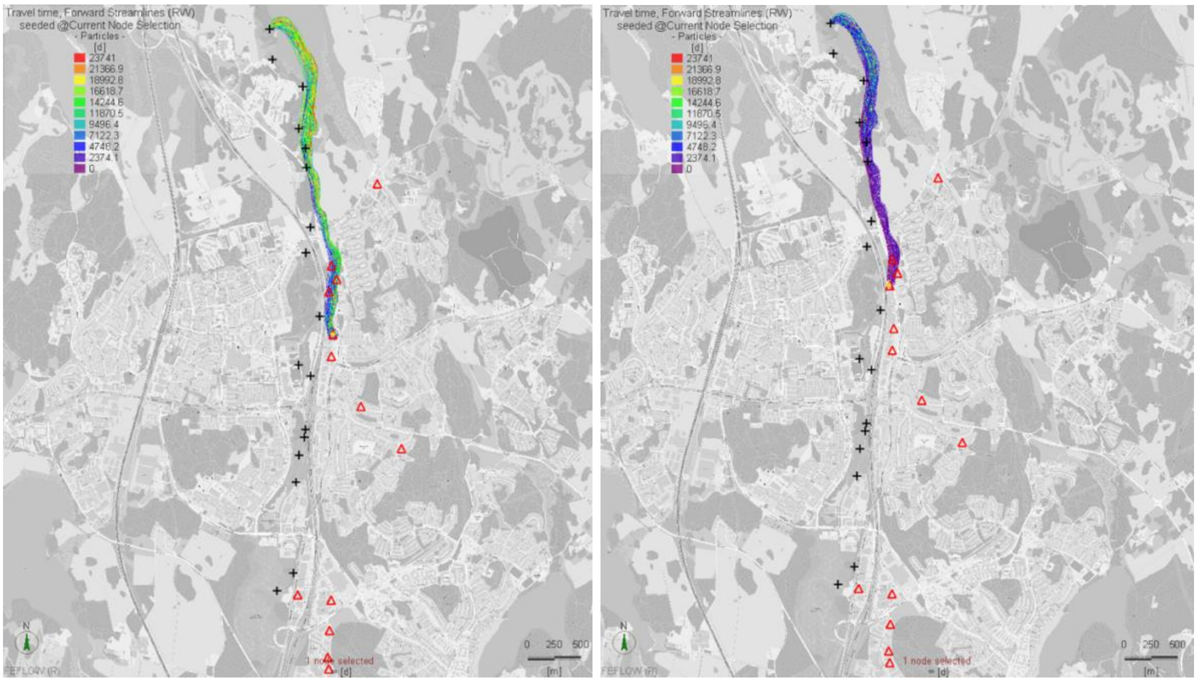

Figure 23: Particle tracking from two Engineering industries using halogenated solvents, EIWHS 9 (left) and EIWHS 10 (right). The yellow dot is the nearest node, the red triangles is the location of the industries, and the black crosses are points were PFAS have been measured 2019, 2022 or 2024.

