

Explanatory model for the occurrence of iron and manganese in the groundwater in Umeålvåsåsen

Master's thesis in the Master's Programme Infrastructure and Environmental Engineering

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Cover:

Illustration of the hydrogeochemistry processes causing iron and manganese dissolve in groundwater.

Department of Architecture and Civil Engineering

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ABSTRACT

High concentrations of iron and manganese are common substances in Swedish groundwater that require treatment before use in drinking water. Elevated concentrations of these elements have been detected by Ramboll in Umeålvåsåsen, a glaciofluvial esker in northern Sweden, which is under consideration as a future groundwater source. This thesis aims to identify the underlying causes of the elevated concentrations and develop an explanatory model applicable to similar projects.

The study combined theoretical background with site-specific data to establish theories of potential underlying causes. Verification of theories was made using statistical analysis, laboratory testing, and GIS-based spatial analyses. The findings indicate a strong correlation between wetlands and high iron and manganese concentrations, supporting the hypothesis of hydraulic connectivity between wetlands and groundwater. Additionally, lower groundwater velocity and deeper wells were found to significantly influence groundwater geochemistry.

The results did not support other potential explanations, such as seasonal variability or the presence of organic lenses. The proposed model emphasizes the importance of early stage hydrogeochemical assessments and provides a methodological framework for identifying underlying contamination sources in future groundwater projects.

These insights contribute to more effective planning and management of groundwater resources in glaciofluvial deposits, avoiding problems with iron and manganese.

Key words: Iron, manganese, groundwater, glaciofluvial esker, wetlands.

Förklaringsmodell till orsaken av järn och mangan i grundvattnet i Umeälvsåsen

Examensarbete inom mastersprogrammet infrastruktur och miljöteknik

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SAMMANFATTNING

Järn och mangan är vanligt förekommande element i Sveriges grundvatten som vid förhöjda halter kan kräva behandling före användning. Förhöjda halter av dessa två ämnen har uppmätts i Umeälvsåsen, en isälvsavlagring i norra Sverige som är under utredning för att användas till dricksvattenförsörjning. Målet med detta arbete var att identifiera de underliggande orsakerna till förhöjda koncentrationer av järn och mangan samt etablera en förklaringsmodell som kan tillämpas i liknande projekt.

Arbetet har kombinerat litteraturstudie med dokumenterade data från området för att etablera teorier gällande underliggande orsaker till problematiken med höga järn- och manganhalter. Teorierna har utvärderats med statistiska tester, laborietester och GIS-analyser. Resultaten visar på stark korrelation mellan våtmarker och förhöjda koncentrationer av järn och mangan, vilket verifierar teorin om att det finns en hydraulisk koppling mellan grundvatten och våtmarkerna i området. Även låg strömningshastighet för grundvattnet i åsen och djupare brunnar visade sig ha en betydande påverkan på grundvattnets kemi.

Resultaten visar på svaga samband för årstidsvariationer och inlagrade linser med organiskt material. Förklaringsmodellen understryker vikten av tidiga hydrogeokemiska undersökningar och presenterar föreslagna metoder som kan användas för att identifiera de underliggande orsakerna till de förhöjda järn- och manganhalterna i framtida grundvattenprojekt. Vilket i sin tur kan främja en mer effektiv planering och implementering av dricksvattenanläggningar i isälvsavlagringar för att undvika problem med järn och mangan.

Nyckelord: Järn och mangan, grundvatten, isälvsavlagringar, våtmarker.

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1 Introduction

Approximately half of Sweden's drinking water comes from groundwater and elevated concentrations of iron and manganese in groundwater are a common problem. This creates challenges since the groundwater exceeding stated threshold values requires treatment for iron and manganese before distribution to consumers. While the presence of iron and manganese is common in groundwater in Sweden, the underlying causes are often uncertain. pH, together with redox potential, are two known parameters that affect the occurrence of dissolved iron and manganese in groundwater (Sparrebom et al., 2022). Gaining a better understanding of the underlying causes of elevated iron and manganese in groundwater could contribute to more effective exploration strategies, which can reduce costly treatment processes at water treatment plants.

1.1 Background

Umeälvssäsen is a glaciofluvial deposit in the form of an esker west of Umeå, see Figure 1.1, and is the focus of extensive groundwater investigations conducted by Ramboll (2024) for the public water utility company, Vakin in Umeå. Between 2018 and 2024, Ramboll carried out detailed hydrogeological investigations along a six-kilometre section of Umeälvssäsen north of Vännäs as a potential site for implementing Managed Aquifer Recharge (MAR). The study was commissioned by Vakin to address the anticipated population growth in Umeå Municipality and their growth target to 200 000 people by 2050 (Umeå kommun, 2024). This growth is expected to exceed the capacity of the existing drinking water supply infrastructure, which already operates near its maximum capacity. To meet future demand, the municipality needs a capacity of the water supply of approximately 560 liters per second (Ramboll, 2024).

The problem with iron and manganese at Swedish drinking water supplies was highlighted by Hägg et al (2018) in a comprehensive survey of 16 MAR facilities. Reducing water conditions are common when usage of groundwater as drinking water source, including MAR facilities. In the survey conducted by Hägg et al. (2018) a majority of the abstracted groundwater required treatment. Reduced water condition dissolve metals, including iron and manganese, causing an increased need of maintenance due to sludge and clogging. Ramboll has encountered similar challenges in multiple projects, including facilities involving utilizing artificial infiltration systems.

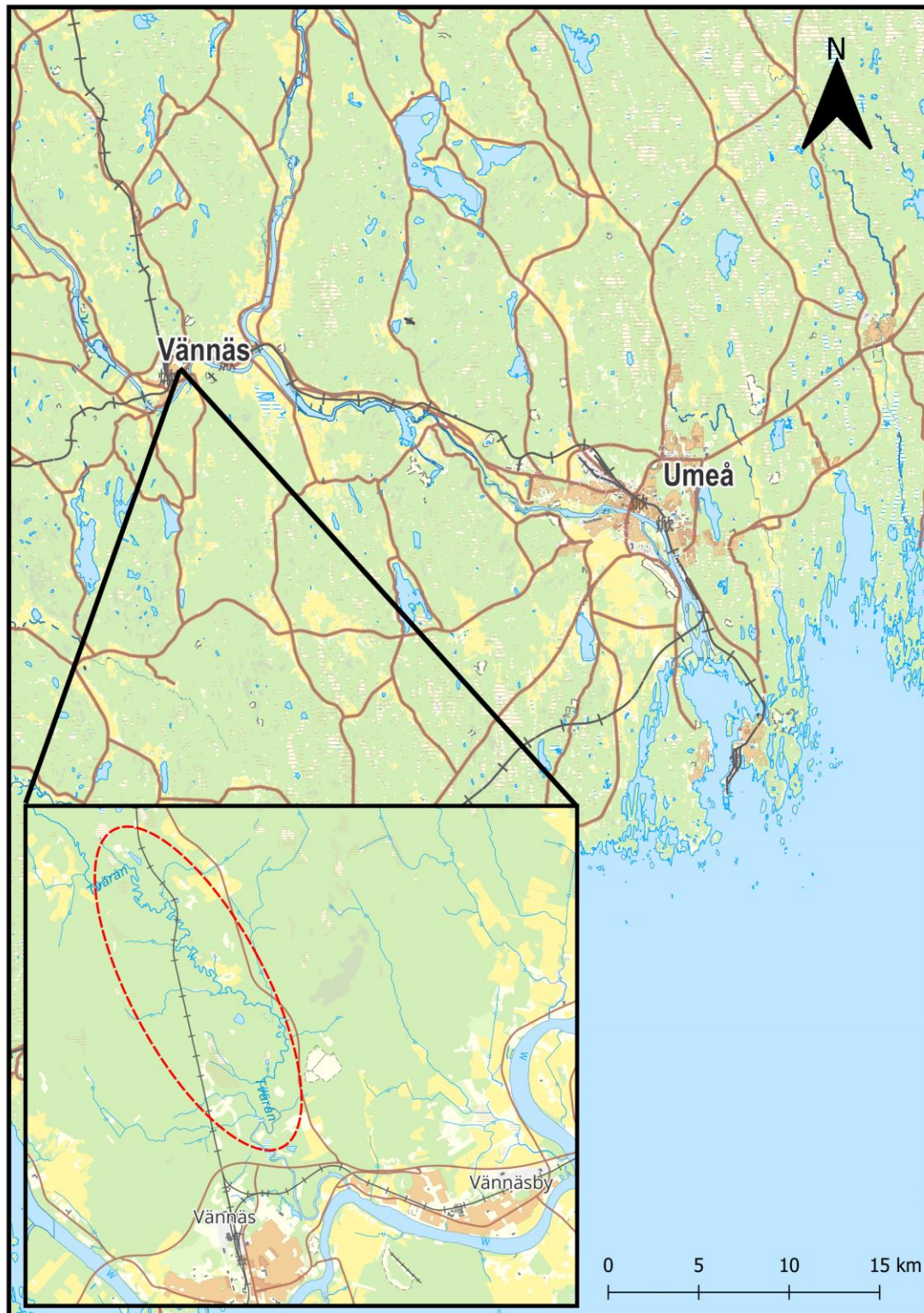


Figure 1.1. Overview of the location of Umeålvssäsen.

The importance of groundwater for humanity is increasing. It is a natural resource that constitutes 50% of Sweden’s drinking water supply systems, as well as an integral part of nature ecosystems. As a drinking water resource, groundwater contributes to environmental sustainability, since the natural filtration process provides high-quality water, often without the need for extensive chemical treatment. Furthermore, it can be replenished by mimicking

natural processes through artificial infiltration. At the same time, Swedish groundwater faces challenges related to anthropogenic influences and climate change, which have contributed to stricter legislation regarding groundwater protection and to the inclusion of high-quality groundwater as a target within Sweden's national environmental quality objectives.

1.2 Aim and Objectives

This project aims to investigate the occurrence of elevated concentrations of iron and manganese in the groundwater of Umeälvssäsen. Potential sources explaining the occurrence of the targeted elements are explored through an evaluation of previously collected data and the development of a theoretical background. By creating a fundamental hydrogeological description of the esker and conducting a deeper evaluation of the investigations than those carried out by Ramboll, the reasons for the elevated concentrations are assessed. The theoretical background, together with the site description and literature review, is used to develop an explanatory model discussing the possible causes of elevated concentrations of iron and manganese. Validation of the explanatory model is carried out by analysing previous research through a literature review.

The following objectives have been established to achieve the aim of this thesis:

- Description of the theoretical background covering Quaternary geology, hydrogeology, and hydrogeochemistry.
- Description of the current geological, hydrogeological, and hydrogeochemical conditions in the study area based on Ramboll's investigations.
- Further development of the site description by identifying potential sources contributing to elevated concentrations of iron and manganese.
- Analysis of the identified potential sources.
- Development of an explanatory model.
- Discussion of the validation of the explanatory model.
- Assessment of how the developed explanatory model can be applied to identify causes of elevated concentrations of iron and manganese in similar projects.

1.3 Limitations

The thesis is limited to a six-kilometre section of Umeälvssäsen north of Vännäs. Furthermore, the thesis considers the iron and manganese water quality parameters, other water quality parameters are not considered. The explanatory model is valid for the site of interest at current state, before implementation of MAR. The approach and structure to handle the question is general and could be implemented for similar projects.

2 Theoretical background

Quaternary geology, hydrogeology and hydrogeochemistry are three main topics that have been investigated to understand the origin, distribution, and behaviour of iron and manganese in groundwater. These topics are described in this chapter.

The Geological Survey of Sweden (SGU) is a governmental authority that provides public geological information and have responsible for groundwater information in Sweden. SGU offers a large repository of data, maps and publications relevant for the topic discussed in this thesis. Various datasets and publications provided by SGU were used.

Other sources used was course literature at Chalmers, in particular recommended books or book sections. These literatures were used to cover the fundamentals of each topic.

2.1 Geology

This section reviews the geological history, including quaternary geology, which is relevant for the thesis to understand and broader the perspective of the occurrence of iron and manganese.

2.1.1 Glaciation

Sweden's geological conditions have been significantly shaped by the last glaciation, which occurred during the quaternary period, resulting in various glacial and post glacial deposits (Sparrebom et al., 2022). In Västerbotten, northern Sweden, the retreat of the most recent ice sheet occurred approximately 9,000 years ago (Eklund, 1991). The thickness and weight of the continental ice sheet exerted considerable pressure on the land surface, leading to a postglacial rebound of the Earth's crust which resulted in a highest shoreline up to meters above the present-day sea level. The ice sheet was most extensive in the northern parts of Sweden, which resulted in the largest isostatic uplift in this area.

2.1.2 Glacial depositing

The dynamic nature of the ice sheet, characterized by continuous movement, facilitated the accumulation of materials through processes such as erosion, transport and deposition (Lindström et al., 1991). Material of different grain size and origin are transported and deposited by the ice in different ways depending on e.g. the temperature of the ice, topography, and source material (bedrock composition, unconsolidated materials, etc.).

The Swedish bedrock is among the oldest in Europe and is part of the Fennoscandian Shield, formed over 4 billion years ago. The bedrock present in the area of interest for this thesis belongs to the Svecokarelian province. The Svecokarelian province are strongly characterized by mineralization, with the northernmost part dominated by mafic and felsic vulcanite's. Mafic minerals mainly consist of abundant iron ore deposits and manganese which is characterise the northern parts of Sweden. The bedrock has been eroded,

transported and deposited. Therefore, iron and manganese minerals are common in Swedish deposit materials.

Large volumes of meltwater, combined with the movement of the ice sheet, resulted in streams that carried glaciofluvial drift particles through the landscape, depositing them in various layers and formations (Lindström et al., 1991).

Melting water from the ice sheet caused meltwater channels carrying materials. The material deposited from the meltwater was sorted according to grain size during the sedimentation process, with larger and denser sediments particles deposited closest to the mouth of the meltwater tunnel (Lindström et al., 1991). The process is influenced by the flow velocity, where the grain size deposited decreases with reduced velocity. The deposited material typically consists of coarse-grained particles, characteristic for glaciofluvial deposits.

A prominent example of glaciofluvial deposits in Sweden are eskers, which are created by meltwater flowing through tunnels in the ice sheet and at the retreating ice-front, near the mouth of the tunnel. The accumulation continued as the ice edge gradually retreated and left significant eskers in the landscape. Above the highest shoreline, supra-aquatic esker deposits remained unaffected by wave action and marine processes. Below the highest shoreline, eskers were deposited in aquatic environments and are referred to as subaquatic eskers, as illustrated in Figure 2.1. These subaquatic eskers were subsequently reworked by wave activity and water movement, resulting in the deposition of fluvial sediments over their surfaces.

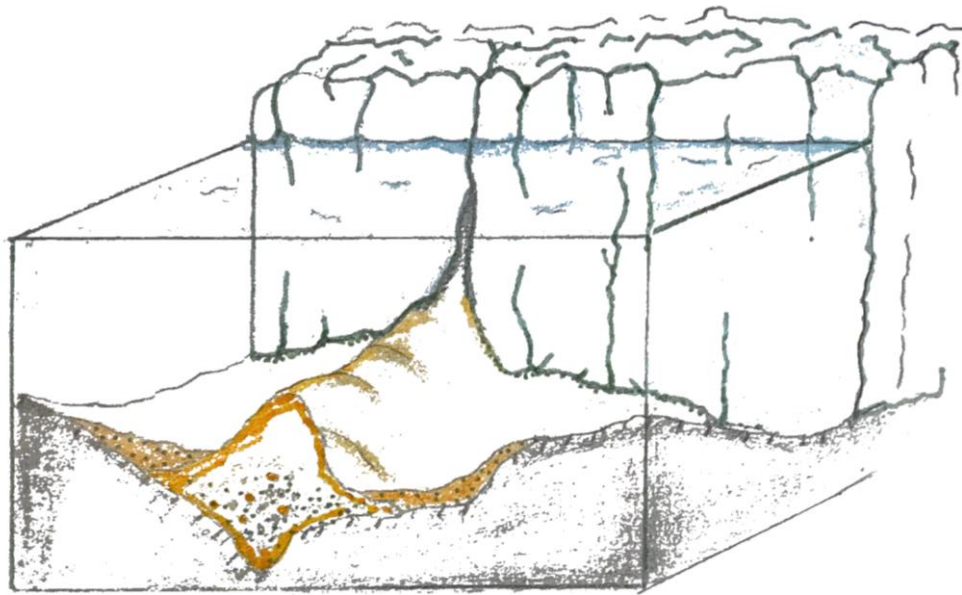


Figure 2.1. Illustration showing the principle depositing of a glaciofluvial subaquatic esker. The material is accumulated at the retreating ice front where the ice river meets stagnant water.

2.1.3 Glacial deposit classification

There are several systems to classify geological materials, and common methods are based on depositional process, grain size distribution or technical properties (Larsson, 2008). Since 2004, a European standard system exists for classification

according to grain size distribution. The classification process is done by visual inspections, sieving, sorting or sedimentation. The classification can be done by visual inspections and weighting. For detailed laboratory classification, samples are taken and sent to laboratory for sedimentation analysis.

For glaciofluvial deposits, the depositional process has a large impact on the structure of the glaciofluvial materials. Seasonal changes in temperature, variations of flow velocity and direction caused layering of deposits (Lindström et al., 1991). The grain size of the material affects the volume ratio between material and pore space. These parameters constitute the geotechnical properties of the material, including density, weight, permeability and capillarity. Generally, eskers are deposited within a river underneath the ice sheet have higher potential to function as a groundwater resource (Sparrebom et al., 2022). They are characterized by high permeability and continuous deposits, favourable regarding groundwater storage and utilization.

After the retreat of the ice sheet, large areas of Sweden were covered by the Baltic Sea (Lindström et al., 1991). Over time, small particles were allowed to settle through sedimentation in stagnant bays resulting in extensive glaciofluvial clay in silt deposits below the highest shoreline of the Baltic Sea. The same process occurred due to flooding of lakes and rivers. These materials are defined as fluvial sediments. Due to the isostatic uplift and drying, these areas have arisen from the ocean and become drained. Therefore, fluvial sediments are classified as post glacial deposits, since their deposit took place after the ice sheet retreated and overlays the glaciofluvial deposits.

The formation of lakes is an excavation made by the ice sheet that is filled with water (Lindström et al., 1991). Often, lakes have an inflow of water through rivers or creeks, transporting sediments into the lake which settle and slowly decrease its volume through the build-up of sediments. Vegetation starts to grow in the stagnant water. Organic material can also enter the lake through water inflow. With time, the vegetation is degraded through microbiological processes consuming oxygen resulting in organic sediment at the bottom. When the lake is completely overgrown, it is considered as a peatland, which consist of these organic deposits.

2.1.4 Mineralogy

Iron is a common element in the subsurface and constitute a part of many minerals and rocks (SGU, 2024b). The occurrence of manganese is similar to iron and the two elements are often found in similar subsurface environment. Both elements are common in Swedish groundwaters. It is primarily found along the north-east coast in areas with extensive peatlands, which create reducing conditions (Maxe, 2013).

Iron is a commonly occurring element in the Swedish subsurface, primarily as a constituent of minerals like carbonates and sulphides (Andersson et al., 2014). The concentration of iron is particularly high in mafic and ultramafic rocks. In Sweden, the highest iron concentrations are found in the northern regions of Lapland, particularly near Kiruna, where mafic and ultramafic lithologies are

prevalent. Glacial deposits derived from the Svecokarelian province, in which Umeå area is located, are strongly associated with metamorphosed mafic and ultramafic rocks, which contain elevated concentrations of several minerals, including iron.

Manganese occurs in the subsurface as an accessory element in minerals, typically in pyroxene and garnet (Andersson et al., 2014). Manganese is abundant in mafic rocks as it can substitute for iron and magnesium in ion form. Till originating from the Svecokarelian province often show elevated concentrations of manganese, commonly derived from black shale.

These two elements are commonly present in groundwater reservoirs within glaciofluvial deposits, which frequently serve as a source of water supply for numerous Swedish municipalities (Hägg et al., 2018). Research has defined oxygen levels in the water as a critical factor influencing the occurrence of iron and manganese together with redox potential. Redox potential describes the behaviour of an element and its willingness to reduce or oxidize (Maxe, 2013).

2.1.5 Organic material

Organic deposits emerge from vegetation mixed with local sediments on site (Lindström et al., 1991). The stratigraphy in a peatland has fine grained material in the bottom with high water content, referred to as mud. The mud layer is followed by material less humified with high content of moss and grass. Classification of organic materials in peatlands is often based on the degree of humification together with wetness. Storage of organic material in the subsurface is a phenomenon common in subaquatic deposits (Fredén, 1994).

Organic material is commonly found in fine-grained postglacial sediments (Karlsson et al., 2021). In geology, organic content serves as an important classification parameter, as it influences the physical and chemical properties of the soil. The accumulation is primarily due to plant residues that undergo incomplete decomposition due to high moisture content. Over time, organic material may become buried by additional sediment layers or redistributed through mechanical processes.

2.1.6 Acid sulphate soil

Sulphate soil is a deposit formed in brackish water on the seabed of the Baltic Sea (Becher et al., 2019). The deposition occurred in deep water or in shallow bays where the water flow was calm and oxygen level low. Their depositional environment is illustrated in Figure 2.2.

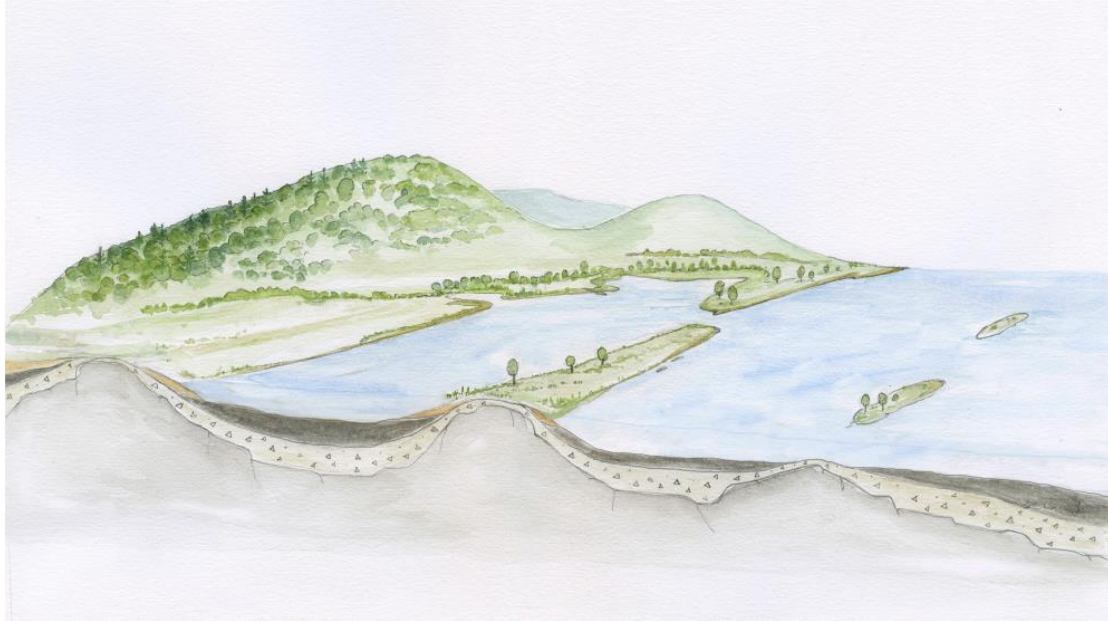


Figure 2.2. Illustration of potential acid sulphate soil and its depositional environment. Acid sulphate soils are known for their black-coloured soil, showed in the picture. Reproduced with permission (Becher et al., 2019).

This created a favorable environment for sedimentation of sulphide minerals. The sediments contain organic material that is oxidized by bacteria. Initially, bacteria utilize oxygen for this oxidation, but when oxygen is depleted, sulfate (SO_4^{2-}) and trivalent iron (Fe^{3+}) is used as oxidants, resulting in sulfide and divalent iron, which reacts and form iron monosulfides (FeS) and pyrite (FeS_2) called potential acid sulphate soil. This process gives the soil or clay a characteristic gray or black color. This is also known as “Svartmocka” in Swedish. Acid sulphate soil does not have a higher content of metals than other soil types. These soils are often found in fine-grained sediments such as silt and clay but can also be found in fine sand sediment (Becher et al., 2019).