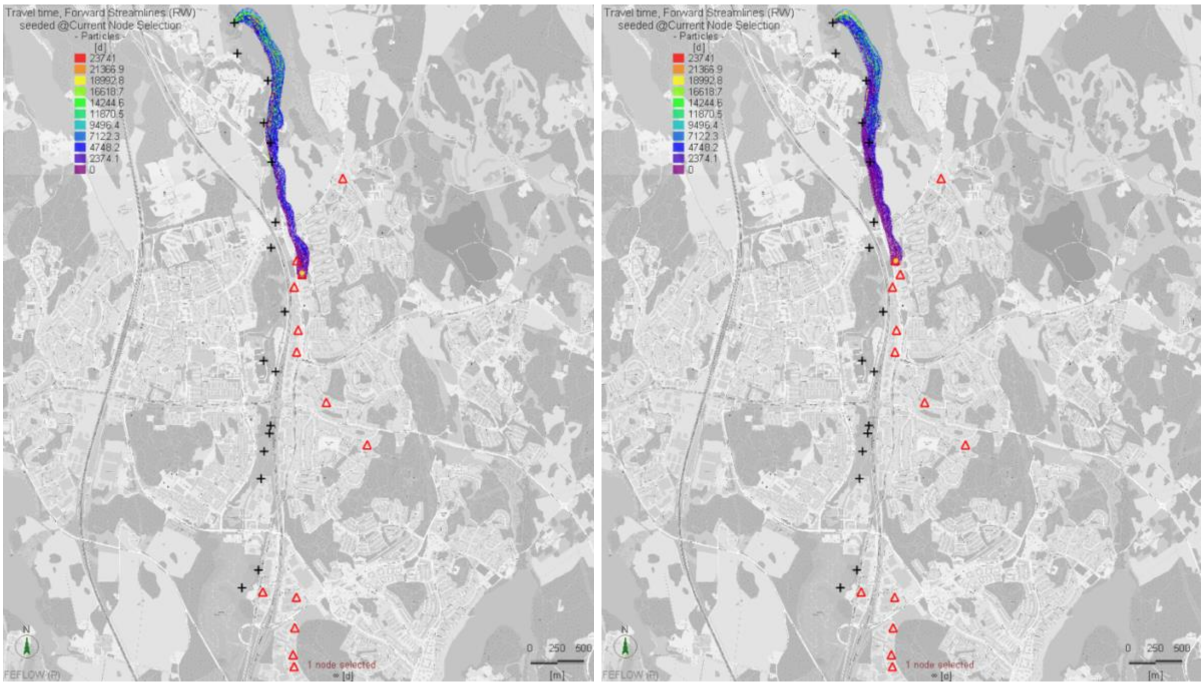

Figure 24: Particle tracking from two Engineering industries using halogenated solvents, EIWHS 11 (left) and EIWHS 12 (right). The yellow dot is the nearest node, the red triangles is the location of the industries, and the black crosses are points were PFAS have been measured 2019, 2022 or 2024.

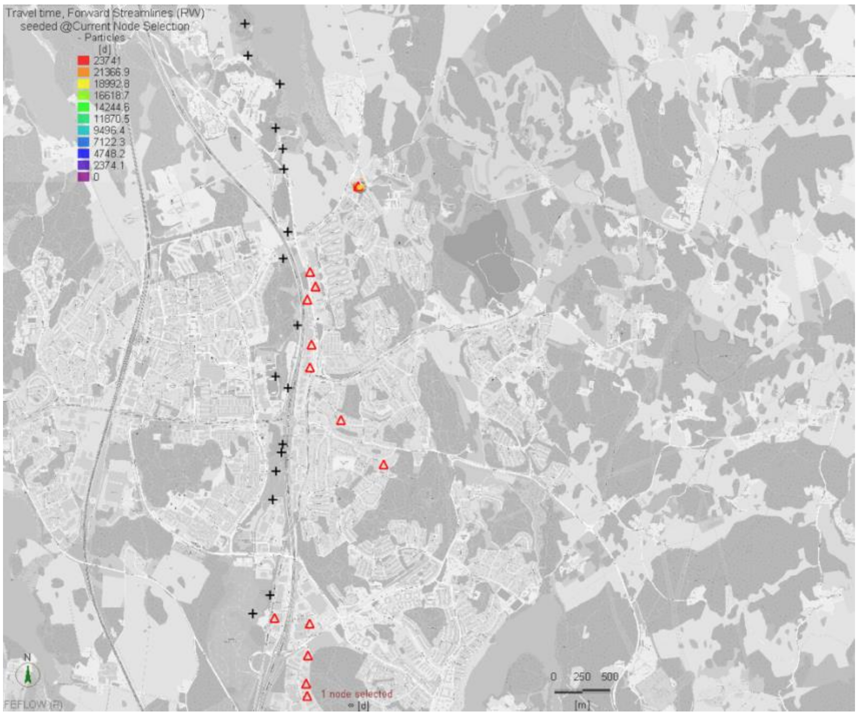

Figure 25: Particle tracking from an Engineering industry using halogenated solvents, EIWHS 13. The yellow dot is the nearest node, the red triangles is the location of the industries, and the black crosses are points were PFAS have been measured 2019, 2022 or 2024.

Without halogenated solvents

Figure 26 presents particle tracking from Engineering industries not using halogenated solvents, EIWOHS 2 (left) and EIWOHS 3 (right). In the case for EIWOHS 2 the particles reach about 600 m and does not touch any of the crosses. The particle tracking from EIWOHS 3 reach almost all the way to the lake in 65 years. The particles are moving quite slow in the beginning and then they seem to speed up. The particles move together in a narrow plume for a while but then there are only some particles moving alone. The particles touch 2 of the crosses.