Acid sulphate soils can be found beneath the highest coastline (Becher et al., 2019). In some areas, potential acid sulphate soils may be covered by younger, sulphide-free deposits. Potential acid sulphate soil refers to soil that has not yet been exposed to oxygen and therefore has not undergone oxidation or experienced a resulting decrease in pH. These layers of sulphate soils occur primarily in areas where the groundwater table is close to the surface, for example in low lying areas such as wetlands. Acid sulphate soils can also form in lacustrine sediments, which means that areas where lake infilling has taken place may contain sediments including sulphate soils. Since the isostatic uplift is most pronounced along the north-east coast of Sweden, sulphate soils are mainly found in this region.

When potential acid sulphate soil is exposed to oxygen, due to lowered groundwater level, the iron sulphides begin to oxidize (Becher et al., 2019). This leads to the formation of sulfuric acid (H_2SO_4), hydrogen ions and iron precipitates, which drastically lower the soil's pH, often to below 4 pH. These changes cause metals to dissolve and mobilize in the water. The oxidized potential acid sulphate soil is named active acid sulphate soil. The soil has a

characteristically brown and red colour due to iron precipitation. Due to the lowered groundwater level, the active acid sulphate soil gets dry and crack, whereas oxygen rich water can reach potential acid sulphate soil and continue the oxidization of potential acid sulphate soil deeper into the ground.

2.2 Hydrogeology

Groundwater occurs naturally within most soil types. Its potential for utilization as a resource depends on the hydrogeological properties of the soil (Sparrebom et al., 2022). Groundwater is defined as water stored beneath the saturated zone (Healy, 2010). The prerequisite is governed by the porosity of the geological material, where water can be stored and move (Sparrebom et al., 2022).

In hydrogeology, a geological deposit that contains groundwater available for utilization is referred to as an aquifer (Sparrebom et al., 2022). It is enclosed by surrounding geological materials causing different pressure levels, determining if the aquifer is confined or unconfined. When the hydrostatic pressure is equal to atmospheric pressure, the aquifer is considered as unconfined. Commonly, unconfined aquifers are close to the surface and consist of coarse-grained material. Confined aquifers are enclosed by dense material layers and are commonly found deeper down in the subsurface. A confined aquifer has potential pressure, which could be unequal to atmospheric pressure and can exceed the groundwater table.

The flow rate is described as flux through a specific area in terms of volume or mass (Sparrebom et al., 2022). The flow moves according to the hydraulic head, corresponding to the hydrostatic pressure of the aquifer. Groundwater moves from high to low hydraulic head and is summarized as the hydraulic gradient. The hydraulic gradient refers to the direction a water particle moves in a three-dimensional space.

In addition to the hydraulic gradient and the flow rate, the permeability is important to define the movement of groundwater (Sparrebom et al., 2022). Hydraulic conductivity (K) is a parameter that describes how easily water can flow through a porous medium, such as soil or rock. It depends on both the properties of the fluid (e.g., viscosity and density) and the characteristics of the material (e.g., pore size and connectivity).

The relationship between hydraulic conductivity, flow rate, and hydraulic gradient is described by Darcy's law, which states that the flow rate through a porous medium is proportional to both the hydraulic conductivity and the hydraulic gradient. Hydraulic conductivity for different fractions of common soils in Sweden have been tabulated by the Swedish geotechnical institute (Larsson, 2008). There is a strong correlation between permeability and grain fraction, where coarse grained materials like gravel have shown high permeability.

A key component of groundwater is the recharge process, defined as water recharging the water table and added to the groundwater storage (Healy, 2010). Recharge is categorized as diffused when precipitation infiltrates the soil layer

and percolate through the subsurface to reach the water table. Focused recharge refers to movement of water from adjacent surface water bodies. The recharge is unique for each groundwater system and their local surface conditions. Such conditions are topography, climate, geology, and land use.

In Sweden, models estimating the recharge's seasonal fluctuations have been determined by using weather data models provided by the The Swedish Metrological and Hydrological institute (Sparrebom et al., 2022). Calculation of groundwater recharge is based on the water balance equation, considering precipitation (both water and snow), evapotranspiration and run-off (Eveborn et al., 2017). The amount of stored water is defined as ΔS and varies over time. The water balance equation is shown in Equation 1.

$$P = ET + R + \Delta S \quad (1)$$

Equation (1) does not take human activities in consideration (Eveborn et al., 2017). Pumping managed artificial recharge and drainage are examples of activities that could affect the water balance in terms of groundwater recharge.

A method to increase groundwater recharge available for utilization is by implementing managed aquifer recharge (MAR) in existing aquifers (Hansson, 2000). MAR means that surface water is infiltrated into an aquifer, through infiltration ponds, sprinkler systems, deep infiltration or induced infiltration. MAR enables enhanced recharge and gives the water favourable parameters similar to natural groundwater (Sparrebom et al., 2022). When the water enters the aquifer, it is exposed to filtration through various materials. In addition, the water is exposed to microbiological and biochemical processes, enhancing its water quality and stabilizing the water temperature.

2.3 Hydrogeochemistry

Hydrogeochemistry describes interactions between groundwater, geological materials and biological systems. It analyses the chemical composition of groundwater, minerals and their impact on water sources.

2.3.1 Oxygen level and Redox potential

Oxygen level and redox conditions are two closely related parameters that influence the solubility and occurrence of various substances in groundwater (Domenico & Schwartz, 1999). Infiltrating surface water initially has high oxygen levels which decreases with depth in the aquifer due to biological degradation and chemical reactions. As oxygen levels decline, the geological environment becomes more anaerobic leading to lowered redox potential, which in turn triggers redox reactions.

Redox reactions involve transfer of electrons and determine the stability of substances, including iron and manganese (Domenico & Schwartz, 1999). In aerobic environments, oxidation reactions dominate, whereas in anaerobic environments, reducing conditions dominate. Common redox reactions in groundwater involve dissolving of metals. Redox conditions are influenced by microbial processes catalysed by the organic matter content, geological conditions, and potential anthropogenic inputs.

Redox potential and oxygen levels are generally associated with the concentrations of redox-sensitive elements such as iron and manganese (Domenico & Schwartz, 1999). High levels of these metals indicate anaerobic conditions and low redox potential.

2.3.2 Alkalinity and pH

pH and alkalinity regulate the chemical balance of groundwater and its ability to resist acidification (Domenico & Schwartz, 1999). pH measures the concentration of hydrogen ions (H^+) on a logarithmic scale, where low values indicate an acidic environment, and high values represent an alkaline environment. Alkalinity reflects the buffering capacity of the water and is primarily determined by bicarbonate ions (HCO_3^-), which are produced through mineral weathering. Alkalinity acts as a chemical buffer by neutralizing the addition of hydrogen ions and preventing rapid pH changes.

pH in groundwater naturally varies between 6 and 8 depending on the geological conditions and external influences (Domenico & Schwartz, 1999). Low pH in groundwater increases the solubility of metals, such as iron and manganese, which may affect drinking water quality and cause corrosion in distribution systems (Domenico & Schwartz, 1999). High pH may cause calcium carbonate precipitation and impact the taste of water. Since pH is sensitive, changes can occur during sampling. Therefore, alkalinity is considered as more reliable indicator of the long-term acidification status of groundwater.

2.3.3 Organic material

Organic substances in the soil are decomposed by microorganisms serving as catalysts in redox reactions (Hölting & Coldewey, 2019a). The microorganisms use oxygen in the reduction process causing anaerobic environment which in turn affect metals solubility. Microbes is a part of the soil's natural biota, serving in the biochemical cycle. There are several ways to determine concentrations of organic matter, where COD and TOC are common measurements for groundwater. COD refer to Chemical Oxygen Demand and refer to the amount of oxygen needed to oxidize the organic matter content (Hölting & Coldewey, 2019b). TOC refer to Total Organic Carbon in the organic compounds present in groundwater.

2.3.4 Iron and Manganese

Iron and manganese in groundwater are found as soluble ions or ions precipitated into solid form (Tekerlekopoulou et al., 2013). Differences in redox potential and pH determine in which form the metals appear. In low oxygen reducing environments, iron exists mainly as Fe^{2+} and manganese as Mn^{2+} , which both are soluble and have high mobility. When the redox potential increases, Fe^{2+} oxidizes to Fe^{3+} , forming insoluble iron hydroxides that precipitate at pH above 4. Manganese oxidation is slower, requiring higher redox potential and pH for Mn^{2+} to convert to MnO_2 in solid form.

The Pourbaix diagrams in Figure 2.3 and 2.4 illustrates these transitions, showing how Fe^{2+} and Mn^{2+} dominate during reducing conditions, while Fe^{3+} and MnO_2 are stable in oxidizing environments.

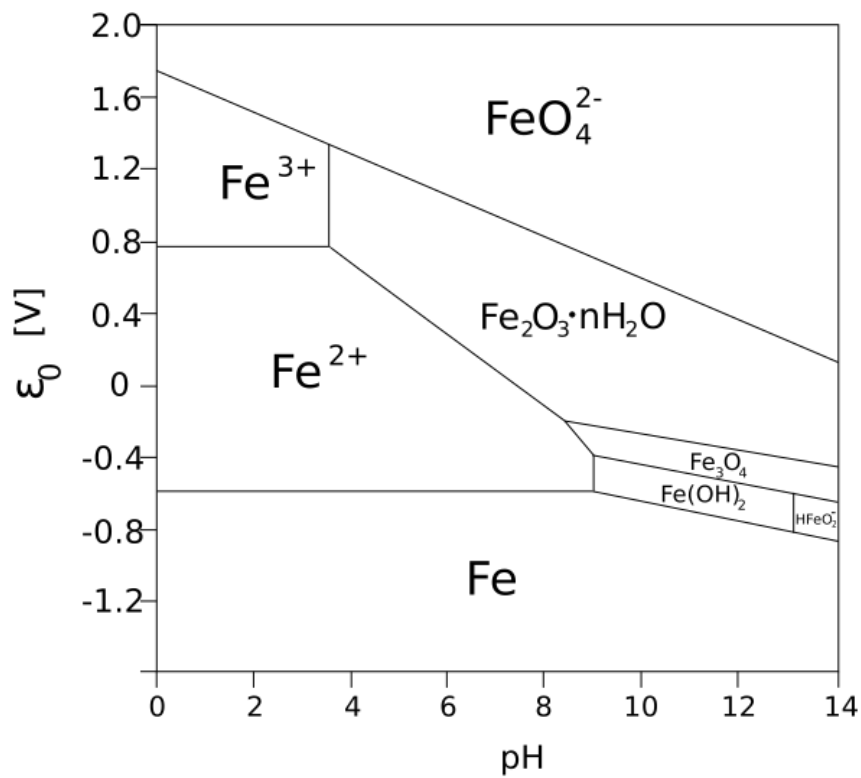


Figure 2.3. Pourbaix diagram showing the state of iron for different redox potentials and pH. $c(\text{Fe}) = 10^{-6} \text{ mol/l}$, $T = 25 \text{ }^\circ\text{C}$ (Früh, 2006).

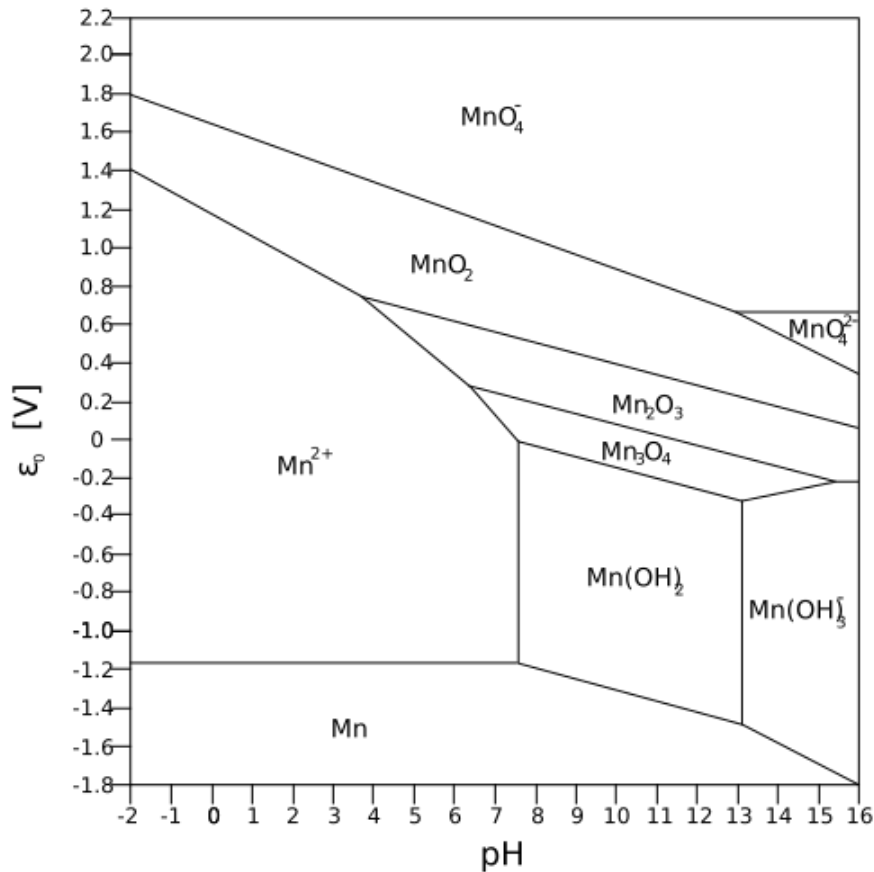


Figure 2.4. Pourbaix diagram showing the state of manganese for different redox potentials and pH. Manganese; $c(Mn) = 1 \text{ mol/l}$, $T = 25 \text{ }^\circ\text{C}$ (Früh, 2006).

Fe^{2+} is dominant in groundwater, since the oxidation to Fe^{3+} requires oxygen, which causes an accumulation of iron in groundwater with reduced oxygen levels (Stumm & Lee, 1961). The oxidation accelerates with increased pH and with increased partial pressure of oxygen, which have been proved by Stumm & Lee (1961). It shows that the oxygen acceleration is proportional to the reaction speed.

SGU provides values that can be used as an assessment basis for groundwater-based drinking water supplies (SGU, 2024b). Elevated levels of iron and manganese are one of the most common problems in Swedish drinking water supplies. SGU's classification for these two substances is presented below in Table 2.1.

Table 2.1. Classification of groundwater concentrations based on SGU (SGU, 2024b).

Classification	Status	Fe [mg/l]	Mn [mg/l]
1	Very low content	<0.1	<0.05
2	Low content	0.1-0.2	0.05-0.1
3	Moderate content	0.2-0.5	0.1-0.3
4	High content	0.5-1	0.3-0.4
5	Very high content	>1.0	>0.4

3 Literature review

The purpose of this literature review is to provide an overview of previous research that is relevant for validating and discussing the theories applied in this thesis.

To find scientific articles discussing the topic, Chalmers library's search function together with other databases containing published articles have been used. The Scopus AI tool was used to find relevant literature and to create an understanding of existing research of the topic and to find similar projects carried out. The AI tool assisted in constructing search strings and to summarize main findings in the literature found.

3.1 Organic material

The study area is situated adjacent to the river Umeälv and its associated river valley. The stratigraphy in these areas of northern Sweden is strongly influenced by deglaciation processes and fluvial erosion (Rosén, 1998). The resulting sedimentary sequence at former glacial meltwater river mouths typically exhibits coarse-grained deposits overlain by fine-grained sediments, accumulated in former marine embayments. As the positions of the meltwater outlets shifted, extensive bay areas developed, which have subsequently been exposed due to isostatic uplift. Concurrently, the river eroded and reworked its own alluvial deposits.

These river deltas and coastal embayments constitute depositional environments conducive to the accumulation of organic matter. Sutfin et al. (2016) studied the depositing environment in floodplains and riparian ecosystems. The study emphasizes that these environments are characterized by low gradient terrain, vegetation and stagnant water (Sutfin et al., 2016). All parameters increase the potential accumulation and storage of organic material. In Borelian regions, which covers large areas of Sweden including Umeälvåsen, the cold temperature together with shallow water table during winter limits the microbial activity in the soil. The result is increased storage of organic material within the soil. As the burial and aggradation of the organic materials continues, they get more stable.

3.2 Loss On Ignition

Furthermore, they are reworked and layered, with potential to affect the hydrogeochemistry without being visible at the surface. Parts of the thesis aimed to investigate deposits within the study area and determine whether there were significant differences in concentrations of organic material in the layered sediments. This could indicate the presence of layered lenses of organic material. The Loss-on-Ignition (LOI) method was applied in laboratory to analyse soil samples collected by Ramboll. Previous studies, such as Sutherland (1998) and Santisteban et al (2003), have shown that LOI is a reliable qualitative method for determining organic material in soil and sediment samples. Sutherland's work on fluvial bed sediments, which may be present in the study area for this thesis, served as an example.

Uncertainties with the analysis is connected to the weighting done before and after burning (Santisteban et al., 2003). Potential substances burned at the same temperature could contribute to additional mass loss. Sutherland (1998) and Santisteban et al (2003) have reported LOI values for different soils, which have been used as reference values, see Table 3.1.

Table 3.1. Loss on Ignition (LOI) values for different soils showing the percentage of organic material in the soil.

Study	Minimum LOI [%]	Mean LOI [%]	Soil type
Sutherland (1998)	5.82	7.16	Medium Sand
Santisteban et al. (2003)	2.63	14.97	Sand and Peat

3.3 Wetlands (Lake and peatlands)

Organic material present at the land surface have been reported to influence the chemical composition of groundwater. A study conducted in the Krycklan catchment, located in Västerbotten close to Umeälvssäsen, investigated variations in iron and manganese concentrations as well as dissolved organic carbon (DOC), and how these variables were affected by spring floods and landscape characteristics (Björkvald et al., 2008). The study was carried out in a boreal stream network. The hypothesis was that iron and manganese would have a positive correlation with increasing wetland coverage.

The study by Björkvald et al. demonstrated a correlation between iron concentrations and wetland coverage. In addition, Björkvald et al. concluding the importance of particulates from silt deposits for iron transportation. The results highlighted the importance of considering both landscape features and surface cover in understanding groundwater geochemistry. The study carried out in Krycklan by Björkvald et al. (2008) saw connections with seasonality flooding during snow melting. Their conclusion stated that the hydrological flowpaths changes with heavy precipitation. Kryckland is located close to Umeälvssäsen, which generates interest for this thesis.

If the groundwater is affected by adjacent wetlands, a hydraulic connection between the system must be present. A study carried out in Finland examine a glaciofluvial esker in Viinivaara and potential discharge to surrounding boreal peatlands (Isokangas et al., 2017). Despite sand and silt rich deposits in the bottom of the peatland, discharge from the groundwater to the peatland occurred. The statement was verified by analyzing oxygen isotopes from water samples taken at different depths of the peatland, groundwater and precipitation. Overall, 28% of the top peat layer of the wetland was groundwater dependent, while 66% of the pore water in the deeper peat layer is estimated to be groundwater.

Previous analyses have primarily relied on vegetation-based assessments, which may respond slowly to changes in hydrology and therefore underestimate the hydraulic connectivity. Similar investigation has been carried out in comparable Boreal peatlands by Lambert et al. (2022). Lambert et al. (2022) showed that

two similar peatlands had significant difference in porewater composition, where the water balanced showed that 56% of the peatland porewater was dominated by groundwater recharge. Their result concludes that the hydraulic connection is vital to understand the wetlands sensitivity to long term hydrological changes and landscape variations. This is also highlighted by Isokangas et al. that emphasize groundwater impact influenced by water abstraction and its effects on nearby peatlands.

To satisfy the requirement of deliverable volume of drinking water, induced infiltration in glaciofluvial eskers is common. Both Hägg et al. (2018) and Jokela et al (2017) have studied several facilities in Sweden and Finland using the technology. Typically, small lakes and rivers in Sweden and Finland, which share similar geological environment, are humic rich because of long-term decay of vegetation (Jokela et al., 2017). Therefore, the infiltrated water can also be a source of organic material.

3.4 Acid sulphate soils

Another potential deposit with potential impact on the concentrations of iron and manganese is sulphate soils, both acidic and potential acidic.

The Littorina boundary is often considered the upper limit for the presence of sulphide-rich sediments (Öborn, 1994). This boundary marks the highest level reached by brackish or marine waters after the last Ice Age, forming approximately 8,500 years ago (Andrén et al., 2011). Studies carried out by Sohlenius et al. (2015) found no evidence of acid sulphate soils in areas that were above where the shoreline was 6,500 years ago. The shoreline 6,500 years ago went through the study area of Umeälvsåsen, see Figure 3.1. The Geological Survey of Finland (GTK) have identified acid sulphate soils extending up to the Littorina boundary and a study carried out by Mäkelä (2013) suggest they may even occur above this level (Mäkelä, 2013).

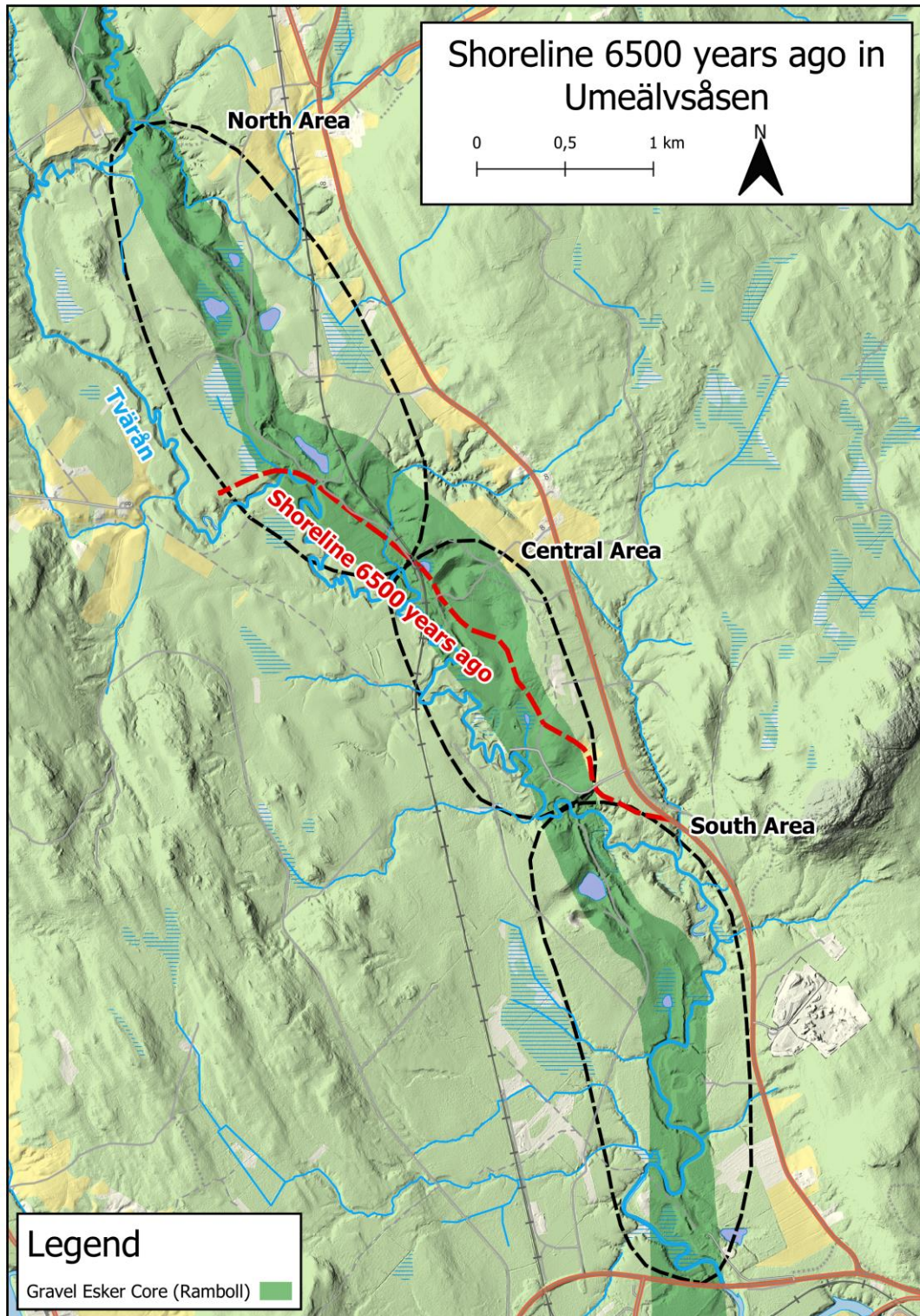


Figure 3.1. Shoreline 6500 years ago in Umeälvsväsen according to SGU (SGU, 2024a).

A study carried out in Finland proved that even coarse-grained materials can exhibit low pH concentration when exposed to oxidation (Mattbäck et al., 2017). The concentrations of sulphur were not significant, but the low buffering capacity caused measured pH values down to pH 2.9 in the soil. No acid sulphate soils were localised in the soil samples. Surrounding groundwater showed

elevated metal concentrations up to 10 times higher than reported background concentrations for Finnish groundwaters.

The study emphasize that the oxidation went faster in the coarse-grained materials in comparison to more fine-grained materials, which traditionally are commonly observed and classified as potential acid sulphate soils (Mattbäck et al., 2017). The rapid decrease can be explained by the low buffering capacity of the soil and the low specific surface of the material. Iron was standing out with extreme high levels according to Mattbäck et.al (2017) and could be visually seen in the testing area as precipitation. The authors therefore highlights that even coarse-grained material could pose sulphide oxidation threats related to groundwater extraction.

3.5 Groundwater velocity and Residence time

The relationship between iron and manganese concentrations and the residence time of the groundwater have been addressed in several scientific articles and literature within the field. An aquifer with low groundwater velocity has longer residence time, which allows chemical processes to take place over longer time and change the chemical status of the groundwater (Falowo et al., 2019). A study taking place in North America used machine learning to identify important parameters influencing the redox condition in groundwater aquifer (Erickson et al., 2021). The aquifers are in glacial deposits, strongly affected by the latest glacial period during the Pleistocene.

The results indicated that groundwater residence time had the greatest influence on the redox potential of the groundwater. Conversely, redox potential was found to be less affected by geochemical reactivity. Utilizing these data, Erickson et al. (2021) developed a model to map potential redox conditions across the study area. The model outcomes suggested that the likelihood of anoxic conditions was associated with well depth. Consequently, Erickson et al. (2021) emphasized that deeper wells are more likely to yield anoxic groundwater, which may affect the mobility and transport of iron and manganese.

Erickson et al. (2021) demonstrated that modeled redox potential levels were not significantly influenced by chemical reactivity. In contrast, opposing findings were reported by Khozyem et al. (2019) in their study of groundwater aquifers in Egypt. Vertical distribution patterns revealed distinct stratification, with iron predominantly present as sulfides (FeS_2) in the deeper stratigraphic layers, resulting from anaerobic and sulfur-reducing conditions. Conversely, the shallow aquifer zones were characterized by the presence of iron carbonates (FeCO_3), driven by higher pH and the availability of carbonate species. This geochemical partitioning highlights the critical role of redox conditions and mineral stability in controlling the speciation and concentrations of iron and manganese in groundwater.

4 Site description of Umeälvssäsen

The site description of Umeälvssäsen was conducted using investigations carried out by Ramboll, SGU's quaternary geological mapping (Eklund, 1991), and theoretical literature on quaternary geology, hydrogeology, and hydrogeochemistry. This section describes the location of the study and the environmental conditions under which it was conducted, as these are essential for the interpretation of the results.

The report made by Ramboll (2024) functioned as the main source describing the site, with detailed descriptions based on investigations in the specific study area of Umeälvssäsen with interest for this thesis. Ramboll has divided the study area into three sub-areas: North, Central and South area. The same division has been applied in this study, see Figure 4.1.

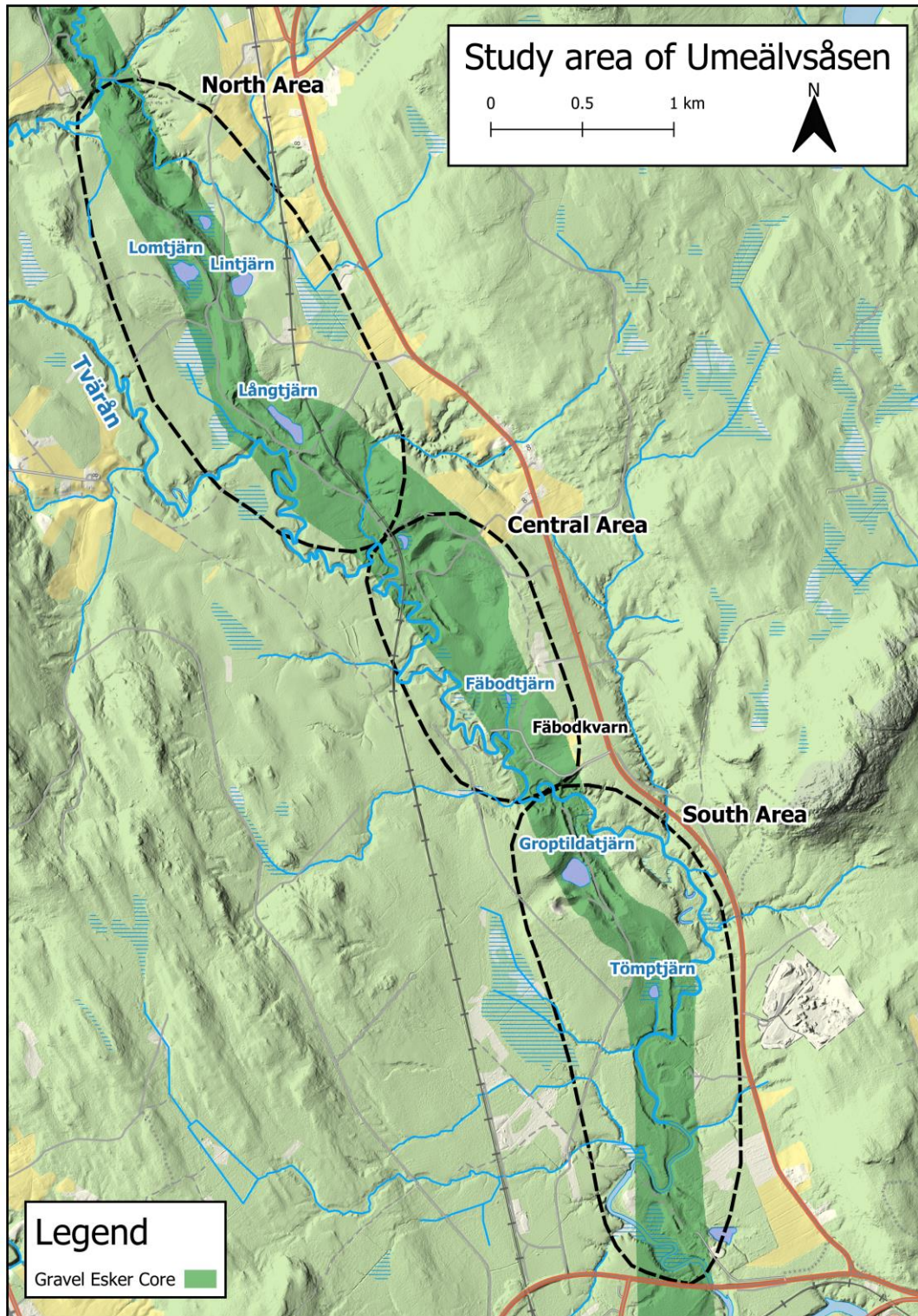


Figure 4.1. Ramboll's division of the study area into three sub-areas: North, Central and South area.

A series of quaternary geological maps provided by SGU with general descriptions of deposited sediments and their distribution in Umeälvsåsen was used. The mapped area is located south of the section of interest (Eklund, 1991). The mapped area is limited and do not cover the study area investigated by Ramboll. The publication was used to describe the deposit of the esker and its surroundings and to discuss potential similarities with the study area.

Additional information from relevant literature have been used, which is focusing on the whole Västerbotten county. This includes studies carried out by SGU (Becher et al., 2019) to describe the potential of acid sulphate soils and organic material.

4.1 Quarternary Geology in Umeälvsåsen

The ice sheet from the last glaciation covered the studied section of Umeälvsåsen until approximately 10,600 years ago (Eklund, 1991). SGU have set up a model that describe the regression of the last ice sheet and simulated the isostatic uplift and visualizes it in their mapping service “Strandförskjutningsmodell” (SGU, 2024a). The model shows that the entire segment of Umeälvsåsen that is of interest in this thesis remained submerged until 7,500 years ago, when the northern part of the esker emerged above the sea level. The southern part of the esker remained submerged until 6,300 years ago according to the simulation.

The dynamic movement of the ice sheet is of importance to trace the origin of the sediment in the esker (Bergström, 1968). In Västerbotten, the mapping of glacial striations indicates that the movement of the ice sheet was from the northwest to the southeast. This has a significant impact on sediment deposition in the coastal area, which incorporates the area of Umeälvsåsen, as the dominant till consists of material derived from the bedrock.

Eklund (1991) studied a segment of Umeälvsåsen, located directly south of the study area, see Figure 4.2 for illustration of the mapped area.



Figure 4.2. The mapped area by Eklund (1991) describing the quaternary geology of the area.

The mapped area by Eklund is located below the highest coastline, characterized by fine-grained marine and lacustrine sediments that have been influenced by postglacial processes and their depositional environment. Above the highest coastline, till and peat are the dominant sediments, and these areas remain unaffected by wave washing. Umeälvssäsen is interpreted as a glacial fluvial esker

formation, where material eroded and was transported with meltwater within the icesheet.

Distinguishing glaciofluvial sediments from fluvial sediments, which have been deposited in watercourse of postglacial origin, was challenging according to Eklund (1991). Both deposits have stratification controlled by water velocity, resulting in alternating layers of fine and coarse-grained material. The differentiation between glaciofluvial and fluvial sediments is particularly difficult in flat terrain and in areas situated below the highest coastline, which was indicated in area of Umeälvsåsen mapped by Eklund.

The glaciofluvial deposits are largely overlain by fluvial and lacustrine sediments, with a thickness varying between 5 and 30 m (Eklund, 1991). In the valley south of the study area, there is an extensive zone filled with fluvial sand, which is most likely reworked glaciofluvial sediments. These have formed due to flooding in the valley and redepositioning of the fine-grained materials.

In the mapped area by Eklund (1991), fine-grained materials that were deposited during both the glacial and postglacial periods have been identified (Eklund, 1991). The glacial fine materials were transported by glacial meltwater streams into the sea during the final retreat of the continental ice sheet. The postglacial fine materials were carried into the sea and lakes by fluvial processes after the glacial epoch.

The depositional environment caused formation of acid sulphate soils. These layers of fine-grained material can be difficult to identify with superficial investigations. Previous drilling has detected layers of acid sulphate soils with a thickness of 10 m in the southern part of the esker (Eklund, 1991). These layers have been found concealed beneath layers of lacustrine or fluvial sediments. The conclusion is that the occurrence of acid sulphate soils is extensive in the area and that it is present in significant thicknesses, according to the publication by Eklund (1991).

The use of “Strandförskjutningsmodellen”, provided by SGU (SGU, 2024a), has shown that the section of the esker examined in this study, along with its surrounding area, was previously located beneath the Baltic Sea. Its position as a former bay suggests that the area may have been favorable for the accumulation and storage of organic material, either originating from the marine environment or transported by glacial meltwater streams. Due to the isostatic uplift and the topography of the area, accumulation of water may have created small lakes, according to the model simulation.

There are several small lakes and marshes in the low-lying terrain stretching along the esker adjacent to Tvärån. Their potential impact was discussed in Ramboll’s investigations (2024). Small lakes and marshes are more common in the South area, where the groundwater environment has been classified as more reductive. The depth of the lakes and their potential hydraulic contact with the groundwater table was investigated by manual water level measurements and during test pumping by Ramboll. No significant hydraulic contact was inferred.

Furthermore, Ramboll's investigation have characterized the geological composition and stratigraphy in Umeälvsåsen. The geological composition has been determined from explorational drillings and soil samples collected every meter during drilling of wells (Ramboll, 2024). The material is evaluated in field to enable comparison between the different depths, see Figure 4.3 for visualisation.



Figure 4.3. Soil samples from exploration drilling in September 2019 (Ramboll, 2024).

The results have been summarized in drilling logs, showing the depth, level, soil classification, lithological log, soil observations and estimated water flow.

4.2 Hydrogeology of Umeälvsåsen

Groundwater level measurements under natural conditions were carried out, showing a decreasing level from North to South (Ramboll, 2024). The highest level being 89 m above sea level in the North area and the lowest at 77 m above sea level in the South area. The hydraulic gradient varies along the esker, see Figure 4.1 (Ramboll, 2024). In the North area, it is relatively high. In the Central area, the gradient is consistent until Tvärån crosses the esker's core. In the South area, the gradient is lower.

The groundwater velocity is generally higher in the North in comparison with the South area, mainly due to the transmissivity difference, see Figure 4.4 (Ramboll, 2024). Though there are some local occurrences of very low velocity in the North area due to groundwater flowing through a small area at a high velocity, making adjacent water flow slow.

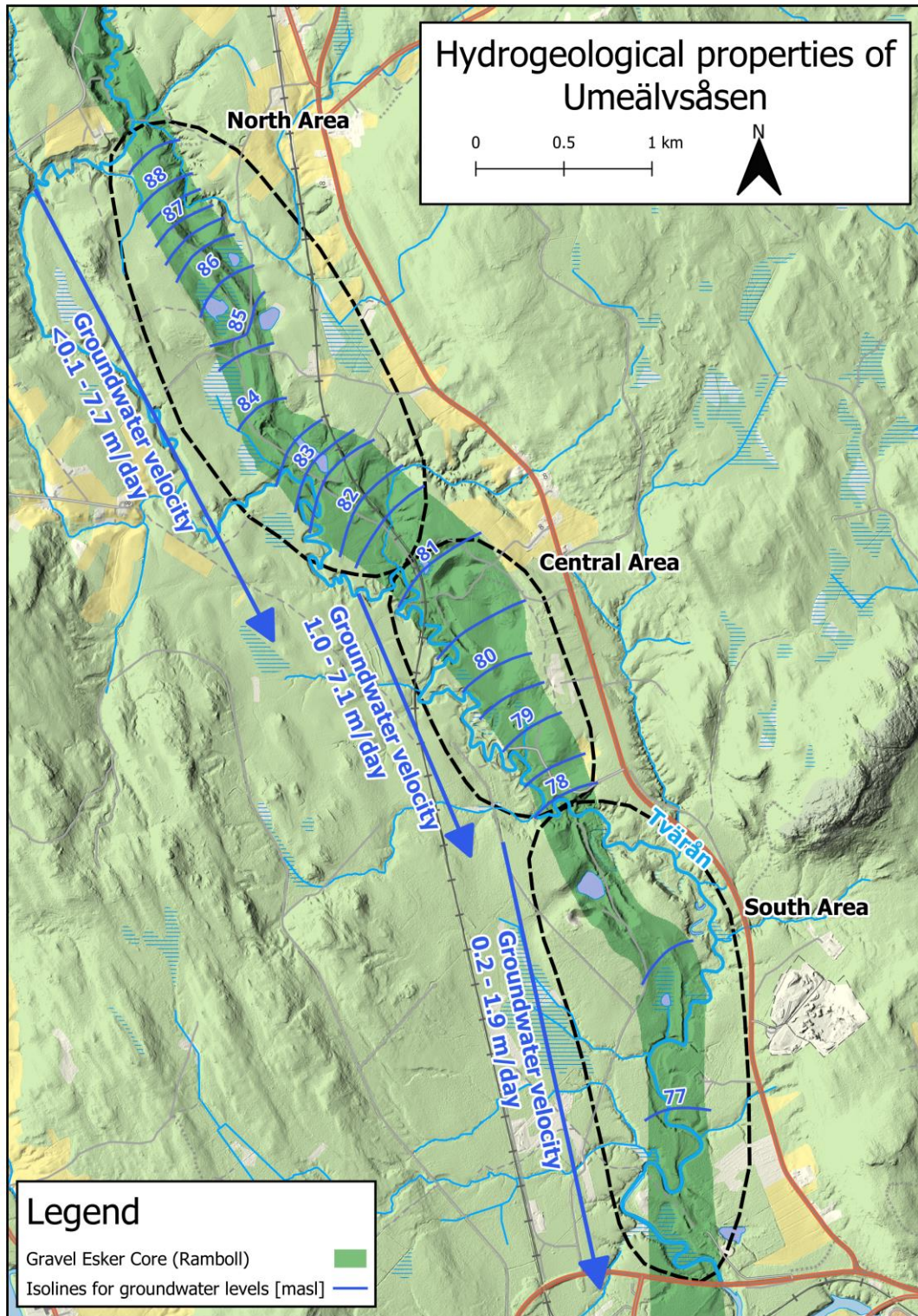


Figure 4.4. Hydrogeological properties of Umeälvssäsen showing isolines for groundwater levels and groundwater velocity in each area.

The groundwater flow was estimated to increase from north to south along the esker (Ramboll, 2024). The flat gradient in the South area suggests a larger cross-sectional area of the esker. In the Central area, the gradient is uniform, indicating no significant restrictions on groundwater flow. In the North area, greater variations suggest that the cross section of the saturated part of the esker

varies, and that flow velocity vary accordingly. This may also be due to the esker being narrower in the North area or the presence of materials with lower hydraulic conductivity. In addition to the cross-sectional area, the transmissivity may also contribute to the large differences in hydraulic gradient. The large difference in hydraulic gradient has an impact on the groundwater velocity in the esker.

Long term test pumping has been conducted at three locations in the study area during the investigation period, with large abstraction volumes over an extended period (Ramboll, 2024). The natural groundwater capacity without artificial infiltration is estimated at 100–150 l/s. There are uncertainties regarding the estimation since steady-state conditions were never reached. Long term test pumping showed that the drawdowns were small relative to the thickness of the saturated zone and that the environmental impact was limited. There is a clear hydraulic connection between the areas, indicating that abstraction in the North area affect downstream conditions.

The estimated capacity of the North area is at least 40 l/s, for the Central area 35 l/s, and for the South area 55 l/s. Test pumping were only conducted at three locations and therefore there is potential for other pumping well locations that remain to be explored.

Groundwater recharge mainly occurs through precipitation infiltrating the esker. It is supplemented by inflow from adjacent areas and from Tvärån (Ramboll, 2024). Infiltration capacity varies depending on soil conditions, with areas of sand and gravel with recharge of up to 375 mm/year, while areas with finer-grained material have significantly lower recharge. Total recharge within the catchment area is estimated to 115–195 l/s, excluding regional groundwater flow.

Tarns adjacent to the Umeälvsåsen esker are considered hydraulically isolated from the aquifer in the esker due to low permeability soil layers, although some leakage may occur (Ramboll, 2024). Tvärån flows parallel to the esker and depending on the seasonal conditions, it act as either a recharge or discharge area. Potential recharge area is located where Tvärån intersects the esker core at the boundary between the Central and South areas.

The conclusion is that recharge from Tvärån is small. In the South area, downstream the intersection between Tvärån and the esker, several oxbow bogs have been detected. Oxbow bogs arises when a river or stream transform and take a new pathway (Obolowski, 2011). They often have a bottom layer covered of organic matter. With time, the riparian vegetation overgrows the open water surface. Their wetness level is dependent of their age and previous hydrological flowpaths.

Nevertheless, there is a potential hydraulic contact with the esker and adjacent deposits. Water level measurement during test pumping showed no lowering of the surface water level in Fäbodtjärn or Grottildtjärn. The conclusion is therefore that there is none or very poor hydraulic contact between the aquifer

in the esker and these two tarns. The same conclusion has been made for several tarns in the area.

4.3 Hydrogeochemistry in Umeälvsåsen

Ramboll's investigation include hydrogeochemical parameters regarding water quality (Ramboll, 2024). The samples were collected during the entire investigation period, with background values collected in 2020 before pumping tests were initiated. Iron and manganese concentrations in the groundwater vary throughout the esker and increase from north to south. Classification of the concentrations is based on SGU's recommendations.

To retrieve water samples that reflect the characteristics of the groundwater, all sampling piezometers or wells that were not subject to test pumping were purged at least three times before collecting samples. The test pumping wells were sampled during continuous pumping and there was consequently no need for purging.

The mean concentrations of iron and manganese measured in the test pumping wells before and after aeration and filtration are presented in Table 4.1. The aeration and filtration were made at laboratory in Umeå. While the levels decreased by aeration and filtration, they remain elevated. In particularly the Central and South parts of the esker, the measured concentrations remain high.

Table 4.1. Mean concentrations of iron and manganese before and after aeration and filtration for which well and area.

Area	Well	Before aeration		After aeration	
		Fe [mg/l]	Mn [mg/l]	Fe [mg/l]	Mn [mg/l]
North	B1N	0.71	0.04	0.10	0.03
Central	B4M	2.74	0.08	1.00	0.08
South	B2S	4.26	0.27	1.42	0.24

The North area generally shows lower iron and manganese concentrations which easily oxidize. The Central and South areas have higher concentrations of iron and manganese present even after aeration. In the South part, the iron concentrations are classified as high or very high levels according to guidelines presented by SGU in Table 2.1.

During the long-term test pumping, samples were taken to observe changes. During test pumping in the Central and South areas, iron concentrations increased in untreated water samples. In the North area, no clear increase in iron concentrations occurred during test pumping. The changes are presented in Table 4.2. Since the iron concentration had large variation before test, no specific value has been determined.

Table 4.2. Changes in concentration of iron and manganese in the South area during long time pumping test.

Area	Before pumping		During pumping	
	Fe [mg/l]	Mn [mg/l]	Fe [mg/l]	Mn [mg/l]
South	4.4	0.2	4–5	>0.3

Oxygen levels and redox potential were not measured in field. The redox condition has been estimated based on other indicator parameters. In this thesis, iron, manganese, sulphate and ammonium have been used to estimate the redox condition. A summary of the indicator parameters is presented as boxplots in Figure 4.5. The groundwater is classified as anaerobic, particularly in the Central and South areas, where low sulphate concentrations have been observed together with high iron, manganese and ammonium concentrations which indicate low redox potential.

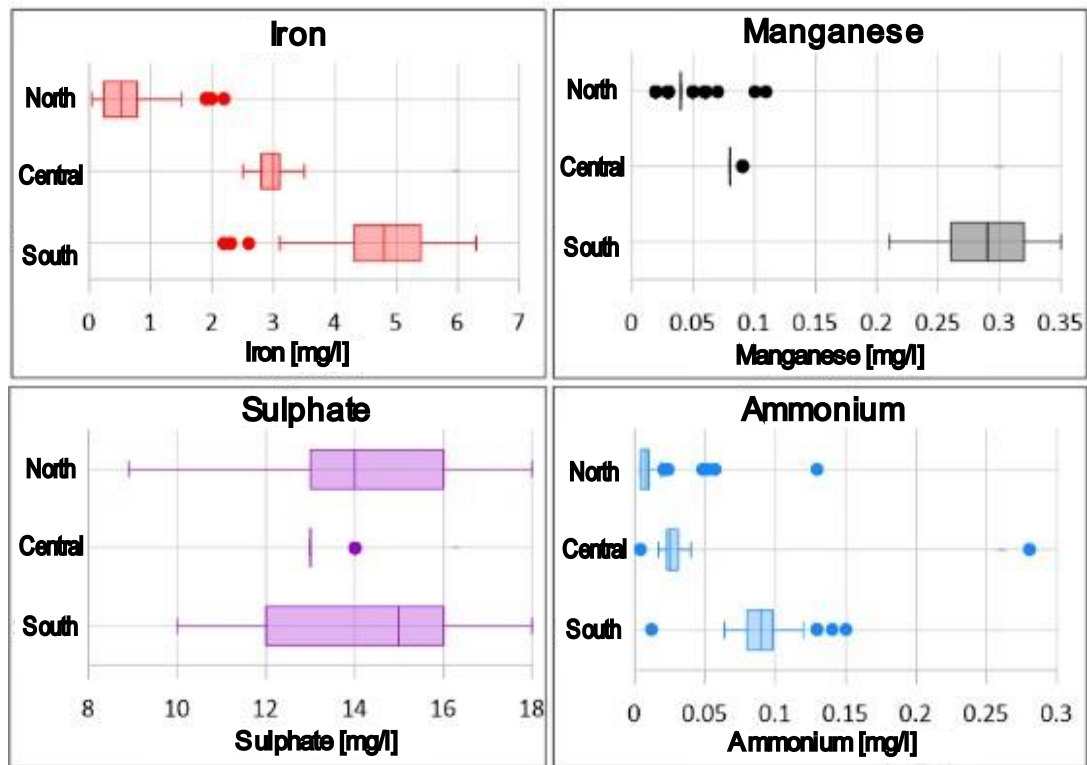


Figure 4.5. Boxplot of indicator parameters used to identify redox conditions. The samples are taken during pumping and shows the 25th percentile, 75th percentile and the median for each parameter as a straight line. Outliers are marked as dots (Ramboll, 2024).