The particles released from EIWOHS 4 (left) and EIWOHS 5 (right) are presented in Figure 27. For EIWOHS 4 the particles changes color fast and then becomes red. Some of the particles reach almost half the distance to the lake in 65 years. In the beginning it is a plume of particles moving in the groundwater but after a while there are only some particles that keeps moving towards the lake. There are 1 cross that is touched by the particles. In the particle tracking for EIWOHS 5 the particles do not reach far from the released node and does therefore not touch any of the crosses.

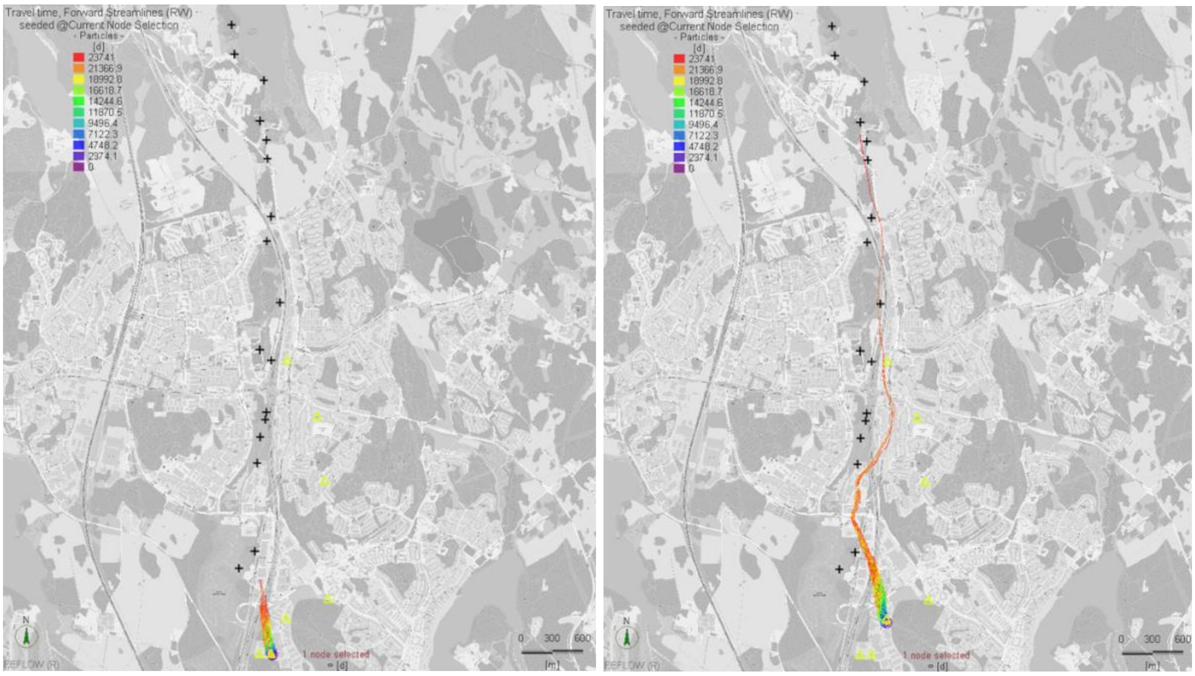

Figure 26: Particle tracking from two Engineering industries not using halogenated solvents, EIWOHS 2 (left) and EIWOHS 3 (right). The yellow dot is the nearest node, the lime-green colored triangles is the location of the industries, and the black crosses are points were PFAS have been measured 2019, 2022 or 2024.

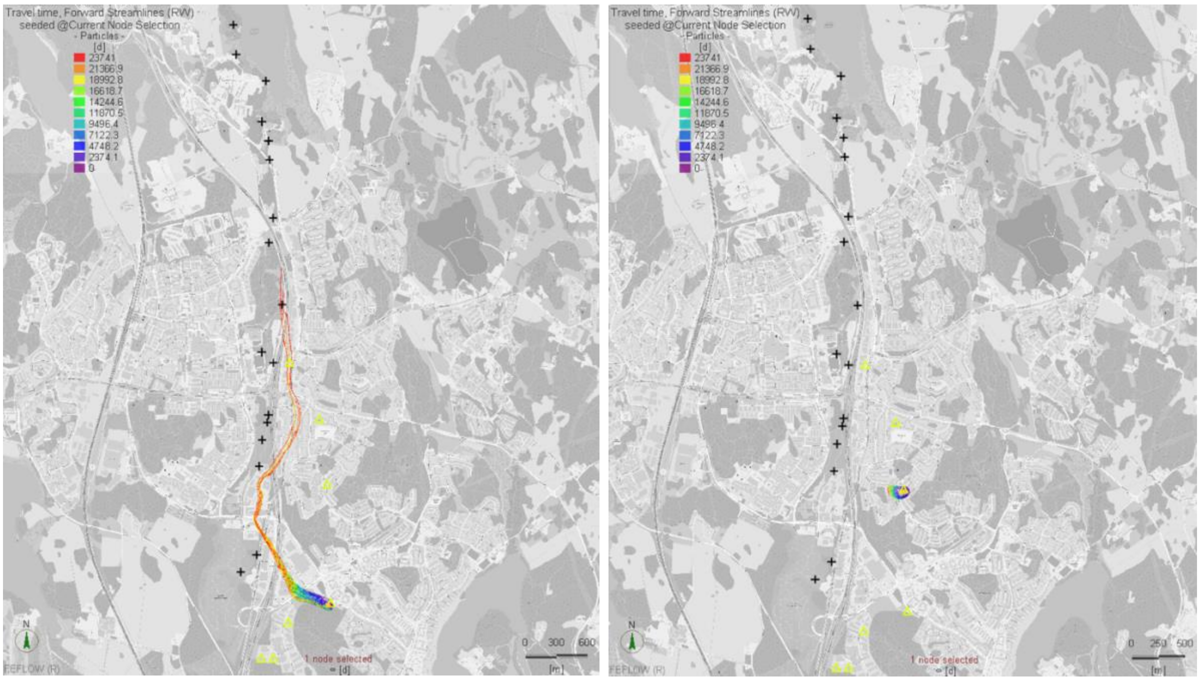

Figure 27: Particle tracking from two Engineering industries not using halogenated solvents, EIWOHS 4 (left) and EIWOHS 5 (right). The yellow dot is the nearest node, the lime-green colored triangles is the location of the industries, and the black crosses are points were PFAS have been measured 2019, 2022 or 2024.

Presented in Figure 28 are the particle tracking of EIWOHS 6 (left) and EIWOHS 7 (right). For EIWOHS 6 the particles are mainly green meaning that they travel quite fast in the groundwater flow, but getting there takes about 40 years. Parts of the plume reaches the most northern cross in this time, but for some particles it takes 65 years. The plume touches 5 of the crosses. For EIWOHS 7 the particles move in a wider plume and faster. Part of the plume is blue indicating a travel time of 20 years. This plume touches the same number of crosses (5) and also reaches all the way to the most northern cross.