Alkalinity and pH have been measured to understand the behaviour of groundwater elements and the buffering capacity. Chemical Oxygen Demand (COD) has been measured to indicate the presence of organic matter in the water samples. The results from samples collected in field are illustrated in Figure 4.6.

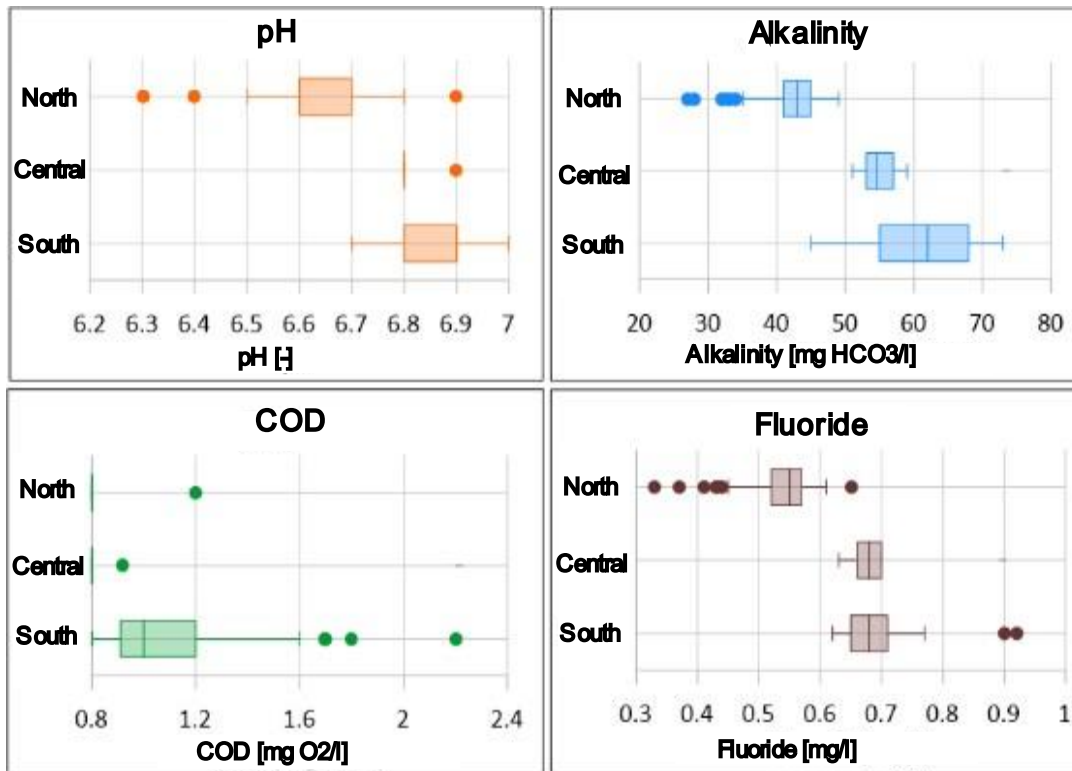


Figure 4.6. Parameters measured to evaluate the groundwaters characteristics. The samples are taken during pumping and shows the 25th percentile, 75th percentile and the median for each parameter as a straight line. Outliers are marked as dots (Ramboll, 2024).

4.4 Detailed area description

Figure 4.7 shows a cross-sectional view of the esker in the North area (Ramboll, 2024). Conceptualization based on investigation drilling and geophysical investigations by Ramboll shows the esker's distinctly prominent core. The core of the esker mainly consists of permeable glaciofluvial material, directly exposed at the surface. Fine-grained deposits in low-lying areas create conditions for small wetlands beside the esker. The grain size of the sediments increases with depth both in the esker's core and lateral areas of the esker. Generally, the lateral deposits follow the same stratigraphic sequence as the esker. Though in some sections, fine sand is found beneath medium sand.

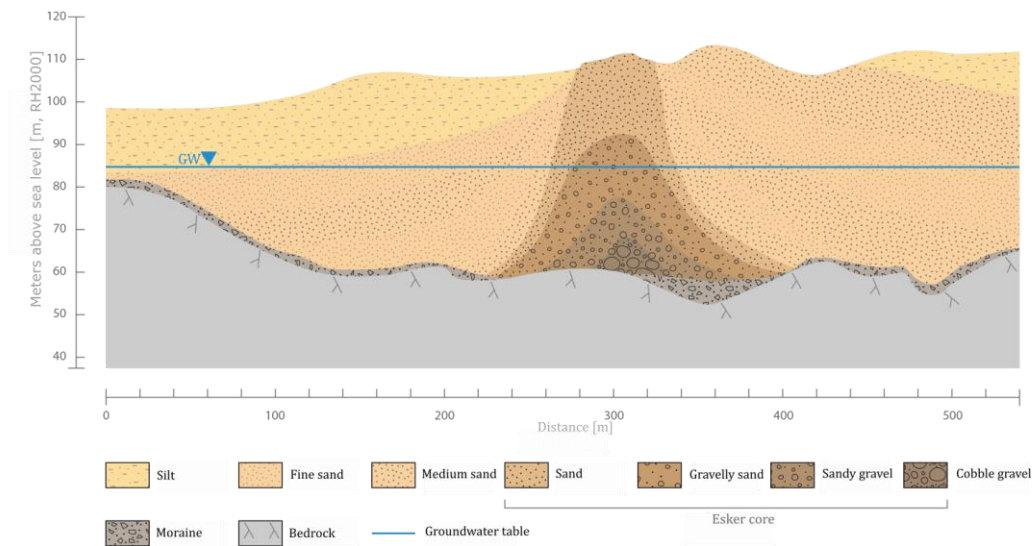


Figure 4.7. Cross section in the North area of the esker with a core thickness of up to 60 m (Ramboll, 2024)

Figure 4.8 shows a cross-sectional view of the esker in the Central area (Ramboll, 2024). Unlike the North, in the Central area the esker is less distinct topographically. Large parts of the core of the esker are covered by fine-grained materials. In the northern part of the Central area, the esker's core is not covered by fine-grained material and there is evidence of large-scale gravel excavation. The thickness of the glaciofluvial deposits reaches up to 70 m, while the unsaturated zone varies between 5 and 13 m. Drillings have indicated that the grain size increases with depth towards the ridge core. The grain size in the lateral deposits exhibits more pronounced variations in layering, reflecting different depositional conditions.

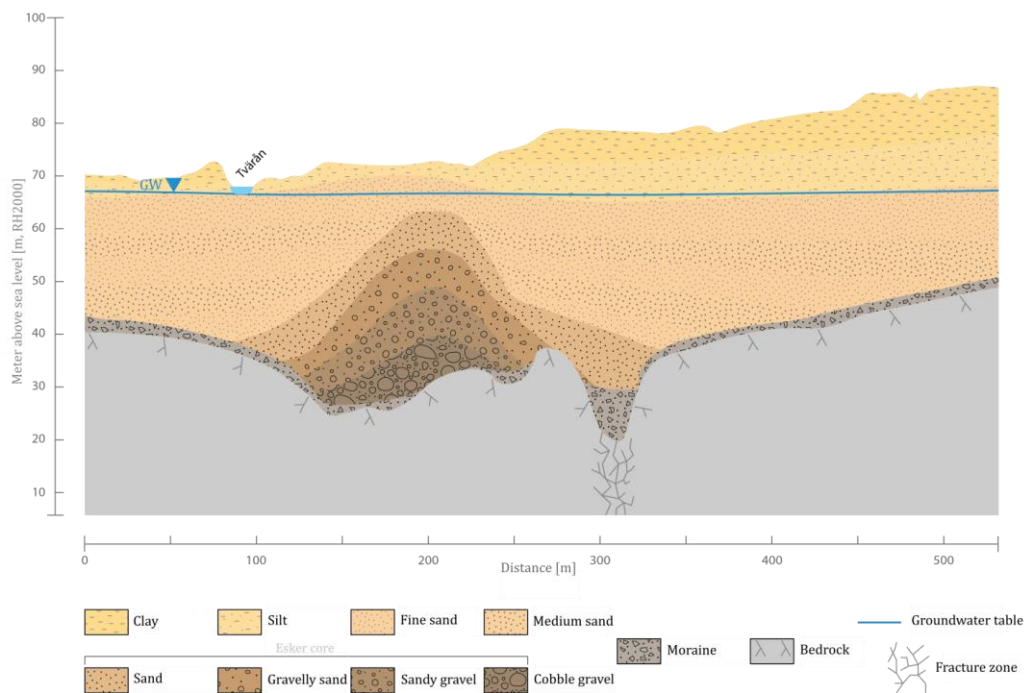


Figure 4.8. Cross section in the Central area of Umeälvssäen showing where the core of the esker reaches a maximum thickness of 70 m with an unsaturated zone ranging from 2 to 10 m (Ramboll, 2024).

Figure 4.9 shows a cross-sectional view of the South area (Ramboll, 2024). The northern part of the subsection has been affected by previous gravel extraction activities. In the central part, near Tömptjärn, the esker remains untouched, forming a distinct ridge feature visible in the terrain. Further south, the esker becomes less visible at the surface and is partially covered by fine-grained sediments. The grain size generally increases with depth towards the core of the esker. In certain locations, such as near Groptildatjärn, the lithology is more complex than in other sections, with the esker being less prominent and coarser deposits interlayered with finer sediments.

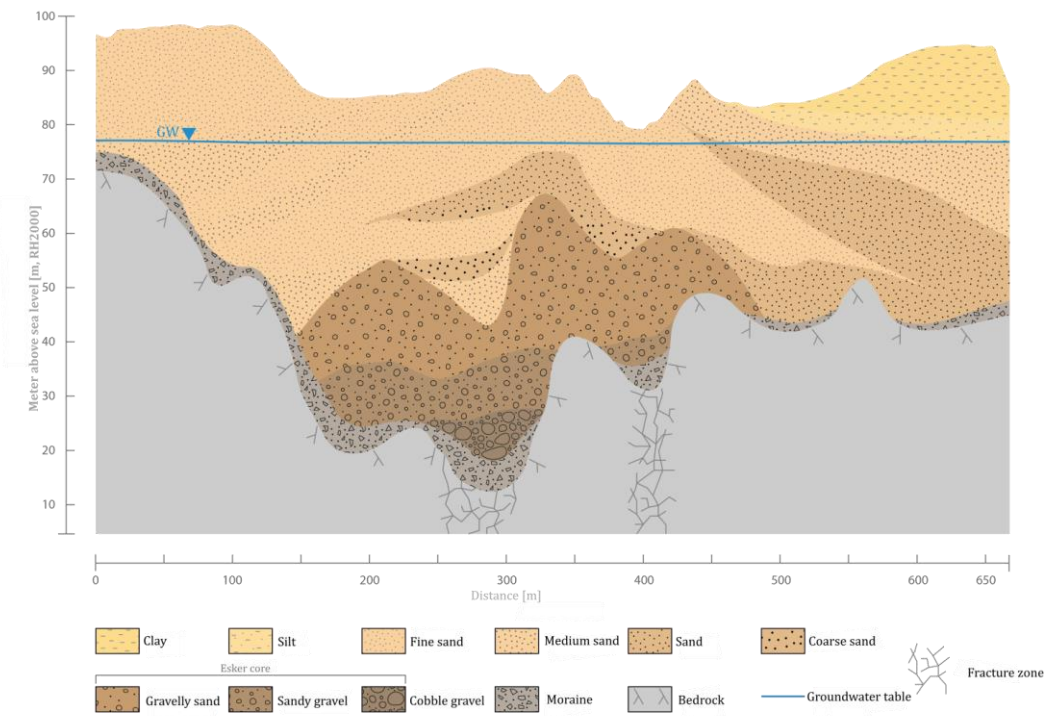


Figure 4.9. Cross-section in the South area of Umeälvssäsen showing the core of the esker reaches a maximum thickness of 70 m with an unsaturated zone ranging from 2 to 10 m (Ramboll, 2024).

5 Methodology for explanatory model

Based on the literature review, theoretical background and site description of Umeålväsåsen, theories to the reason of elevated iron and manganese concentrations were developed.

This was followed by an evaluation of the theories through statistical analysis based on the existing data from Ramboll. The development and evaluation of the explanatory model was an iterative process, continued until a satisfactory explanatory model was obtained. Figure 5.1 shows a flowchart of the conducted steps to develop and evaluate the theories to obtain a valid explanatory model.

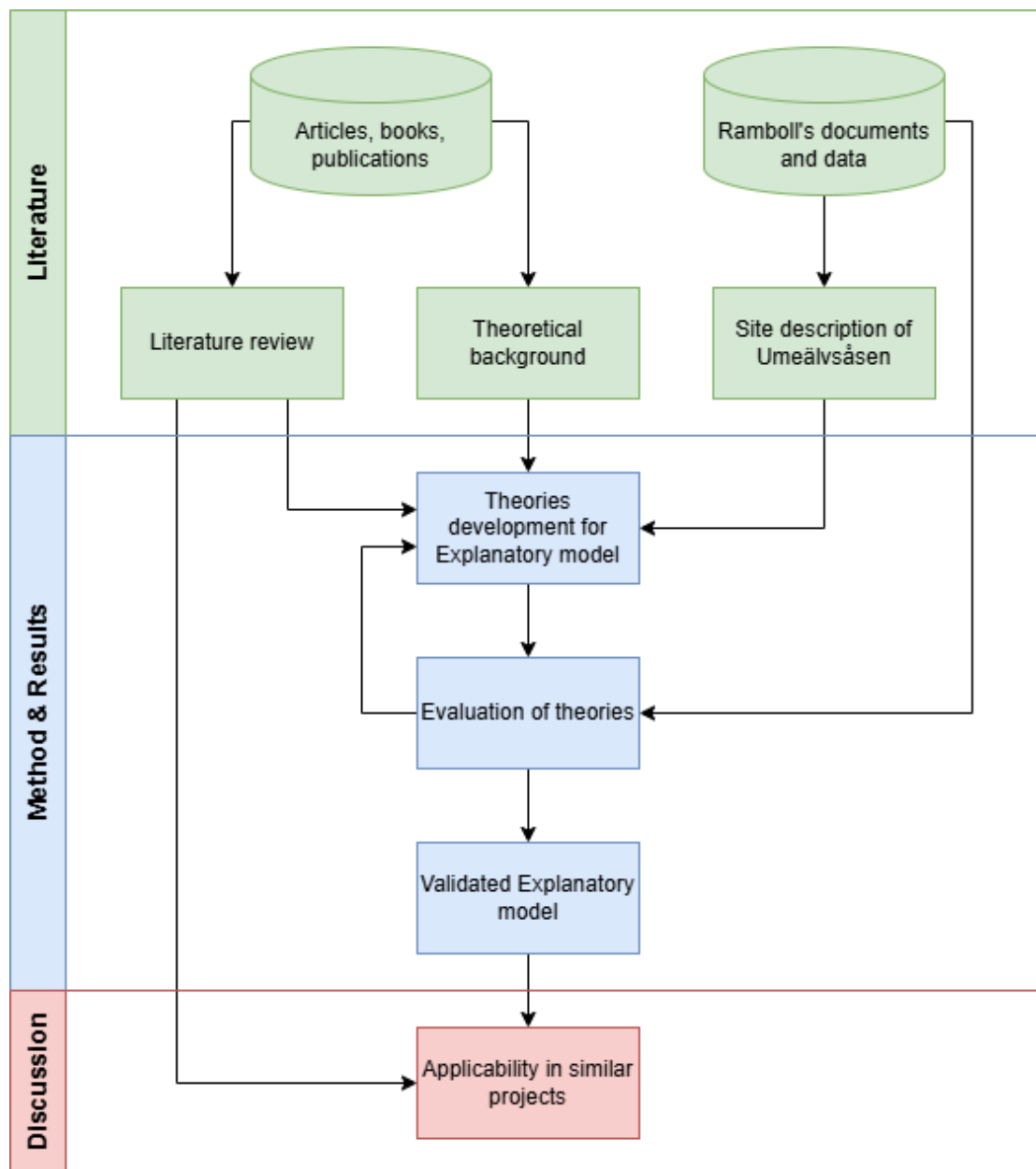


Figure 5.1. A flowchart of the conducted steps of the work to develop and evaluate the theories to obtain a valid explanatory model.

5.1 Development of explanatory model

Different theories for elevated iron and manganese concentrations in groundwater in Umeälvssäsen have been identified based on the theoretical background, site description of Umeälvssäsen, and the literature review.

The geological deposition has a potential impact on the groundwater quality. The origin of the material in the esker, how it is deposited, what compounds and minerals present in the ground all influences the iron and manganese concentrations in the groundwater. Furthermore, the hydrogeochemistry plays a crucial role in the occurrence of dissolved iron and manganese in the groundwater. Low oxygen levels in the groundwater contributes to reducing conditions which lowers the redox potential and the pH. The acidic environment triggers iron and manganese to dissolve and mobilize in the groundwater. The following theories were established as potential explanations:

- Seasonal weather fluctuations affecting the groundwater recharge and hydrological flow paths cause significant differences in water quality.
- The depth of the wells affects the concentrations of iron and manganese by low oxygen levels which enhance the solubility and mobility of iron and manganese.
- Acid sulphate soils causing low oxygenated groundwater contributes to the solubility and mobility of dissolved iron and manganese.
- Sediments rich in organic material embedded in the ground reduce the groundwater's oxygen level in groundwater due to microbial degradation. Further, it contributes to reducing conditions in the groundwater affecting the solubility and mobility of dissolved iron and manganese.
- Surface deposits rich in organic material in proximity to Umeälvssäsen, such as peatlands and lakes, causing low oxygenated groundwater due to microbial degradation.
- Lower groundwater velocity lowers the oxygen level, which contributes to higher solubility and mobility of iron and manganese.

These theories have been investigated and analysed through different methods in this chapter. Ramboll's previous investigations and collection of water samples and subsequent analyses in an accredited laboratory were used as a basis for the analysis.

5.2 Data processing

The provided dataset was compiled and processed by Ramboll. It contains 326 water samples from 25 wells across the study area. Samples from both undisturbed conditions and continuous pumping was included. Each sample have a corresponding date and well name and it includes measurements for numerous water quality parameters of which those of interest in the analysis are shown in Table 5.1.

Table 5.1. Measurement result of indicator parameters used to identify redox conditions of the different esker areas.

Parameters of interest	Unit
Iron (Fe)	mg/l
Manganese (Mn)	mg/l
pH	-
Sulphate	mg/l
Ammonium	mg/l
COD	mg O ₂ /l
Alkalinity	mg HCO ₃ /l

Undisturbed conditions were defined as water samples collected from a well without active pumping. Though, the well was purged three times the well's water volume before samples were collected to avoid extreme outliers caused by standing water affecting the water quality parameters. Continuous pumping was defined as water samples collected from a well while maintaining a constant pumping rate over an extended period.

Outliers and potential measurement errors have been removed to provide a more reliable dataset. The identified outliers were primarily samples taken from observation wells with stagnant water, which yielded highly deviating results.

Figure 5.2 illustrates the distribution of water samples collected during both continuous pumping and undisturbed conditions. Figure 5.2 also shows the number of wells from which these samples were taken. In the North area there are water samples influenced by Ramboll's tracer test and in the South area there are water samples affected by Ramboll's infiltration test, which were excluded in the analysis since there were indications that these tests had an impact on the water samples, which was evaluated by visual observations. The Central area was in some analysis excluded or split up into the North or South area due to insufficient number of water samples.

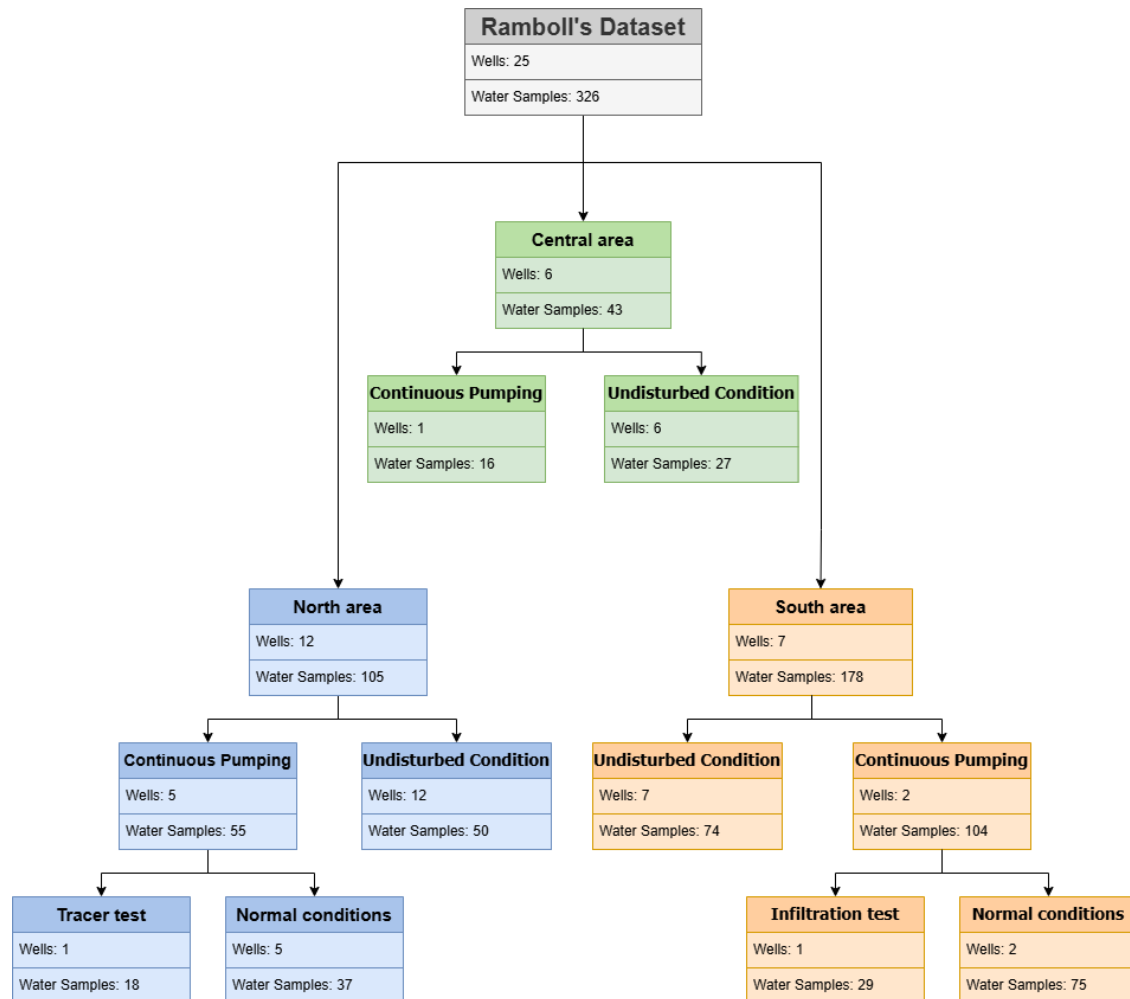


Figure 5.2. Structure of provided dataset regarding water quality from Ramboll and number of samples and wells for each area and pumping status.

5.3 Statistical data analysis

Analysis was done by using Excel statistical analysis toolpak. All data parameters were evaluated by using descriptive statistic tool, summarizing and evaluating the general statistic of the input data. The water quality parameters were categorized into North, Central and South area and within each area, the samples were divided into undisturbed conditions and continuous pumping. Depending on the central tendency and variance, the student t-test was further applied to test the significance of the populations mean values. The calculated degrees of freedom were used to support the evaluation of the dataset's appropriateness to give reliable statistical answers.

Welch's t-test was used since the population sizes were unequal for the water quality parameters of interest, especially iron and manganese concentrations (Ruxton, 2006). This method has been evaluated to be more reliable according to Ruxton (2006) and is easily deployed in Excel.

To investigate differences in water samples and their statistical significance, unequal variance t-test have been used. Student's t-test express if the differences between two populations mean is statistically significant or not (Ruxton, 2006). The distinguish is done by comparison of the data distributions. The process is

conducted by establishing a null hypothesis saying there is no statistical difference between the mean values of the data populations. If the null hypothesis is rejected, there is a statistically significant difference. To apply the method, the data groups must follow an approximated normal distribution to obtain a reliable result from the test. The statistical degrees of freedom together with the mean and variance of each data set was presented to obtain the extent of the analysis.

The purpose of the test was to determine if the observed differences in water quality parameters between the different areas are statistically significant and not a coincidence. Water quality samples from the North area of the esker has been evaluated in comparison to the South area, both during undisturbed conditions and continuous pumping. Samples have also been individually compared between undisturbed condition and disturbed conditions due continuous pumping in the North and South area respectively.

To evaluate the statistical relationship between water quality parameters and established theories, Excel correlation tool was applied using Pearson rank correlation coefficient. The Pearson correlation coefficient together with scatter plots was used to evaluate negative or positive correlation between the investigated parameters. Conducted correlation tests are shown in Table 5.2.

Table 5.2. Conducted correlation tests.

Conducted Correlation tests
Correlation between water quality parameters.
Well depth correlation with iron and manganese.
Wetland area and correlation with iron/manganese/COD.
Groundwater velocity correlation with iron and manganese.

There are assumptions that the data should fulfil to get reliable result from Pearson correlation analysis (Schober & Schwarte, 2018). It has been judged that the data handled in this thesis fulfil these requirements.

- Both data sets should be derived from random, representative samples.
- Both data sets should be continuous and approximately follow a bivariate normal distribution, or at least each variable should follow a univariate normal distribution.
- The relationship between the two data sets must be linear.
- There should be no relevant outliers in the two data sets that have a disproportionately impact.
- Each observation is measured independently.

Scatter plots was made in addition to the correlation test, which is motivated by Schrober & Schwarte (2018) since the visible inspection together with the r-value enable a more robust evaluation. In addition, the R^2 value was calculated to evaluate how much of the variation in a water quality parameter could be explained by the external variable.

The calculation of the correlation coefficient is made according to Equation 2. Variables X and Y represents values from the two different groups of parameters (Laerd Statistics, 2020). By subtracting the mean from each observation, the distance from the average value is calculated. By using the equation, the measurements are standardized and allow to compare the parameters movement together independent of their units.

$$r = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2 \sum(y-\bar{y})^2}} \quad (2)$$

The correlation coefficient, referred to as r-value, shows the linear relationship between two parameters, varying between 1 and -1 (Schober & Schwarte, 2018). A positive value shows that the associated parameters change in the same magnitude in the same direction and a negative value shows changes in the same magnitude the opposite direction. The r-value are moving towards 1 or -1 when the data points are approaching a distribution following a straight line.

To evaluate the strength of a correlation, the magnitude of the correlation coefficient is interpreted with an assessment of its strength. There is no universal rule for interpreting the results of the Pearson correlation coefficient. Depending on which data being analysed and the purpose, different approaches may be applied. Even a small value of the correlation coefficient can be significant within some research fields.

The size of the Pearson correlation coefficient (r) was assessed using the following conventional guidelines presented by Hinkle, Wiersma and Jurs (2003) and Schober & Schwarte (2018). See Table 5.3 for interpreted magnitude of correlation coefficients. Correlation analysis has been combined with scatter plots and Student's t-test to assess the values of the water sample parameters and to evaluate how these values vary individually and in relation to other parameters.

Table 5.3. Magnitude of correlation coefficients and interpretation of their strength (Hinkle et al., 2003).

Correlation coefficient magnitude	Interpretation
± 0.9 - 1.0	Very strong correlation
± 0.7 - 0.9	Strong correlation
± 0.5 - 0.7	Moderate correlation
± 0.3 - 0.5	Weak correlation
± 0.0 - 0.3	Non or very weak correlation

To determine to what extent the sampled data estimate the underlying population, confidence intervals was conducted (Hazra, 2017). Confidence intervals were calculated for each Pearson correlation coefficient using Fisher's z-transformation (Taraldsen, 2023). The transformation converts the r-value into a variable z, that follows an approximately normal distribution, thereby facilitating the construction of confidence intervals. Fisher's z-transformation is a standard technique in correlation analysis, enhancing the accuracy and

interpretability of statistical inference. The confidence interval was calculated with a confidence level of 95%, presenting the lower confidence value and upper confidence value.

Correlation tests between each parameter of interest was performed. This was done in the North and South area, both in undisturbed conditions and during continuous pumping to see potential relations between the water quality parameters.

5.4 Seasonal variations

t-tests was applied within the areas during different time periods to see if changes in water quality parameters was seasonal. Since the location of the study area is affected by seasonal weather changes contributing to snow melting and heavy precipitation, changes in hydrological flowpaths potentially affect the water quality. The division into time periods was done according to precipitation patterns since it is directly linked to groundwater recharge, see Figure 5.3 for division.

Measurements from Ramboll’s investigations of the groundwater levels was used to determine significant periods for the specific area. The esker aquifer is affected by heavy snow melting during the first spring months, followed by dry summer months. During autumn, the groundwater recharge mainly consists of rain. From December, the main precipitation consists of snow.

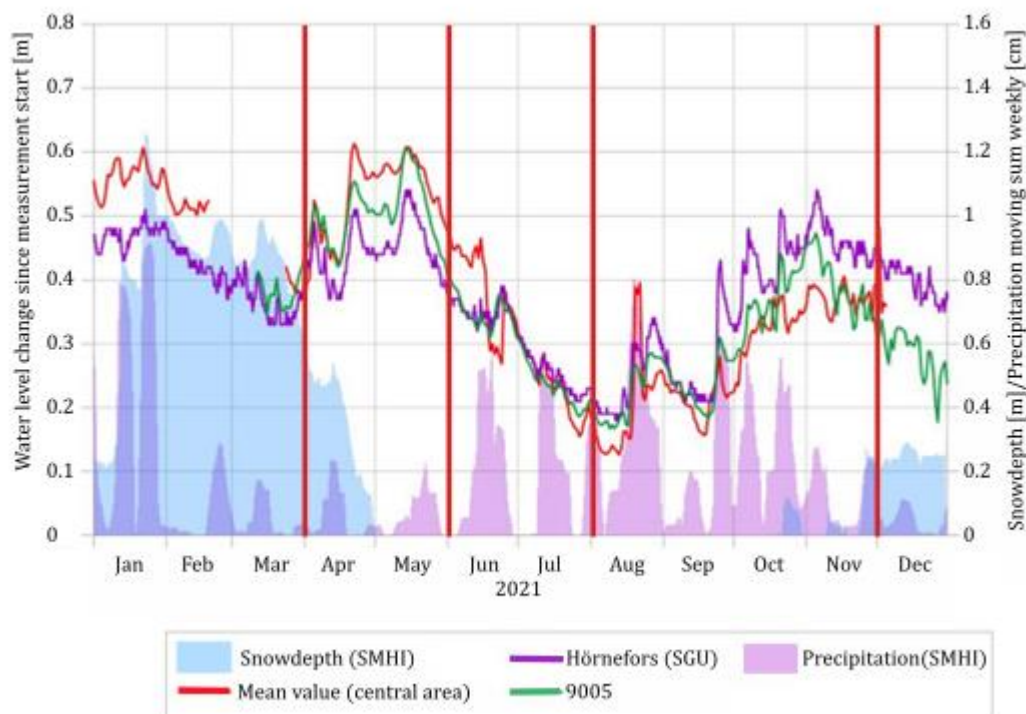


Figure 5.3. Variations in groundwater levels over one year. In addition, measurements of snow depth and precipitation collected from Swedish Meteorological Institute (SMHI) are included (Ramboll, 2024).

A summary of the divided groups that were tested is shown in Table 5.4.

Table 5.4. Number of samples for each group based on time period.

Time Period	North area		South area	
	Undisturbed Condition	Continuous Pumping	Undisturbed Condition	Continuous Pumping
April-May	8	9	5	11
June-July	11	16	13	18
August-November	31	14	45	34
December-March	0	11	11	8

5.5 Well depth

An analysis of the wells' depth was conducted to investigate potential correlations between well depth and iron and manganese concentrations. Ramboll's drilling logs for each well was examined and depth between ground surface level to bottom of the well was determined (Ramboll, 2023). The well depths were then compiled to the dataset with water quality parameter measurements and a correlation test was conducted between well depth and iron and manganese concentrations.

5.6 Field observations – Acid sulphate soils

The documentation conducted by Ramboll included pictures from excavations showing the stratigraphy, accumulated materials from test pumping and surrounding water bodies. Together with grain size distribution curves and geophysical investigations a summarised judgement of the esker material and surrounding deposits have been made.

Water samples have been assessed with an observation regarding strength and characteristics of the smell. These values were summarised in the data sheet and have been used to indicate potential substances and organic material.

5.7 Laboratory testing – Organic rich sediments

To quantify if there is a correlation between increased iron levels in the South area and lenses with high content of organic material in the soil. Loss on Ignition (LOI) test was applied as experimental method. LOI is widely used to determine the content of organic material and carbonates (Heiri et al., 2001). It is done by heating the samples until organic matter is oxidised and converted to carbon dioxide and ash. The organic material content is determined by weighting the sample before and after the heating procedure, where the weight loss corresponds to the organic material content. LOI is time efficient and relatively inexpensive in comparison to other available methods. The method can be standardised by using same sample size, positioning and temperature in the oven, which minimize experimental errors.

The method has been examined and discussed in several studies (Santisteban et al., 2003; Sutherland, 1998; Larsson, 2008), and the potential uncertainties that may lead to misleading results are thoroughly recorded. Its advantages provide strong justification for its implementation and target eventual layered lenses of organic materials, see Figure 5.4. No soil samples have been analysed previously

within the project. It is anticipated that this investigation will offer new perspectives and valuable insights.

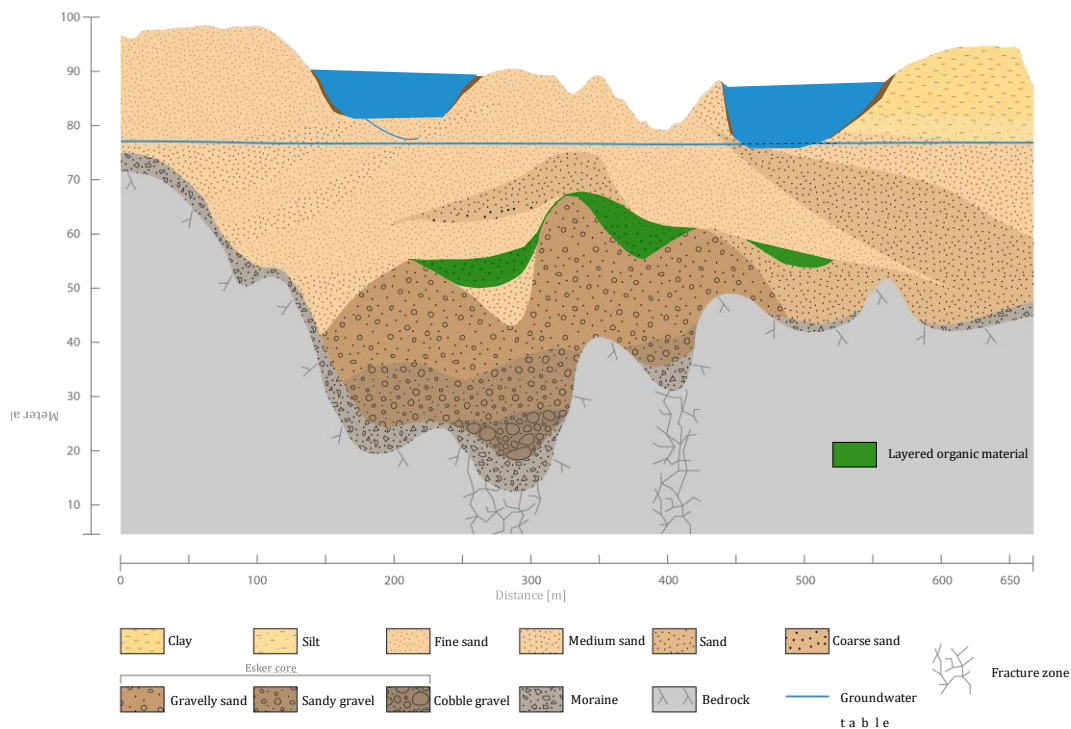


Figure 5.4. Conceptual figure showing potential lenses of organic material layered in the esker material.

Samples of interest have been collected from different drilling holes in the area, shown in Table 5.5. The samples were collected by Ramboll during field investigations and have been stored at Vakin in Umeå. The selected samples were sent to Gothenburg for testing by the authors of this thesis.

Table 5.5. A summary of the soil samples that were tested using LOI.

Drilling point	Area	Depth 1	Depth 2	Depth 3
R2002	South	22.5 - 23.5	23.5 - 24.5	32.5 - 33.5
R1910	South	28 - 29	34-40	51 - 52
R1911	South	16-17	32-33	37.38
R1901	Central	25 - 26	32 - 33	40 - 41
R1902	Central	18 - 19	24 - 25	37 - 38
R1904	Central	20 - 21	35 - 36	53 - 54
R2004	North	23 - 24	46 - 47	51 - 52
R1803	North	28 - 29	38 - 39	54 - 55

The procedure applied is taken from the Swedish method SS 28113 (Svensk Standard, 1981). The test was carried out at Chalmers water laboratory with support from Amir Saeid Mohammadi at the ACE department at Chalmers during spring 2025.

5.8 Analysis of impact from Wetlands

An analysis was conducted to evaluate potential impact of wetlands (peatlands and lakes) and their influence on the concentrations of iron, manganese, and COD in Umeälvssäsen's groundwater. The analysis was done using geographical, geological and hydrogeological data and modelling in the open-source program Quantum Geographic Information System (QGIS) in combination with statistical analysis. The first analysis was based on a basic scenario of the groundwater influence area. The second analysis was based on the groundwater model in MODFLOW to determine the groundwater influence area.

The first part investigated how iron, manganese and COD concentrations correlated with the area of wetlands within the radius of influence from the pumping wells.

First, areas with high organic material were identified using Skogsstyrelsen's and Swedish University of Agricultural Science's (SLU) mapping service "Torvkartan" (A. Ågren, 2022). The map identifies peatlands based on soil moisture and provides peat depth data ranging from 0 to 88 cm. Peatlands deeper than 88 cm are categorized as "88 cm or deeper," making the true depth uncertain.

In Sweden, a peatland is defined as an area with a peat thickness of at least 50 cm (A. M. Ågren et al., 2022). Therefore, only peatlands deeper than 50 cm were considered in the analysis. These peatlands, along with lakes determined in QGIS, were identified and marked for the area of interest. The analysis used the term "wetlands" to describe both peatlands and lakes.

Second, the unsaturated zone beneath each wetland was determined. The aim was to assess if there are potential hydraulic contact between the wetlands and the groundwater since it was uncertain based on previous investigation. The average depth of peatlands in the northern part of Sweden is 1.5 m (Franzén et al., 2012).

All wetlands were put into one out of three categories depending on unsaturated zone thickness. The first category included wetlands with an unsaturated zone thickness ≤ 1.5 m, which was assumed to be wetlands most likely hydraulic connected to the groundwater. The second category included all wetlands with an unsaturated zone thickness between 1.5 and 5 m. This was done since there were uncertainties of the actual depth of each wetland. The third category included wetland with an unsaturated zone > 5 m, which was believed to not be in hydraulic contact.

The thickness of the unsaturated zone was determined using Ramboll's geological and hydrogeological model within QGIS. Figure 5.5 illustrates all identified wetlands in the study area.

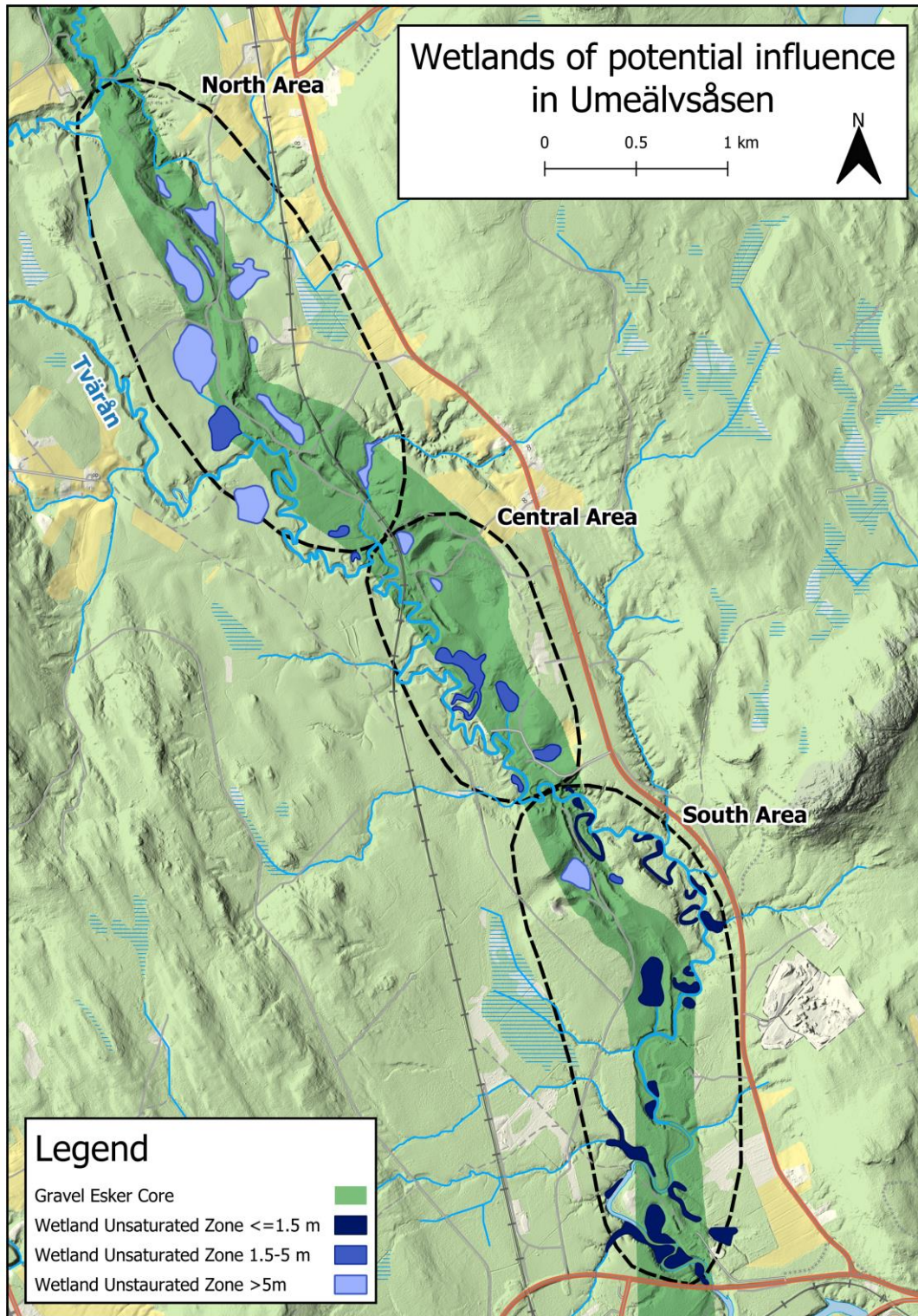


Figure 5.5. Wetlands in Umeälvsåsen categorized by the thickness of the unsaturated zone for undisturbed conditions.

The analysis was conducted for both undisturbed conditions and during continuous pumping during test pumping. As groundwater levels decline during pumping, two separate unsaturated zone depths were determined for each wetland. One for undisturbed conditions and one during continuous pumping.

The surface area of wetlands located within the radius of influence from a pumping well was calculated. This was done for all wells in the study area with at least three collected water samples. The following criteria were applied to determine whether a wetland was within the area influenced by well or not. These criteria were stated to reach a reliable and realistic result:

- The groundwater level in the wetland must be higher than the groundwater level in corresponding well.
- The wetland must also be within 200 m of the esker core.
- The wetland must be located within 1,500 m of the well.

These assumptions and constraints were defined to focus the analysis on wetlands located near the wells, as their proximity suggests a higher probability of influencing the water quality.

In the final part, the data describing the area of each wetland was compiled with the corresponding iron, manganese, and COD concentrations for each well, and a correlation test was performed.

A second analysis was made to evaluate how iron, manganese and COD concentrations correlated with the time dependent growth of wetland area influenced during a long-term test pumping. This was done in the South area in two adjacent wells, B2S and B3S, and the test pumping continued for approximately two years (764 days). The same definitions and scenarios of wetlands in part one is used in part two.

The radius of influence was determined using Ramboll's groundwater model. This model is based on the finite difference method in MODFLOW-USG and operated through the Groundwater Vistas 8 interface. The model incorporates a three-dimensional geological representation of the esker, interpolated from multiple cross-sections using Surfer. Groundwater flow under test pumping conditions was analysed using particle tracking via the Mod-PATH3DU transport simulator, which visualizes flow paths and travel times to the wells. This model defined the influence area by the groundwater's residence time, and not by geographically constraints as in part one.

The model was used to simulate the groundwater flow during the long-term test pumping at a rate of 50 l/s in well B2S. The actual long-term test pumping was conducted in both B2S and B3S and had a pumping flow between 43-75 l/s together, with a flow of 20-36 l/s in B2S and 23-39 l/s in B3S. Although the simulated flow differentiated between the simulation and the actual test pumping, it was assumed sufficiently representative for the analysis. Another assumption was that the influence from wetlands was negligible at the start of pumping and increased progressively as the radius of influence increased. While some influence from wetlands likely existed from the beginning, this was disregarded since only the changing groundwater flow and direction was of interest.

During the long-term test pumping, pressure transducers was used to see eventual impact of the surface water level in certain lakes within the study area. By visual inspections of the equipment, assumptions regarding hydraulic contact could be made. This was done to evaluate the assumptions made regarding the unsaturated zone thickness.

After the simulation, the increase in radius of influence over time during the test pumping was used to calculate the area of wetlands within the influence area. Figure 5.6 shows a conceptualization of the increased area of wetland influenced during the long-term test pumping.