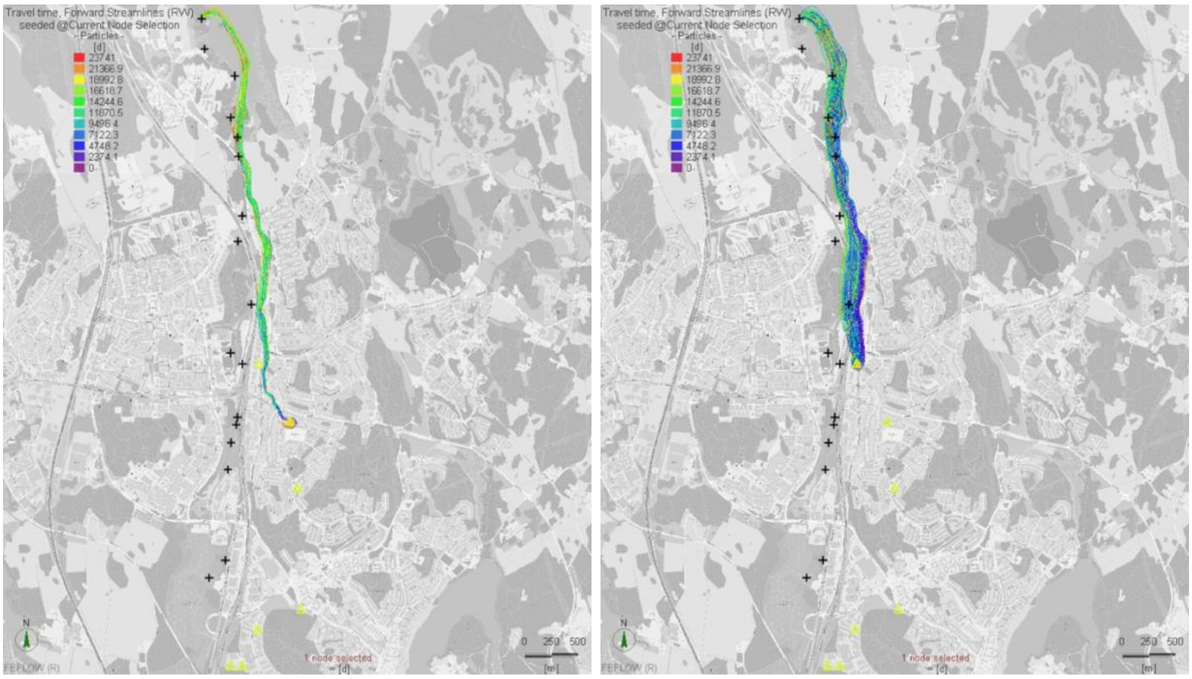

Figure 28: Particle tracking from two Engineering industries not using halogenated solvents, EIWOHS 6 (left) and EIWOHS 7 (right). The yellow dot is the nearest node, the lime-green colored triangles is the location of the industries, and the black crosses are points were PFAS have been measured 2019, 2022 or 2024.

8.7.4. Surface treatment

The surface treatment on the esker is located near the lake and therefore the particles released from the nearest node of it almost all reach the most northern cross as seen in Figure 29. The color of the particles is mostly purple and blue, almost all the way to the most northern cross, meaning that it takes less than 20 years for the particles to reach it. The particles seem to move in a wide plume all the way to the lake. The particles touch a total of 5 sample points.

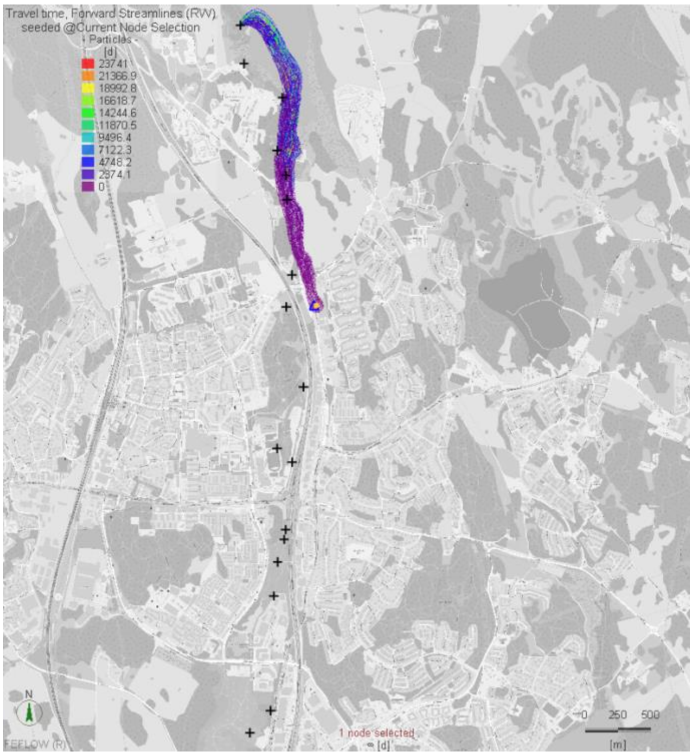

Figure 29: Particle tracking from a surface treatment located on the esker. The yellow dot is the nearest node, the blue triangle is the location of the industry, and the black crosses are points were PFAS have been measured 2019, 2022 or 2024.

8.7.5. Electrical engineering industry

In Figure 30 particle tracking from an electrical engineering industry is presented. The particles have blue and purple colors in the beginning and then changes to green before yellow and red is included in the particles. There seems to be a small plume moving in the esker all the way to the edge of the lake. The particles cross about half of the sample points on its way to the lake. From the edge of the lake some of the particles that makes it through and reaches the most northern cross. The particles reaching the most northern cross vary between green or red meaning that it takes them 40 to 65 years to reach it.