Increase of Area Wetland Over Time During Pumping

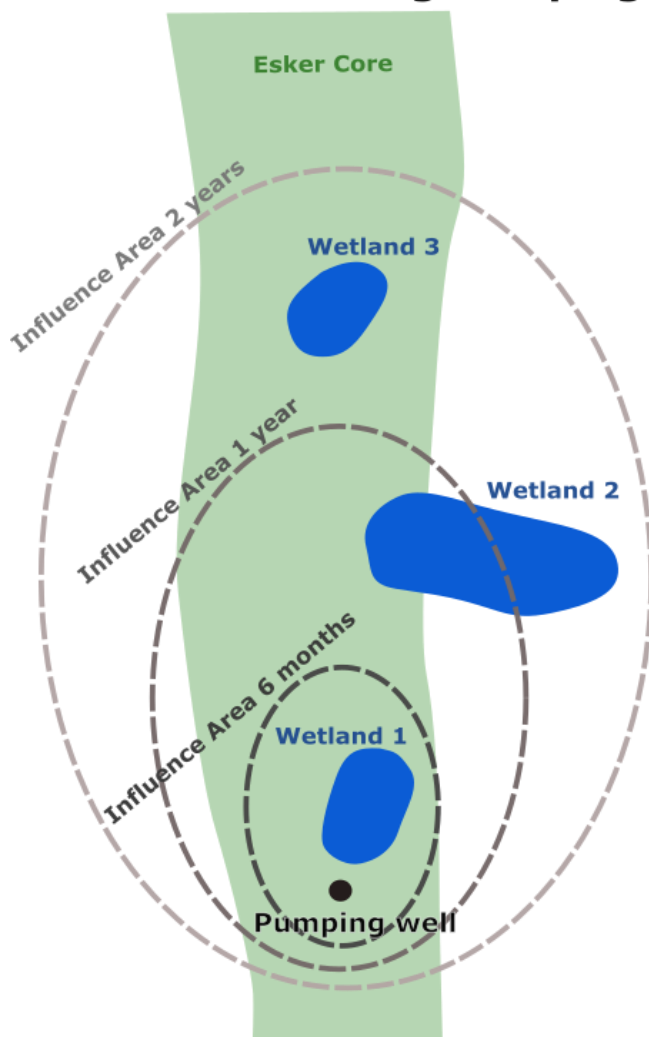


Figure 5.6. Conceptualization of the increase of wetland area over time during pumping. The conceptualization shows how the area of wetlands affected increases with time.

Finally, the data describing the time dependent change in wetland area was compiled with corresponding iron, manganese, and COD concentrations in B2S and B3S, and a correlation test was performed.

5.9 Analysis of impact from groundwater velocity

An analysis was conducted to investigate potential correlation between groundwater velocity and the water quality parameters iron, manganese and alkalinity. The analysis was done using geographical, geological and hydrogeological data in QGIS provided by Ramboll (2024), in combination with statistical methods.

The actual groundwater velocity is difficult to determine and varies in the esker aquifer, but an estimated average velocity between wells was calculated by Ramboll (2024) for undisturbed conditions. The average velocities were calculated between wells located as central in the esker's cross section as possible. Calculated groundwater velocities are shown in Figure 5.7.

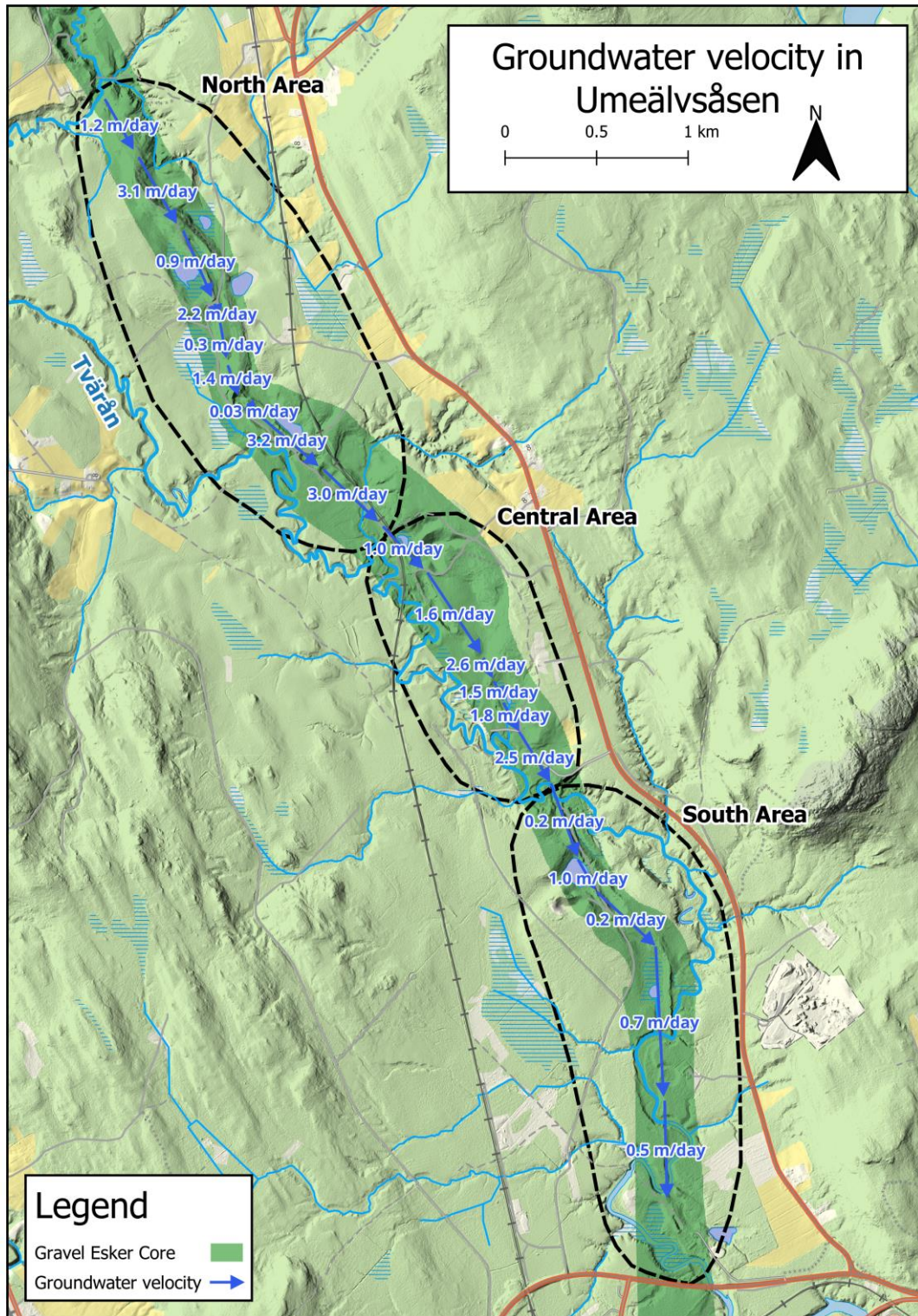


Figure 5.7. Average groundwater velocity in Umeälvssäsen between wells for undisturbed conditions calculated by Ramboll (2024). The illustrated velocities are in the lower end of the calculated span of velocities.

To conduct a correlation analysis between groundwater velocity and the concentrations of iron, manganese, and alkalinity, the average velocity within a 500 m upstream distance from each well was calculated and assigned to each respective well. This approach is based on the assumption that the groundwater

velocity prior to reaching a well has the greatest influence on the extent of the dissolution and mobilization of iron and manganese. In contrast, groundwater velocities farther upstream or downstream of the well are not expected to influence iron and manganese concentrations to the same extent.

Lower groundwater velocity should enhance iron and manganese dissolution since the groundwater have more time to become oxygen depleted caused by microbial degradation of organic material, compared to higher velocity.

Lastly, the average groundwater velocity assigned for each well were put together with corresponding iron, manganese and alkalinity sample data and a correlation test were performed.

6 Results

Results from the analysis of established theories for the occurrence of elevated iron and manganese concentrations are presented, in addition to a general characterization of Umeälvssäsen.

6.1 Characterization of Umeälvssäsen

Umeälvssäsen have distinct characteristics that differs in a variety of ways, especially when comparing the North and South area. These essential characteristics and differences are presented in this chapter.

Figure 6.1 shows a cross-section of the esker in the North area, illustrating the areas characteristics. The esker core is distinct and clearly visible without post-glacial sediment deposits on the top. The groundwater table is well below the surface level, making the unsaturated zone substantial where hydraulic contact with wetlands is less likely. The hydraulic gradient is high, and groundwater moves relatively quickly compared to the South area.

Water quality parameters of interest are generally lower in the North area in comparison with the South area. Mean iron concentration are 1.84 mg/l in undisturbed conditions and is statistically significantly lower at 0.65 mg/l during continuous pumping. Mean manganese concentration are 0.05 mg/l in undisturbed conditions and is not statistically significantly different during continuous pumping.

Appendix A present for which water quality parameters there is a statistically significant difference. See Appendix B for the water quality parameters' mean concentrations.

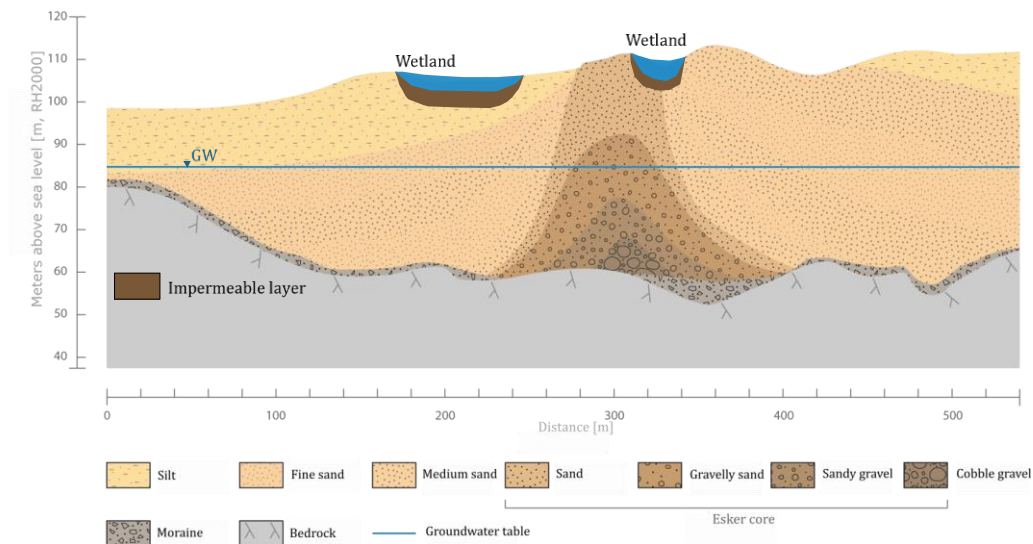


Figure 6.1. Cross-section of Umeålsåsen in the North area with characteristic features, showing substantial unsaturated zone and impermeable layers at the bottom of wetlands.

Figure 6.2 shows a cross-section of the esker in the South area, illustrating the areas characteristics. The esker core is less distinct compared to the North area and not clearly visible with more post-glacial sediment deposits. The groundwater table is close to the surface level, making hydraulic contact with the wetlands more likely. The wetland in the South area consists of many oxbow bogs, which is non-existent in the North area. The hydraulic gradient is low, resulting in slower groundwater velocity which is almost stagnant.

Water quality parameters of interest are generally higher in the South area in comparison with the North area. Mean iron concentrations are 4.6 mg/l in undisturbed conditions and is significantly higher at 4.9 mg/l during continuous pumping. Mean manganese concentrations are 0.25 mg/l in undisturbed conditions and is significantly higher at 0.29 mg/l during continuous pumping. Though, at the end of the continuous pumping the concentrations are even greater, with an iron concentration of 6.0 mg/l and a manganese concentration of 0.35 mg/l.

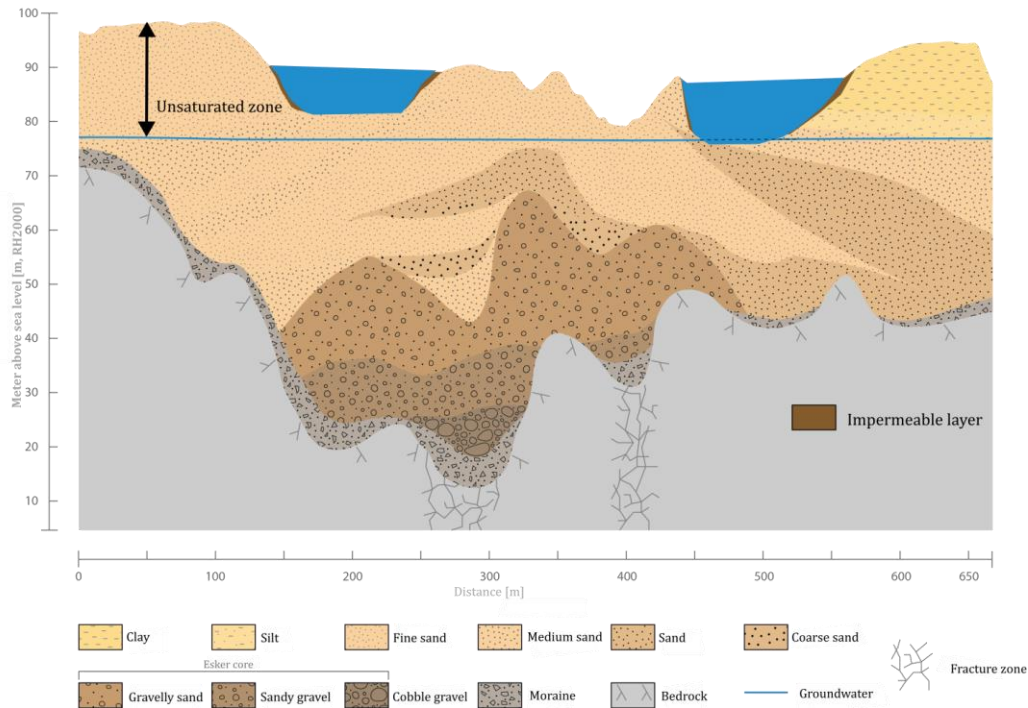


Figure 6.2. Cross-section of Umeälvssäsen in the South area with characteristic features, showing less substantial unsaturated zone and less sedimented organic layers in the bottom of the wetlands.

Table 6.1 shows the surface area of wetlands within the esker area. The Central area have the least wetland area and North and South have roughly the same area of wetlands, even though the type of wetland differentiates.

Table 6.1. Wetland area within the North, Central and South area categorized in different unsaturated zones.

Wetland area in Umeälvssäsen's surrounding			
Wetland area [m ²]	North area	Central area	South area
Wetland area Unsaturated zone ≤1.5 m	0	0	160 500
Wetland area Unsaturated zone 1.5-5 m	33 600	63 400	2600
Wetland area Unsaturated zone >5 m	173 200	9800	18 000
Wetland area All	206 800	73 200	181 100

In the North area, wetlands with an unsaturated zone >5 m dominates, with two wetlands having an unsaturated zone ≤5 m. This indicates that hydraulic contact between wetlands and the groundwater are less likely. There are also more lakes in the North area than in the Central and South area.

In the Central area, wetlands with an unsaturated zone between 1.5 and 5 m dominates, even though there are two wetlands with an unsaturated zone >5 m. There is also one oxbow bog formed by the old pathway of Tvärån.

In the South area, wetlands with an unsaturated zone ≤ 1.5 m dominates, with only one wetland with an unsaturated zone between 1.5 and 5 m, and one lake with an unsaturated zone > 5 m. There are many oxbow bogs formed by the old pathway of Tvärån and all of these have an unsaturated zone ≤ 1.5 m. The small unsaturated zone indicates that wetlands in the South area are in hydraulic contact with the groundwater.

Lastly, the results from the correlation tests between water quality parameters for North and South area in undisturbed condition and during continuous pumping are shown in Appendix C. There were generally more positive correlations than negative, indicating that the water quality parameters of interest change together. Though, the result shows mostly very weak correlations along the whole esker.

In summary, the studied section of Umeälvsåsen have significant differences, both regarding water quality parameter concentrations, but also regarding deposit formation, wetlands, hydrogeological properties and surface morphology.

6.2 Seasonal variations

T-test results carried out to investigate if there was statistically significant difference between the mean values for iron and manganese concentrations sampled at different times are shown in Appendix D. The result showed that several data groups were insufficient to give a statistical reliable result and that there was no statistically significant difference within the North and South area in undisturbed conditions and during continuous pumping. Thus, the result is that there is no statistically significant difference between iron and manganese levels taken at different times of the year.

6.3 Well depth

Table 6.2 shows results from the correlation test between well depth and iron and manganese concentrations for North and South area in undisturbed condition and during continuous pumping. The results showed very weak correlations in the North area for both undisturbed condition and during continuous pumping ($r = -0.19$ to 0.17). In the South area, a weak positive correlation is shown ($r = 0.41$ to 0.49), except for a strong positive correlation for manganese concentrations in undisturbed conditions ($r = 0.78$). This indicates that deeper wells do not contribute to higher concentrations in the North area, but in the South area there was some correlations indicating higher concentrations in deeper wells. The confidence intervals show no value stretching over 0, which indicates that all correlations are statistically significant for chosen confidence level.

Table 6.2. Correlation test between iron and manganese concentration and well depth for North and South area in undisturbed conditions and during continuous pumping. The table present calculated *r*-value with corresponding confidence intervals.

Correlation Iron and Manganese with Depth		
<i>r</i> -value [Confidence Interval]	Iron concentrations	Manganese concentrations
Depth North area Undisturbed Condition	-0.18 [-0.01; -0.34]	0.05 [-0.12; 0.22]
Depth North area Continuous Pumping	0.17 [0.00; 0.35]	-0.19 [-0.01; -0.35]
Depth South area Undisturbed Condition	0.41 [0.20; 0.58]	0.78 [0.67; 0.86]
Depth South area Continuous Pumping	0.49 [0.30; 0.65]	0.43 [0.22; 0.60]

6.4 Acid sulphate soils

Ocular inspections made in-situ by consultants at Ramboll pointed out that no visual evidence of acid sulphate soil occurrence was determined during drillings and excavations. No additional excavations and drillings have been done during this thesis which could have rejected the statement that there is no acidic or potential acidic sulphate soils in the area.

6.5 Organic rich sediments

Results from LOI laboratory testing on sediment samples collected in different wells and depths are shown in Table 6.3. The test results show a generally low amount of organic material in all tested sediments even though there are some differences.

Average organic material of samples in the North area are 4.49 g/kg, in the Central area 5.46 g/kg, and in the South area 6.45 g/kg. There is a statistically significant difference between North and South area, but not between the Central area and the other two areas.

Table 6.3. Results from Loss on Ignition (LOI) test, showing amount of organic material in grams per kilograms dry sediment.

Organic material in sediments				
Well name	Area	Soil type	Depth [m]	Organic material [g/kg]
R2004	North	Medium Sand	23-24	4.03
R2004	North	Cobble Coarse Sand	46-47	4.82
R2004	North	Cobble Coarse Sand	51-52	3.96
R1803	North	Fine Sand	28-29	5.05
R1803	North	Medium Sand	38-39	3.51
R1803	North	Coarse Sand	54-55	5.60
R1901	Central	Coarse sand	25-26	6.90
R1901	Central	Coarse sand	32-33	3.88
R1901	Central	Medium Sand	40-41	3.98
R1902	Central	Coarse Sand	18-19	4.52
R1902	Central	Coarse Sand	24-25	6.21
R1902	Central	Cobble Coarse Sand	37-38	6.42
R1904	Central	Coarse Sand	20-21	4.57
R1904	Central	Sand	35-36	4.77
R1904	Central	Cobble Coarse Sand	53-54	7.85
R2002	South	Sandy Gravel	22.5-23.5	4.15
R2002	South	Sandy Gravel	23.5-24.5	5.81
R2002	South	Gravelly Sand	32.5-33.5	6.72
R1910	South	Fine Sand	28-29	7.45
R1910	South	Medium Sand	34-40	7.12
R1910	South	Gravelly Sand	51-52	8.05
R1911	South	Sand	16-17	5.86
R1911	South	Gravelly Sand	32-33	6.95
R1911	South	Gravelly Sand	37-38	5.90

A conclusion can be drawn that there is organic material in the soil material but there were no samples indicating the theory of stored lenses layered in the esker, which was expected to appear as extreme values in the tested data set.

6.6 Wetlands (Lake and peatlands)

Table 6.4 shows results from the first part of the wetland analysis with undisturbed conditions and the basic scenario of the influence area. The results for wetland area with unsaturated zone ≤ 1.5 m and 1.5-5 m have a moderate to strong positive correlation with iron, manganese and COD concentrations ($r=0.52$ to 0.80). Wetlands with an unsaturated zone >5 m have moderate to strong negative correlation ($r= -0.63$ to -0.70). The confidence level is generally high. No confidence interval stretches over 0, which indicates statistically significant values for chosen confidence level.

Table 6.4. Correlation test between iron, manganese and COD concentrations and increasing wetland area across the whole esker in undisturbed condition with basic scenario for influence area.

Correlation Iron/Manganese/COD with Wetland Area			
Undisturbed Condition Basic Scenario			
<i>r-value</i> <i>[Confidence Interval]</i>	Iron concentrations	Manganese concentrations	COD concentrations
Wetland area			
Unsaturated zone ≤1.5 m	0.52 [0.39; 0.63]	0.78 [0.70; 0.84]	0.66 [0.55; 0.75]
Wetland area			
Unsaturated zone 1.5-5 m	0.76 [0.68; 0.82]	0.80 [0.73; 0.85]	0.66 [0.55; 0.75]
Wetland area			
Unsaturated zone >5 m	-0.63 [-0.52; -0.72]	-0.70 [-0.60; -0.78]	-0.65 [-0.54; -0.74]

Table 6.5 shows results from the wetland analysis during continuous pumping with the basic scenario of the influence area. The results for wetlands area with an unsaturated zone ≤ 1.5 m and 1.5-5 m shows a strong to very strong positive correlation with iron, manganese concentrations ($r=0.86$ to 0.98). The correlation with COD concentrations has a moderate positive correlation ($r=0.51$ to 0.61). Wetlands with an unsaturated zone >5 m have weak to strong negative correlation with iron, manganese and COD concentrations ($r=-0.44$ to -0.86). The confidence level is generally high, independent of unsaturated zone thickness.

Table 6.5. Correlation test between iron, manganese and COD concentrations and increasing wetland area across the whole esker during continuous pumping with basic scenario for influence area.

Correlation Iron/Manganese/COD with Wetland Area			
Continuous Pumping Basic Scenario			
<i>r-value</i> <i>[Confidence Interval]</i>	Iron concentrations	Manganese concentrations	COD concentrations
Wetland area			
Unsaturated zone ≤1.5 m	0.94 [0.92; 0.96]	0.98 [0.97; 0.98]	0.61 [0.50; 0.70]
Wetland area			
Unsaturated zone 1.5-5 m	0.94 [0.92; 0.96]	0.86 [0.81; 0.90]	0.51 [0.38; 0.62]
Wetland area			
Unsaturated zone >5 m	-0.86 [-0.81; -0.90]	-0.78 [-0.71; -0.84]	-0.44 [-0.30; -0.56]

Wetlands assumed to be in hydraulic contact with the groundwater (unsaturated zone ≤1.5 m), contributes to higher iron, manganese and COD concentrations compared to wetlands that are assumed not to be in hydraulic contact (unsaturated zone >5 m). Wetlands in hydraulic contact during continuous pumping seems to affect iron, manganese concentrations more than in undisturbed conditions. This indicates that pumping induces water inflow from the wetlands, which does not occur to the same extent under undisturbed conditions.

Table 6.6 shows results from the second part of the wetland analysis with the groundwater model scenario in the South area during continuous pumping. The results show a moderate to strong positive correlation between wetland area and iron and manganese concentrations ($r=0.61$ to 0.89). COD concentrations

show a very weak negative correlation ($r=-0.19$ to -0.29). The unsaturated zone thickness under the wetlands do not seem to affect the correlation in this analysis, indicating that all wetlands independent of unsaturated zone thickness within the pumping wells' influence area are in hydraulic contact with the groundwater.

Table 6.6. Correlation test between iron, manganese and COD concentrations and increasing wetland area in South area during continuous pumping for scenario with groundwater model-based influence area.

Correlation Iron/Manganese/COD with Wetland Area Continuous Pumping Groundwater Model Scenario			
<i>r-value</i> <i>[Confidence Interval]</i>	Iron concentrations	Manganese concentrations	COD concentrations
Wetland area Unsaturated zone ≤ 1.5 m	0.74 [0.58; 0.85]	0.89 [0.81; 0.94]	-0.25 [-0.50; 0.04]
Wetland area Unsaturated zone 1.5-5 m	0.62 [0.41; 0.77]	0.67 [0.47; 0.80]	-0.29 [-0.003; -0.53]
Wetland area Unsaturated zone >5 m	0.61 [0.39; 0.76]	0.83 [0.71; 0.90]	-0.19 [-0.45; 0.10]

Figure 6.3 shows how iron concentrations increase from 4.1 mg/l at the start of the long-time test pumping to 6.0 mg/l at the end of the test pumping in well B2S in South area. Simultaneously, the increase of wetland area within the pumping well's increasing influence area are shown for wetlands with different unsaturated zones. At the end of the test pumping, 63,000 m^2 wetland area lays within the pumping wells' influence area, of which 40% are wetlands with an unsaturated zone ≤ 1.5 m or between 1.5 and 5 m. The R^2 shows that 52% of the variation of iron concentrations are explained by the increase of wetland area.

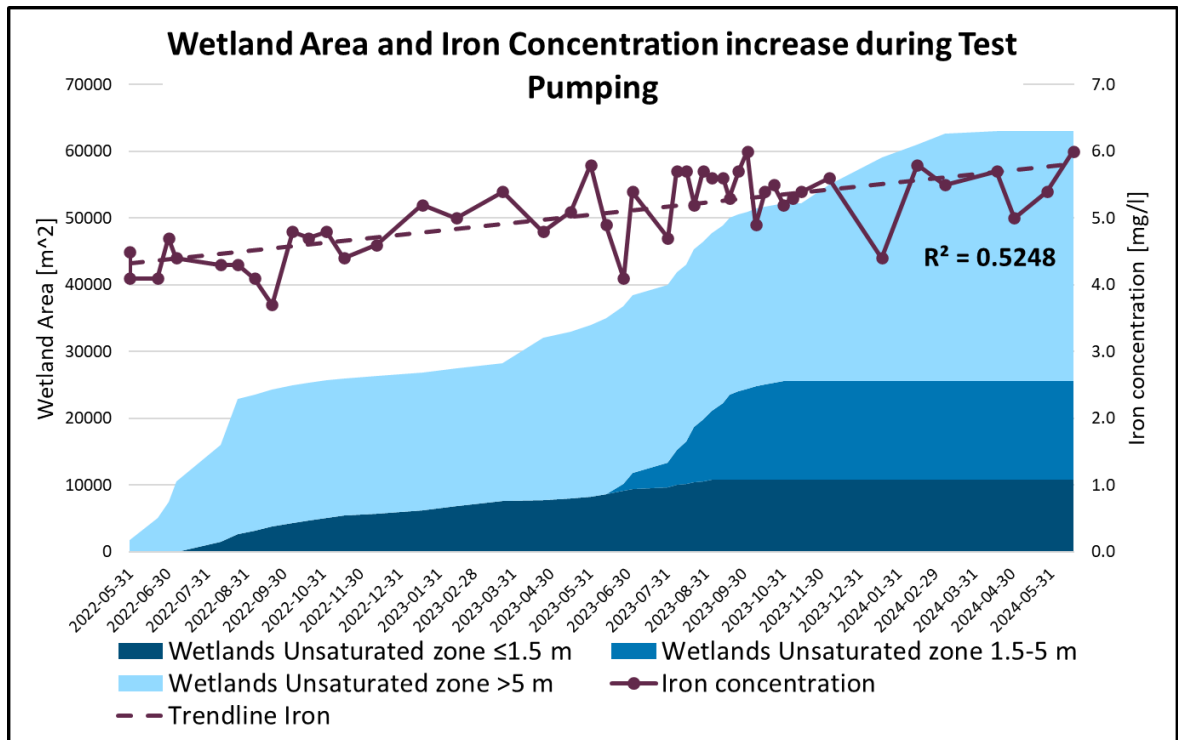


Figure 6.3. Iron concentration in pumping well B2S during long-term test pumping together with increasing wetlands area due increasing influence area. R^2 showing how much of the increase in iron concentrations that can be explained by the increase in wetland area.

Figure 6.4 shows how manganese concentrations increase from 0.22 mg/l at the start of the long-time test pumping to 0.33 mg/l at the end of the test pumping. Simultaneously, the increase of wetland area within the pumping wells' increasing influence area are shown for wetlands with different unsaturated zones. The R^2 shows that 75% of the increase variation of manganese concentrations are explained by the increase of wetland area.

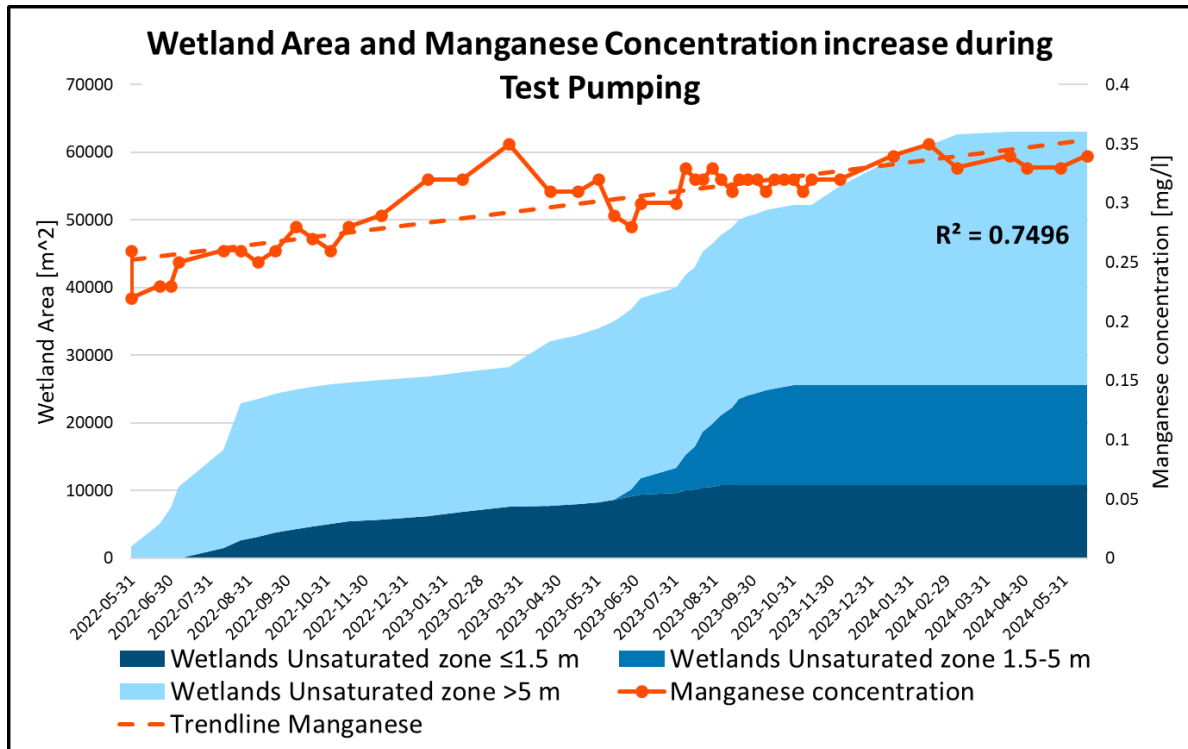


Figure 6.4. Manganese concentration in pumping well B2S during long-term test pumping together with increasing wetland area due increasing influence area. R^2 showing how much of the increase in manganese concentrations possible explained by the increase in wetland area.

Figure 6.5 shows how COD concentrations variation from the start of the long-time test pumping to the end of the test pumping. COD concentrations from the first and last test shows a small increase from 0.8 to 0.87 mg/l, but a small decrease in COD can be seen overall by the linear trendline. Though, the variations differ greatly and the R^2 shows that only 8% of the variations of COD concentrations are explained by the increase of wetland area. Even though wetlands influence iron and manganese concentrations, COD concentrations in the pumping well do not change extensively during the test pumping.

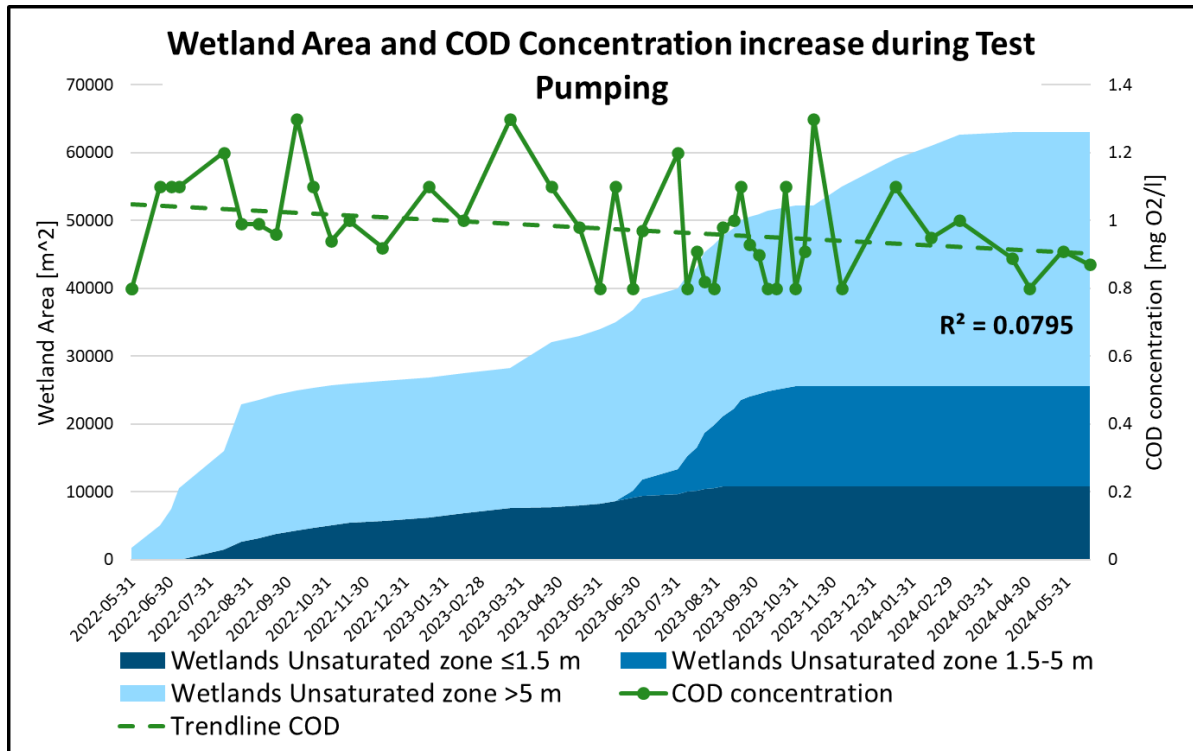


Figure 6.5. COD concentration measurements in pumping well B2S in South area during long-term test pumping together with increasing wetland area due increasing influence area. R^2 showing how much of the increase in COD concentrations that can be explained by the increase in wetland area.

In addition, visual observations made in field with water depth gauge showed no lowering of the surface water level in the two lakes, Fäbodtjärn and Groptildatjärn, closest to the pumping wells B2S and B3S during long-term test pumping. The results indicate that these lakes are not in hydraulic contact with the groundwater even though Fäbodtjärn's unsaturated zone are 1.8-2.5 m thick and close to the assumed thickness of hydraulic contact. Groptildatjärn's unsaturated zone is 6.4 m and is not within the assumed thickness to be in hydraulic contact.

Summarized, wetlands seem to have an influence on iron and manganese concentrations, especially if the unsaturated zone is ≤ 1.5 m or between 1.5 and 5 m. For wetlands with an unsaturated zone > 5 m, the results are contradictory between the three conducted correlation analysis of the two basic scenarios and groundwater model scenario. The results for COD concentrations are also contradictory, showing no consistent positive nor negative correlation between the three correlation tests. During continuous pumping, wetlands with an unsaturated zone ≤ 1.5 m or between 1.5 and 5 m seem to influence iron and manganese concentrations even greater, but the influence on COD concentrations do not change with the same magnitude.

Whether a wetland is in actual hydraulic contact with the groundwater remain uncertain.

6.7 Groundwater velocity

Table 6.7 shows the results from the correlation test between groundwater velocity for undisturbed conditions and iron, manganese and alkalinity. The results show a strong negative correlation for iron ($r=-0.76$), manganese ($r=-0.81$) and alkalinity ($r=-0.76$). Corresponding confidence interval is small, showing the strength of the r -value.

Table 6.7. Correlation test between groundwater velocity for undisturbed conditions and iron/manganese/alkalinity concentrations.

Correlation groundwater Velocity with Iron/Manganese/Alkalinity	
<i>r</i> -value [Confidence Interval]	Groundwater Velocity
Iron	-0.76 [-0.68; -0.83]
Manganese	-0.81 [-0.74; -0.86]
Alkalinity	-0.76 [-0.67; -0.83]

Figure 6.6 shows the scatter plot for iron concentration variation with groundwater velocity. The R^2 value shows that 58% of the variation in iron are explained by groundwater velocity. In the North area where the groundwater velocity ranges from 1.2 to 3 m/day, the iron concentrations vary from 0.05 to 3.2 mg/l. In the South area where the groundwater velocity ranges from 0.2 to 0.3 m/day, the iron concentrations vary from 1.4 to 7.8 mg/l.

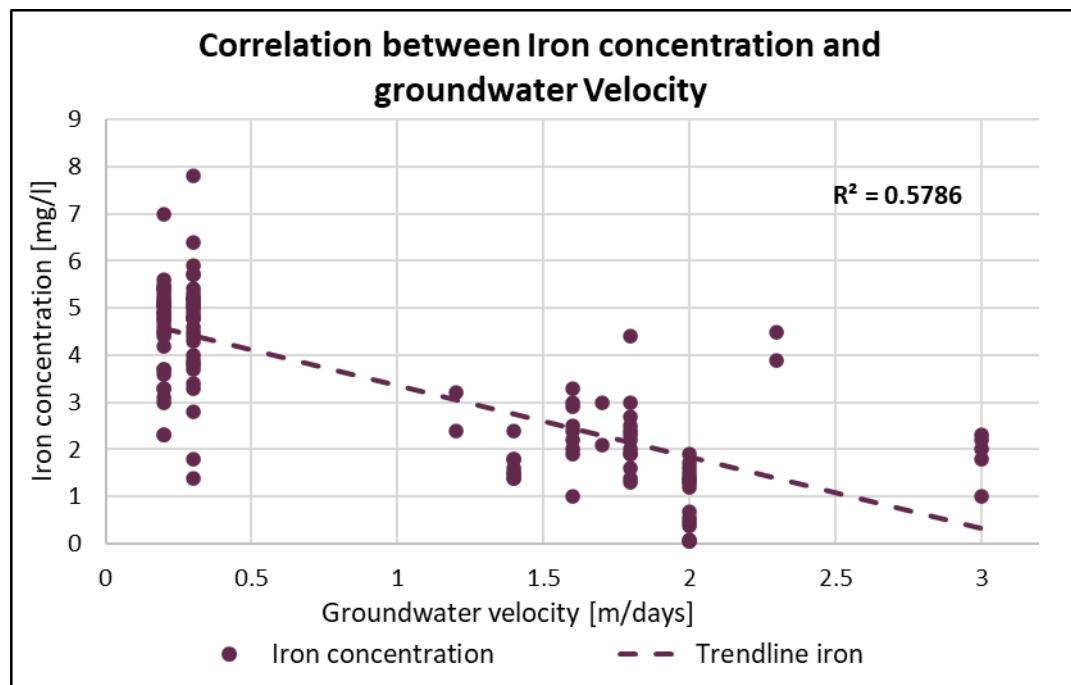


Figure 6.6. Scatter plot showing the variation in iron concentration together with groundwater velocity. In addition, a trendline of iron increase with lower groundwater velocity are represented.

Figure 6.7 shows the scatter plot for manganese concentration variation with groundwater velocity. The R^2 value shows that 66% of the variation in manganese are explained by groundwater velocity. In the North area where the

groundwater velocity ranges from 1.2 to 3 m/day, the manganese concentrations vary from 0.02 to 0.17 mg/l. In the South area where the groundwater velocity ranges from 0.2 to 0.3 m/day, the manganese concentrations vary from 0.12 to 0.29 mg/l.

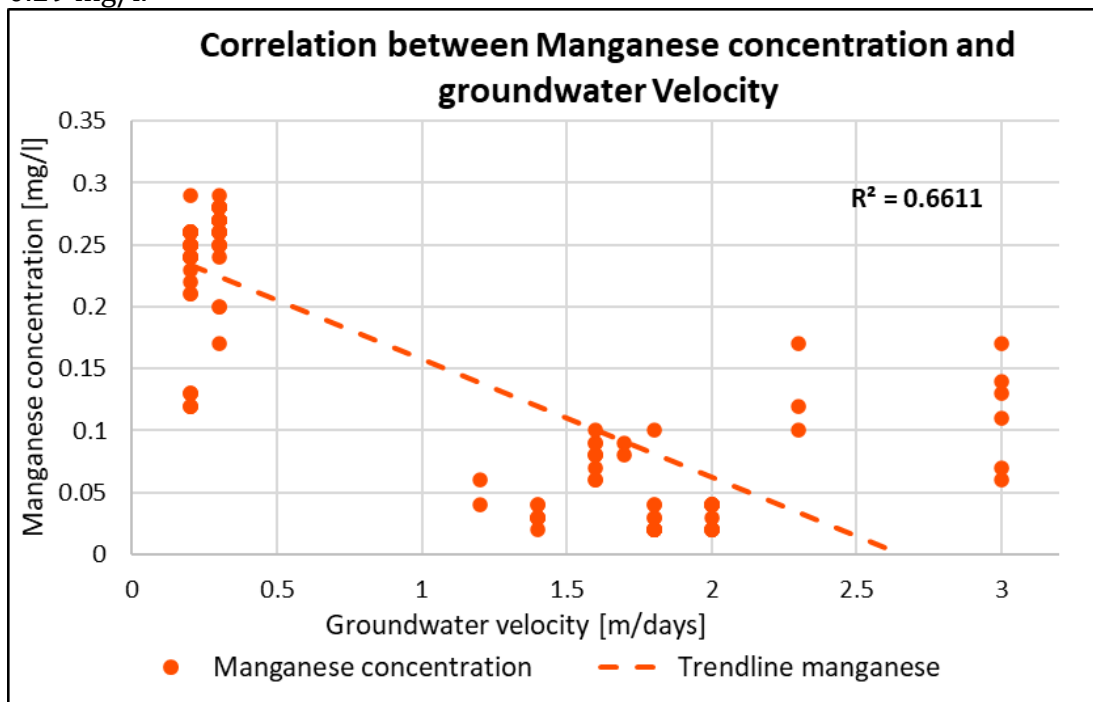


Figure 6.7. Scatter plot showing the variation in manganese concentration together with groundwater velocity. In addition, a trendline of manganese increase with lower groundwater velocity are represented.

Figure 6.8 shows the scatter plot for alkalinity concentration variation with groundwater velocity. The R^2 value shows that 57% of the variation in alkalinity are explained by groundwater velocity. In the North area where the groundwater velocity ranges from 1.2 to 3 m/day, the alkalinity concentrations vary from 37 to 59 mg/l. In the South area where the groundwater velocity ranges from 0.2 to 0.3 m/day, the alkalinity concentrations vary from 48 to 70 mg/l.

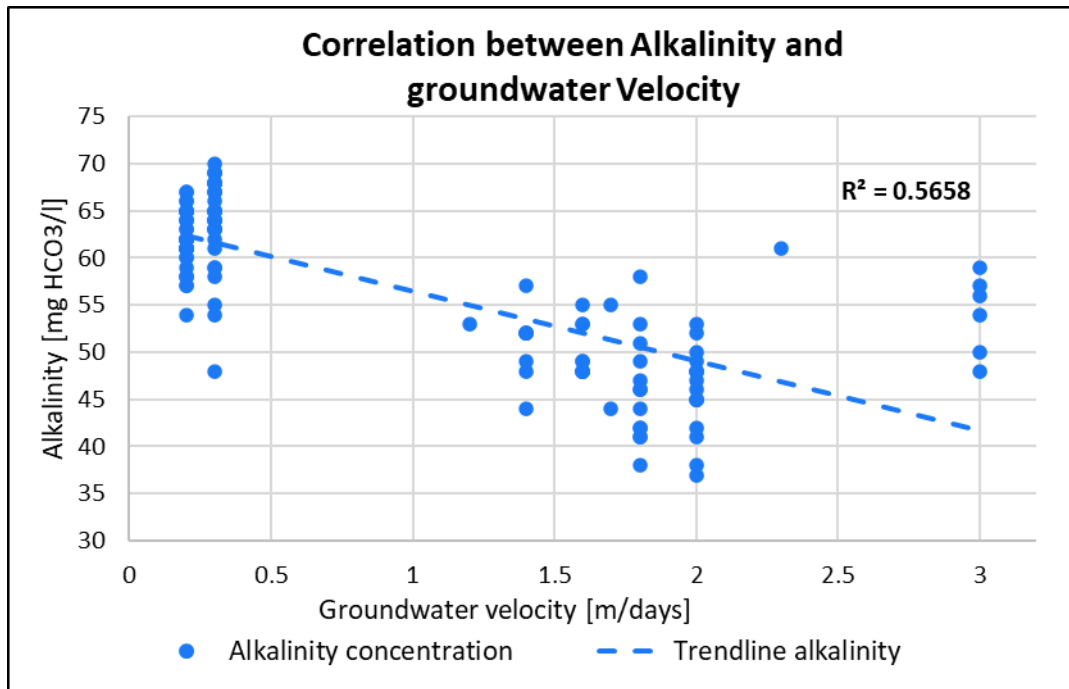


Figure 6.8. Scatter plot showing the variation in alkalinity concentration together with groundwater velocity. In addition, a trendline of alkalinity increase with lower groundwater velocity are represented.

6.8 Summary of Explanatory model

Results with respect to the theories regarding the occurrence of elevated iron and manganese concentrations in Umeälsåsén provided an overview and understanding of the situation. Some theories were proven to be more likely than others, and others were proven to not have a significant impact on the result.

The largest contributor to elevated iron and manganese concentrations, according to the conducted tests, are wetlands with a small unsaturated zone. In Umeälsåsén these are located in the South area which is dominated by oxbow bogs. The second most influencing theory is groundwater velocity. The third is well depth.

Some theories were proved to not be a sufficient reason to elevated iron and manganese concentrations, according to the conducted tests. These were seasonal variations, acid sulphate soils and organic rich sediments. However, their potential influence cannot be totally dismissed.

7 Discussion

Established theories and their corresponding results are discussed and evaluated and together with literature review. A final comprehensive explanatory model for the occurrence of elevated iron and manganese are presented. In addition, a discussion regarding new insights given by this thesis is presented and how it could be used for future investigations. Finally, limitations and possible improvements within of the scope of this thesis are presented.

7.1 Explanatory model of Umeälvssäsen

The result indicates that the differences between the North and South area regarding esker and landscape characteristics have significant impact in the water quality parameters.

The result fills a gap of knowledge detected by Ramboll during their work with Umeälvssäsen. This thesis present potential theories and their contributing factor to the problem. Some of the listed theories have been rejected through the investigative methods presented. The discussion interprets the result together with knowledge gained from research within the field, which enable reflection on the methodology.

7.1.1 Characterization of Umeälvssäsen

By combining information from Ramboll's investigation with various cartographic sources, it becomes evident that the studied areas exhibit distinct characteristics across several parameters. After establishing that differences in water quality, particularly regarding iron and manganese concentrations, are statistically significant, this thesis has focused on examining site-specific characteristics that may explain the observed variations.

The most prominent differences between the areas are the hydraulic gradient, the structure of the esker deposits, the thickness of the unsaturated zone, and the characteristics of the peatlands. The interrelation between the parameters and their individual contribution to the problem is complex. To determine the magnitude of each contribution is challenging. Uncertainty remains regarding the underlying causality. As multiple environmental and hydrogeochemical factors may contribute to elevated concentrations of iron and manganese, several potential causal mechanisms have not been explored in detailed within the scope of this thesis.

This thesis compares data from two geographically separate areas. In this context, the data sets are considered sufficiently large to reflect the natural variability within the North, Central and South area respectively. A more detailed characterization of the distribution of wetlands, lakes, and watercourses, and their potential hydraulic connection to the aquifer, enhances the ability to predict water quality issues at an early stage. To strengthen the validity of the findings, future studies could benefit from a more standardized sampling design, conducting measurements at regular intervals and employing consistent methodologies. Moreover, extending the sampling period would improve

reliability, as hydrogeological processes operate over long-time scales. Therefore, continuous monitoring over several years is recommended.