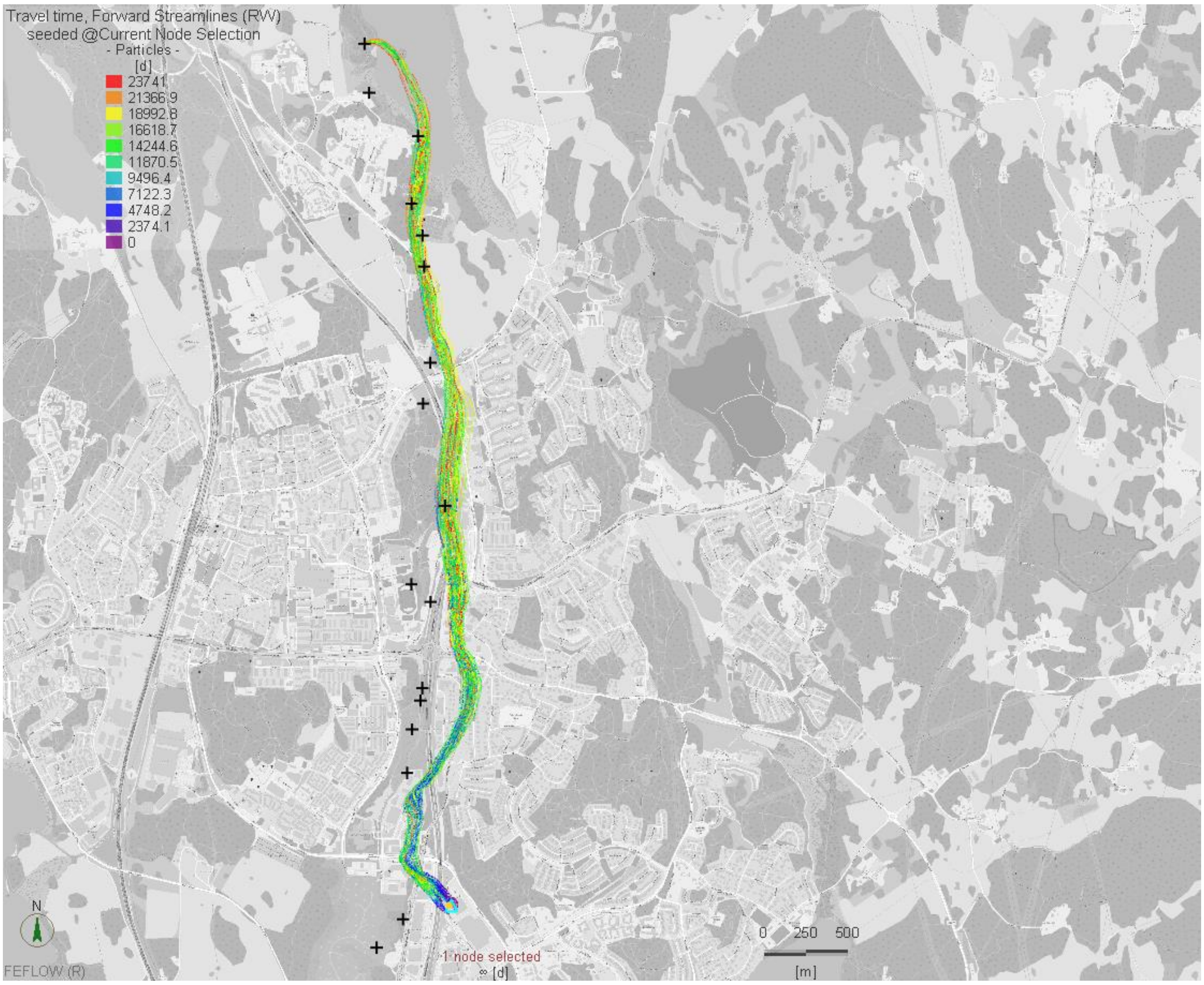

Figure 30: Particle tracking from an electrical engineering industry. The yellow dot is the nearest node, the light blue triangle is the location of the industry, and the black crosses are points were PFAS have been measured 2019, 2022 or 2024.

8.7.6. Interim storage & sorting station for waste

For the interim storage and sorting station for waste 1, IS&SS 1 in Figure 31, none of the particles reach the edge of the lake after 65 years. The particles start as a plume but quickly dissolves into particles moving on their own. The particles touch none of the sample points.

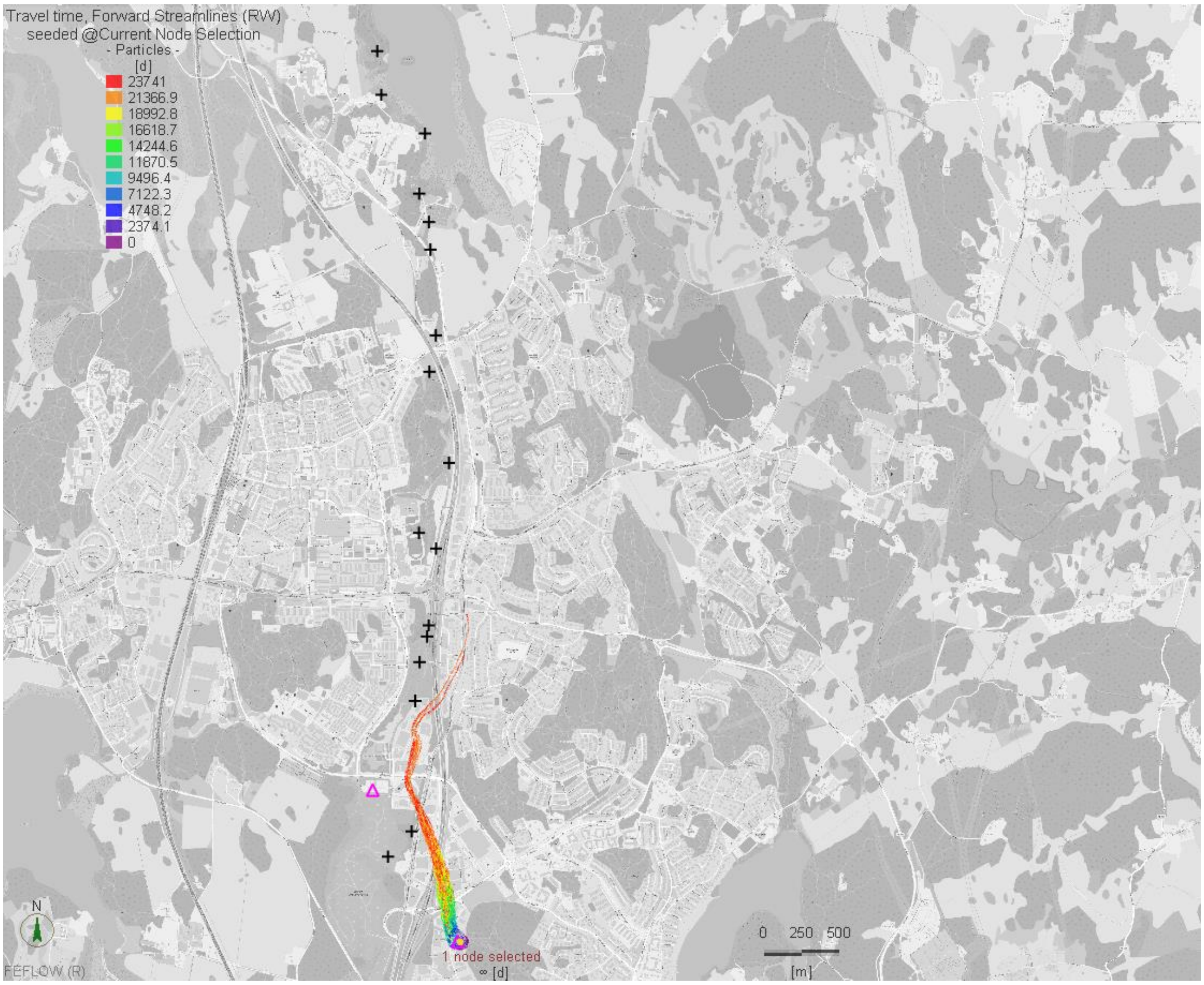

Figure 31: Particle tracking from the interim storage and sorting station of waste 1, IS&SS 1. The yellow dot is the nearest node, the purple triangle is the location of the industry, and the black crosses are points where PFAS have been measured 2019, 2022 or 2024.