7.1.2 Seasonal variations

Since groundwater recharge is strongly linked to precipitation patterns, this was identified as a plausible factor influencing the changes in water quality data. The esker is also intersected by the Tvärån stream, which has been identified as a potential groundwater recharge- and discharge area, which is subject to annual variation in flow dynamics. The results of the statistical tests conducted showed that there was no statistically significant difference in water quality parameters between the time periods into which the data were divided.

The division of the time periods was based on reported precipitation data from SMHI and Krycklan. As no precipitation data were available within the study area itself, regional data from SMHI and Krycklan, close to Umeålsåsen, were used. This introduces a spatial uncertainty in the temporal categorization of the dataset. Although the statistical tests suggested that no significant difference existed, the limited number of independent observations reduced the statistical power, thereby weakening the reliability of the findings. The conclusion is supported by looking at the degrees of freedom for the statistical analysis. After the division into time periods, the number of independent observations in the dataset was low, indicating a small sample size and consequently lower reliability of the statistical outcome.

Ramboll collected isotope samples from the groundwater and Tvärån during their investigations. They performed analyses of oxygen isotopes and ion balances during their processing of the water quality data. No isotope samples were taken from the wetlands or precipitation. A more detailed analysis of these parameters, in combination with annual variations, could potentially have led to different conclusions regarding the influence of precipitation and the origin of the groundwater in the esker.

Previous research investigating iron and manganese concentrations in Boreal streams within the Krycklan catchment area found a strong influence attributed to annual variations in precipitation, as well as snowmelt and spring flooding. The study was partially using oxygen isotopes to examine the variations. Oxygen isotope analysis has also been employed in other studies examining hydraulic connections between wetlands and groundwater, where it has proven useful in tracing water sources and composition. The exclusion of oxygen isotope analyses was due to time limitations in the scope of this thesis.

7.1.3 Well depth

Positive correlation between deeper wells and increased iron and manganese concentrations have been judged to be moderate. Possible explanations discussed in previous studies is changes in mineral composition between the stratigraphic layers. LOI test showed low levels of organic material layered in the ground and no significant differences regarding depth and percentage of organic material. Instead, deeper wells receive groundwater with longer residence time.

This enables hydrogeochemical processes that change the redox potential and, consequently, alter the chemical status of the groundwater.

Deeper investigations addressing the mineral composition and their variation with depth could contribute to new insights and potentially further explain the correlation.

7.1.4 Acid sulphate soils

In Västerbotten, several occurrences of potential acidic and acidic sulphate soils have been identified, and large areas are classified as potential sulphate soil zones according to a simulation model provided by SGU (SGU, n.d.).

Field investigations carried out by Ramboll did not reveal any clear evidence of sulphate soils, and there are no previously reported findings from the study area. Consequently, there is limited evidence to support the hypothesis that acid sulphate soils are responsible for the elevated concentrations of iron and manganese observed in the area. Nevertheless, further investigations are required to confirm this conclusion. New drillings or excavations are needed to verify their potential presence in the studied area of Umeälvssäsen and might have change the result.

Additionally, studies conducted in Finland, whose geological history and characteristics are similar to those of Sweden, have demonstrated that acidic and potentially acidic sulphate soils also can be present in coarse-grained deposits. These soils typically occur as fine-grained materials, classified as silt and clay, exhibiting a distinct grey or rusty red coloration. Therefore, future investigations should consider a broader range of sediment types to accurately assess the occurrence and impact of sulphate soils.

7.1.5 Organic rich sediments

Previous research has demonstrated that floodplains and riparian ecosystems function as carbon sinks, where organic material can be stored over extended time periods without undergoing significant decomposition. By examining the Quaternary geology of the area and its geological characteristics, it can be established that the Umeälvssäsen is located in a region strongly influenced by glaciofluvial processes associated with the retreat of the latest continental ice sheet, as well as by isostatic uplift.

This supports the hypothesis that the area surrounding the esker constituted a depositional environment favorable for the accumulation and preservation of organic matter. These deposits may later have been overlain by younger, fine-grained sediments because of erosion and sediment transport, a theory consistent with the stratigraphy observed in the lateral areas of the esker.

In this thesis, Loss on Ignition (LOI) analysis was employed to quantify the presence of such organic-rich deposits. The results indicated low values of LOI. Articles presenting values used as references shows that the values cannot be classified as organic soil. Therefore, no clear evidence for layered lenses of organic rich deposits was discovered in the area for this thesis.

All samples used in this thesis were previously collected by Ramboll and stored at Vakin in Umeå. During transportation and storage, the samples may have been subjected to processes potentially affecting their organic matter content. This constitutes a significant source of uncertainty in the Loss on Ignition (LOI) analyses and the resulting data. Furthermore, the selection of samples for analysis was constrained by time limitations, which did not permit testing of the entire sample set. Nonetheless, the occurrence of organic material is higher in the northern area compared to the southern area, in line with the observed concentrations of iron and manganese.

The assessment of which samples were of highest interest was based on visual observations and water quality data from each well. Samples displaying characteristics indicative of organic material and originating from wells with elevated iron concentrations were prioritized for analysis. Consequently, unexamined samples remain, which may have altered the interpretation of the results had they been included in the study.

7.1.6 Wetlands (Lakes and Peatlands)

The results of the statistical analyses conducted show a statistically significant positive correlation between iron, manganese, and wetland coverage. Given the strength of this correlation, these findings are evaluated to be strong and investigated in more detail. Previous research on wetland coverage and correlation with iron and manganese has demonstrated that seasonality has possible statistically significant impact. In contrast, the statistical analyses performed in this thesis indicate that seasonal variation did not exert a statistically significant influence on the iron and manganese concentrations. Further analysis, for example by analysis of oxygen isotopes, could be useful to strengthen the result.

The influence of organic matter on surrounding surface water and groundwater has been previously addressed in the scientific literature. Most studies have primarily focused on surface water and its response to various temporal dynamics and hydrological events. Investigating the influence on surface water is often more practicable, as the hydrological connectivity to wetlands is easier to establish. For this thesis, the hydraulic connection between wetlands and the groundwater system has been identified as a relationship that is challenging to quantify. Previous studies in similar environments have been able to determine the relationship, which shows that it is possible to investigate the relationship by targeted investigations. Isotope analysis of peatlands porewater have been applied as method to state the relationship.

If a hydraulic connection exists between wetlands and groundwater, it may initiate a process in which oxygen-rich groundwater encounters an environment rich in organic matter. This interaction can catalyze microbial decomposition processes that consume dissolved oxygen, leading to a rapid decrease in redox potential. As the water continues to move from the wetland through esker deposits, naturally rich in iron and manganese, these elements is mobilized due to the acidic conditions. See Figure 7.1 for a conceptualization of the processes

taking place. Consequently, the extracted groundwater exhibits elevated iron concentrations, which precipitate upon exposure to oxygen again.

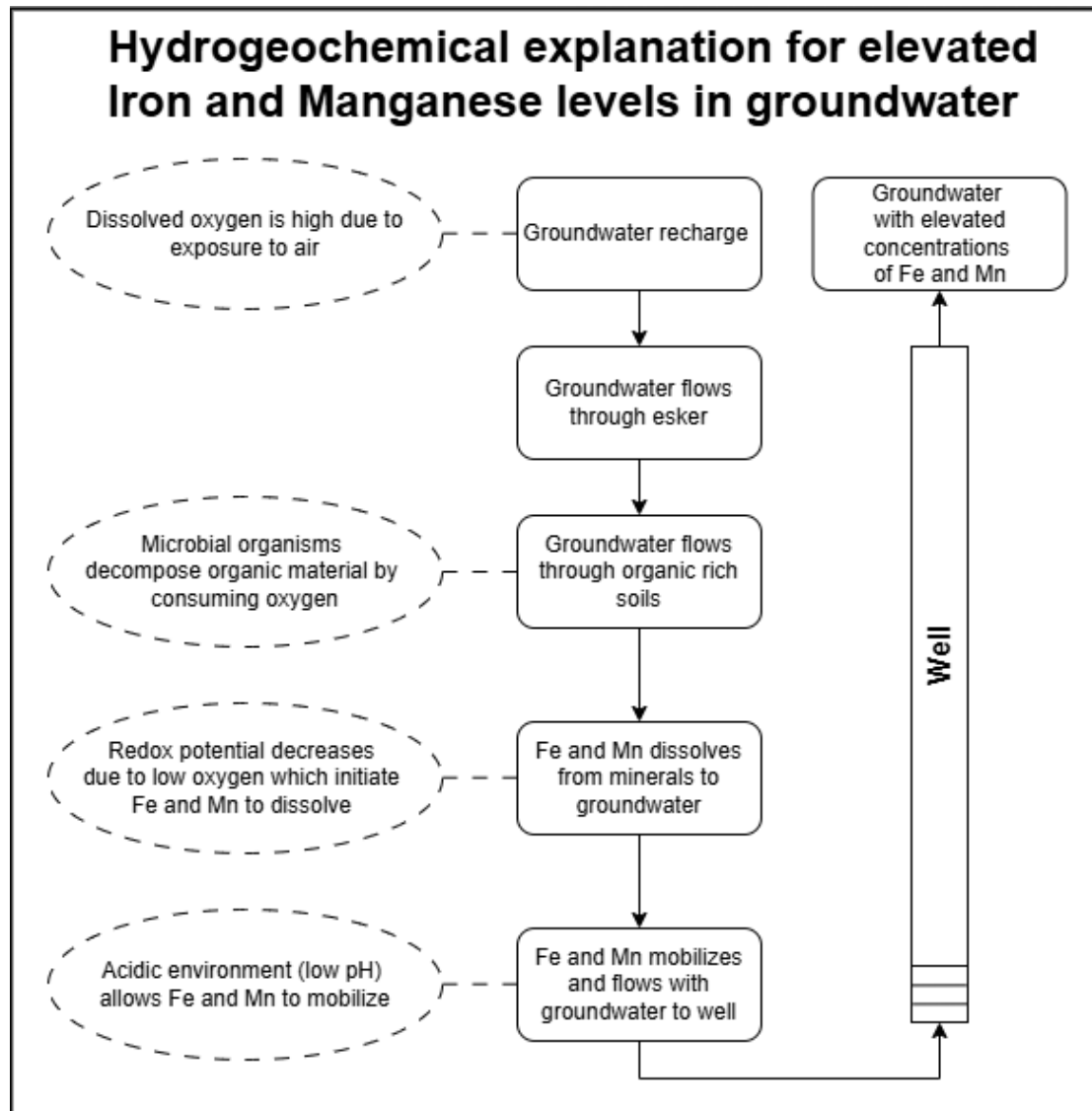


Figure 7.1. Flowchart describing the hydrogeochemical processes taking place for groundwater to develop elevated Iron (Fe) and Manganese (Mn) concentrations.

The wetlands in the southern part of the study area are characterized as oxbow bogs, and their formation history suggests a higher likelihood of hydraulic connectivity. Given that these wetlands were once part of the active flood path of Tvärån, the overgrowth and infilling processes have been ongoing since their hydrological disconnection. This supports the hypothesis that the underlying bottom sediments may not be entirely impermeable, potentially allowing for exchange between the wetland and surrounding groundwater systems.

In summary, the result of this thesis shows strong evidence for positive correlation between increased iron and manganese concentrations and wetland area. This finding is supported by literature and characterization of Umeälvsåsen.

7.1.7 Groundwater velocity

Correlation tests show strong negative correlation between alkalinity, iron and manganese and groundwater velocity. The relationship is expected and can be explained by the fact that lower groundwater velocity leads to a longer time for redox processes to occur, gradually altering the chemical composition of the groundwater. This phenomenon has been discussed in the literature and account for the strong correlation observed. It can be validated by using measurement of alkalinity. It is considered sufficient to explain the significant differences in iron and manganese concentrations to a certain degree. The theory itself is considered to not be the only explanation and should be viewed as a one of several contributing factors.

7.2 Explanatory model approach in similar projects

The aim of this study is to identify the underlying causes of elevated concentrations of iron and manganese in the southern investigation area and to evaluate the methodological approach used to investigate these underlying causes in relation to their impact on water quality. This thesis focuses on investigations made in early stage.

By clarifying the underlying factors contributing to elevated levels of iron and manganese at an early stage, a deeper understanding of the mechanisms behind the water quality issues can be achieved. This understanding enables more effective planning and implementation strategy for groundwater abstraction, with consideration to both sustainability and cost-efficiency. Such a strategic approach may also support the identification and exclusion of areas with a higher risk of long-term water quality problems, thereby reducing the need for subsequent treatment measures.

The methods used in this thesis suggest investigation methods that can be applied by using data commonly in hydrogeology projects. Discussion how the investigation methods can evolve and be more detailed are presented together with scientific literature with similar approach. The explanatory model achieves sustainability within the economic, environmental and social domain. By identifying the underlying causes of increased concentrations of iron and manganese, the cost for subsequent treatment decreases, less additive chemicals are needed, and a high-quality long-term drinking water supply can be implemented.

Further development of the explanatory model suggests a framework with incremental information how to target increased concentrations of iron and manganese. By presenting appropriate investigation methods and tools, the process could be applied depending on the aquifer and landscape characteristics. By providing reference values from similar sites and their features, an evaluation could be made regarding the suitability for the aquifer to serve as a long-term drinking water supply. With the supporting information regarding the underlying causes, further steps in the process handling construction and implementation of infiltration basins and extraction wells can be made to avoid areas with higher risk of water quality problematics.

7.3 Limitations

The work carried out is based on previous investigations and sampling conducted by Ramboll. No visits have been done at the area and no additional samples have been collected.

To investigate water quality, several statistical analyses have been applied to the water samples compiled by Ramboll. There is always a degree of uncertainty, as many analyses assume that the tested data meet specific conditions required for the testing method to produce reliable results.

Therefore, multiple tests, together with plotted diagrams, have been used to strengthen the assessment of relationships between different data sets. Despite these efforts, the fact remains that the results can be interpreted with varying degrees of confidence and causality.

By developing a systematic sampling strategy from start and strategically logging, the statistical analyses could have been strengthened and support findings of trends and variation patterns with more convincing strength. In addition, a new sampling strategy regarding sampling position could target theories presented in this thesis, for example include sampling from wells close to the oxbow bogs.

Further, increased studies of the composition of the bedrock and soil material could have given new insights. By analysing in more detail where the material has emerged and their mineral composition. Since these minerals is the source of iron and manganese, their occurrence, spreading and geochemical properties is curious to fully address the problem with increased iron and manganese in groundwaters.

Field studies that could contribute to strengthen or reject presented theories is more reliable measurements of redox potential and oxygen in-situ. Redox potential together with oxygen have been shown to have a significant impact on the hydrogeochemistry of groundwaters and specifically for the solubility of iron and manganese. To understand the origin of groundwaters and potential hydraulic connection to surface water bodies, analyses of oxygen isotopes have been reviewed to be a reliable technique.

8 Conclusions and recommendations

The aim of this thesis was to create an explanatory model for the occurrence of elevated iron and manganese concentrations in Umeälvsåsen. The result together with collected theoretical background, literature review and site description have resulted in an analysis of the potential underlying sources and their contribution to elevated iron and manganese concentrations. The conclusion of this thesis is:

- Elevated concentrations of iron and manganese is highly dependent on the hydraulic contact with wetlands. Hydraulic contact with groundwater is more likely for young wetland formations like oxbow bogs and should therefore be considered when prospecting areas for groundwater abstraction and MAR.
- Groundwater with lower velocity appears to be associated with elevated concentrations of iron and manganese. The consequentially extended residence times are likely to occur in deeper extraction wells.
- Comprehensive description of the esker characteristics and depositional history, together with the landscape properties is essential for understanding the hydrogeochemistry of a glaciofluvial esker. This knowledge supports the selection of appropriate investigation methodologies and monitoring strategies.
- Initial investments in investigations targeting the underlying sources of elevated iron and manganese concentrations could contribute to more efficient investigation in early stage and minor the risk for extraction of groundwater in need of extensive groundwater treatment.

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Appendix A

T-test (two tail) for South and North area with Undisturbed condition and Continuous pumping					
<i>Red ($p \geq 0.05$) = not statistically significant different</i> <i>Green ($p < 0.05$) = statistically significant different</i>	North vs. South Undisturbed condition	North vs. South Continuous pumping	Undisturbed condition vs. Continuous pumping North area	Undisturbed condition vs. Continuous pumping South area	Infiltration vs. Non-Infiltration South area
Iron	3E-22	3E-72	3E-08	3E-02	4E-06
Manganese	7E-44	3E-87	6E-01	4E-08	2E-04
pH	8E-04	1E-28	5E-05	3E-02	2E-12
Sulphate	2E-04	2E-02	6E-04	6E-03	7E-25
Ammonium	6E-08	2E-44	5E-01	9E-09	7E-01
COD	5E-08	2E-11	9E-01	3E-01	3E-08
Alkalinity	9E-26	6E-40	2E-09	3E-01	2E-21

Appendix B

Descriptive statistics for Water quality parameters								
Area	Condition	Parameter	Unit	Mean	Median	Standard deviation	Sample variance	Number of tests
North area	Continuous pumping	Iron	mg/l	0.65	0.52	0.54	0.30	55
		Manganese	mg/l	0.04	0.04	0.02	2.64E-04	55
		pH	-	6.61	6.60	0.11	0.01	55
		Sulphate	mg/l	14.02	14.00	1.88	3.52	55
		Ammonium	mg/l	0.01	0.01	0.02	3.83E-04	55
		COD	mg O ₂ /l	0.81	0.80	0.05	2.91E-03	55
		Alkalinity	mg HCO ₃ /l	41.44	43.00	4.86	23.58	55
	Undisturbed condition	Iron	mg/l	1.84	1.65	1.24	1.53	50
		Manganese	mg/l	0.05	0.04	0.04	1.66E-03	50
		pH	-	6.75	6.70	0.21	0.04	50
		Sulphate	mg/l	12.34	13.00	2.79	7.78	50
		Ammonium	mg/l	0.02	0.01	0.06	3.39E-03	50
		COD	mg O ₂ /l	0.81	0.80	0.06	3.20E-03	50
		Alkalinity	mg HCO ₃ /l	48.50	48.00	5.90	34.87	50
Central area	Continuous pumping	Iron	mg/l	2.98	3.00	0.28	0.08	16
		Manganese	mg/l	0.08	0.08	4.03E-03	1.63E-05	16
		pH	-	6.81	6.80	0.03	6.25E-04	16
		Sulphate	mg/l	13.19	13.00	0.40	0.16	16
		Ammonium	mg/l	0.04	0.03	0.06	4.13E-03	16
		COD	mg O ₂ /l	0.81	0.80	0.03	9.00E-04	16
		Alkalinity	mg HCO ₃ /l	55.00	54.50	2.34	5.47	16
	Undisturbed condition	Iron	mg/l	4.24	4.40	2.08	4.32	27
		Manganese	mg/l	0.11	0.10	0.03	8.26E-04	27
		pH	-	6.96	7.00	0.17	0.03	27
		Sulphate	mg/l	12.63	13.00	2.65	7.01	27
		Ammonium	mg/l	0.03	0.02	0.01	2.01E-04	27
		COD	mg O ₂ /l	0.92	0.82	0.19	0.04	27
		Alkalinity	mg HCO ₃ /l	57.22	58.00	8.61	74.10	27

Area	Condition	Parameter	Unit	Mean	Median	Standard deviation	Sample variance	Number of tests
South area	Continuous pumping	Iron	mg/l	4.71	5.00	0.82	0.67	104
		Manganese	mg/l	0.29	0.29	0.03	9.93E-04	104
		pH	-	6.86	6.90	0.07	0.01	104
		Sulphate	mg/l	14.18	15.00	2.26	5.12	104
		Ammonium	mg/l	0.09	0.09	0.02	2.72E-04	104
		COD	mg O ₂ /l	1.09	1.00	0.26	0.07	104
		Alkalinity	mg HCO ₃ /l	60.50	62.00	9.88	97.52	104
	Undisturbed condition	Iron	mg/l	4.60	4.90	1.13	1.28	74
		Manganese	mg/l	0.25	0.26	0.06	3.83E-03	74
		pH	-	6.86	6.90	0.08	0.01	74
		Sulphate	mg/l	14.05	14.00	1.73	2.98	74
		Ammonium	mg/l	0.07	0.07	0.02	4.89E-04	74
		COD	mg O ₂ /l	0.96	0.85	0.21	0.05	74
		Alkalinity	mg HCO ₃ /l	63.34	63.00	5.04	25.43	74

Appendix C

Correlation test Water quality parameters							
South area Undisturbed condition							
<i>r-value</i>	Iron	Manganese	pH	Sulphate	Ammonium	COD	Alkalinity
Iron	1.00						
Manganese	0.30	1.00					
pH	0.50	0.44	1.00				
Sulphate	-0.20	-0.45	-0.26	1.00			
Ammonium	-0.03	0.37	0.22	-0.11	1.00		
COD	-0.11	0.02	-0.13	0.14	0.20	1.00	
Alkalinity	0.43	0.62	0.67	-0.09	0.35	0.09	1.00
South area Continuous pumping							
<i>r-value</i>	Iron	Manganese	pH	Sulphate	Ammonium	COD	Alkalinity
Iron	1.00						
Manganese	0.70	1.00					
pH	0.30	0.19	1.00				
Sulphate	0.51	0.81	-0.01	1.00			
Ammonium	0.10	0.26	-0.17	0.41	1.00		
COD	0.03	-0.03	0.08	-0.10	0.36	1.00	
Alkalinity	0.28	0.28	0.34	0.14	0.01	0.12	1.00
North area Undisturbed condition							
<i>r-value</i>	Iron	Manganese	pH	Sulphate	Ammonium	COD	Alkalinity
Iron	1.00						
Manganese	0.39	1.00					
pH	0.14	0.53	1.00				
Sulphate	-0.01	0.00	-0.18	1.00			
Ammonium	0.65	0.46	0.03	-0.01	1.00		
COD	0.49	0.12	0.17	-0.13	0.01	1.00	
Alkalinity	0.55	0.40	0.10	-0.29	0.27	0.28	1.00
North area Continuous pumping							
<i>r-value</i>	Iron	Manganese	pH	Sulphate	Ammonium	COD	Alkalinity
Iron	1.00						
Manganese	0.41	1.00					
pH	-0.22	-0.59	1.00				
Sulphate	0.09	0.48	-0.52	1.00			
Ammonium	-0.03	0.00	0.03	0.08	1.00		
COD	-0.13	0.06	-0.02	0.07	0.25	1.00	
Alkalinity	-0.10	-0.48	0.54	-0.20	0.22	0.13	1.00

Appendix D

T-test (two tail) for Iron over different time periods						
Red ($p \geq 0.05$) = not statistically significant different Green ($p < 0.05$) = statistically significant different	Apr-May vs. Jun-Jul	Apr-May vs. Aug-Nov	Apr-May vs. Dec-Mar	Jun-Jul vs. Aug-Nov	Jun-Jul vs. Dec-Mar	Aug-Nov vs. Dec-Mar
North area Undisturbed condition	0.709	0.988	no data	0.270	no data	no data
North area Continuous pumping	0.593	0.721	0.382	0.242	0.031	0.443
South area Undisturbed condition	0.182	0.290	0.414	0.428	0.191	0.398
Soth area Continuous pumping	0.328	0.170	0.057	0.810	0.326	0.256

T-test (two tail) for Manganese over different time periods						
Red ($p \geq 0.05$) = not statistically significant different Green ($p < 0.05$) = statistically significant different	Apr-May vs. Jun-Jul	Apr-May vs. Aug-Nov	Apr-May vs. Dec-Mar	Jun-Jul vs. Aug-Nov	Jun-Jul vs. Dec-Mar	Aug-Nov vs. Dec-Mar
North area Undisturbed condition	0.144	0.207	no data	0.573	no data	no data
North area Continuous pumping	0.383	0.059	0.057	0.009	0.010	0.926
South area Undisturbed condition	0.456	no data	no data	0.038	0.506	0.111
Soth area Continuous pumping	0.789	0.445	0.134	0.410	0.063	0.137