# Groundwater chemistry evaluation and a GIS-based approach for determining groundwater potential in Mörbylånga, Sweden

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**Dissertations in Geology at Lund University,**
**Master's thesis, no 531**
**(45 hp/ECTS credits)**

**Department of Geology**
**Lund University**
**2018**

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**Cover Picture:** Långe Jan lighthouse at the south cape of Öland. Photo © Nikolas Benavides Höglund

# Abstract

NIKOLAS BENAVIDES HÖGLUND

Benavides Höglund, N., 2018: Groundwater chemistry evaluation and a GIS-based approach for determining groundwater potential in Mörbylånga, Sweden. *Dissertations in Geology at Lund University*, No. 531, 46 pp. 45 hp (45 ECTS credits)

**Abstract:** Recently, several regions in southern Sweden suffered extremely low groundwater levels following a long-term infrequency in rainfall. In response, irrigation was banned in many of the affected municipalities during 2016–2017, amongst which Mörbylånga municipality was one. Because nearly half of the nation's drinking water is extracted from groundwater, protecting and managing this vital resource in a sustainable manner is essential. The public sector, spearheaded by the Geological Survey of Sweden (SGU), is now increasing their efforts in the search for additional groundwater resources, as well as in the management of existing ones.

The aim of this thesis, which is written in collaboration with SGU, is to evaluate the groundwater quality of Mörbylånga municipality. The evaluation is based on more than 1400 groundwater analyses, sampled from private and municipal wells over the last 8–10 year period. The samples, analyzed for physiochemical and microbiological content, are compared to guideline values elaborated by SGU and the National Food Agency (Livsmedelsverket). In addition, 26 maps were created based on georeferenced data from private wells, showing the spatial distribution of the analyzed parameters. Furthermore, an estimation of the groundwater potential in the municipality was performed, using a GIS-based approach. By integrating spatial geodata in a multi-criteria analysis, three additional maps were created, which, together with other material, can be used as a base for future groundwater exploration. Results of the evaluation show, for the studied period, a better groundwater quality in municipal wells, compared to private wells. Significant concentrations of nutrients and microorganisms were detected in private wells, especially in the northern and eastern parts of the municipality. High concentrations of lead were in a few occasions encountered in both municipal and private wells and a cyclical variation in concentrations of sodium, sulfate and calcium in one of the municipal wells could possibly be linked to saltwater intrusion. The source for these observations, and suggested measures, are discussed. Furthermore, the GIS-analyses undertaken in this study reveal an area of approximately 2.5 $km^2$ with higher than average groundwater potential. The area is conveniently located with regards to users and infrastructure. Suggestions for how to proceed the work with the GIS results are discussed as well.

**Keywords:** Groundwater chemistry, Groundwater potential, Mörbylånga, Öland, Chemical analysis, Hydrogeology, GIS, Multi-criteria analysis, Water quality guidelines, Groundwater deficit, Water shortage

**Supervisor(s):** Charlotte Sparrenbom, Peter Dahlqvist, Mattias Gustafsson

**Subject:** Quaternary Geology, Hydrogeology

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# Sammanfattning

NIKOLAS BENAVIDES HÖGLUND

Benavides Höglund, N., 2018: Utvärdering av grundvattenkemi samt en GIS-baserad metodik för uppskattning av grundvattenpotential i Mörbylånga, Sverige. *Examensarbeten i geologi vid Lunds universitet*, Nr. 531, 46 sid. 45 hp.

**Sammanfattning:** Till följd av ovanligt låg nederbörd drabbades stora delar av södra Sverige av extremt låga grundvattennivåer under 2016–2017. För att undvika problem med vattenförsörjningen införde flera kommuner, inklusive Mörbylånga kommun, ett bevattningsförbud. Eftersom grundvatten utgör ungefär hälften av Sveriges dricksvatten är det viktigt att skydda och förvalta denna grundläggande resurs på ett hållbart sätt. Sveriges Geologiska Undersökning (SGU), tillsammans med berörda kommuner, undersöker nu olika möjligheter för att finna nya grundvattentillgångar, samt arbetar fram underlag för en bättre förvaltning av befintliga tillgångar.

Syftet med denna studie, som utförts i samarbete med SGU i Lund, är att utvärdera den kemiska grundvattenkvaliteten i Mörbylånga kommun. Denna utvärdering är baserad på mer än 1400 vattenanalyser utförda på kommunala och privata brunnar de senaste 8–10 åren. Proverna, som är analyserade för kemiska och mikrobiologiska parametrar, har jämförts med riktvärden utfärdade av SGU och Livsmedelsverket. Utöver detta har 26 stycken haltkartor skapats, baserat på georefererad vattenkemidata från privata brunnar. Dessa kartor visar halter (i enlighet med SGUs gränsvärden) samt den geografiska spridningen för de parametrar som analyserats i kommunen. Vidare har en GIS-baserad analys tillämpats för att göra en uppskattning av grundvattenpotentialen i Mörbylånga kommun. Genom att integrera rumsliga geodata i en multikriterieanalys skapades ytterligare tre kartor som, tillsammans med annat material, kan ligga till grund för sökandet efter framtida grundvattentillgångar. De resultat som arbetats fram visar att grundvattenkvaliteten är högre i kommunala brunnar jämfört med privata brunnar. Höga halter av näringsämnen och mikroorganismer uppmättes i de privata brunnarna, särskilt i de norra och östra delarna av kommunen. Periodvis uppmättes även höga halter av bly i både kommunala och privata brunnar. I en av de kommunala brunnarna upptäcktes ett cykliskt mönster vid en jämförelse av natrium-, sulfat- och kalciumkoncentrationer, eventuellt orsakat av saltvatteninträngning. Vidare visar resultat från GIS-analysen ett område på ca 2,5 $km^2$ där grundvattenpotentialen förväntas vara högre än den genomsnittliga för kommunen. Detta område ligger nära både användare och infrastruktur. Ytterligare observationer, samt förslag till åtgärder diskuteras vidare i denna studie.

**Nyckelord:** Grundvatten, Grundvattenkemi, Grundvattenpotential, Mörbylånga, Öland, Vattenkemianalys, Hydrogeologi, GIS, Multikriterieanalys, Gränsvärde, Dricksvatten, Vattenbrist

**Handledare**: Charlotte Sparrenbom, Peter Dahlqvist, Mattias Gustafsson

**Ämnesinriktning**: Kvartärgeologi, Hydrogeologi

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# 1 Introduction

Öland is the second largest island in Sweden, situated off the southeastern shores of Småland province (Fig. 1A). Recently, a deficiency in the water supply sprung as a result of a long-term infrequency in rainfall over the region, causing particularly low groundwater levels on Öland (SGU 2016). In order to avoid straining the remaining groundwater resources, Mörbylånga municipal office issued a ban on irrigation and other unnecessary water use (Mörbylånga 2017). The ban, introduced in March 2016, was lifted in October 2017, following a period of more abundant rainfall. At the time of writing, the groundwater levels are now recovering to a normal state (SGU 2018). However, this, and other recent groundwater related issues in southern Sweden gained public attention and was recognized by the government as an urgent concern. Because of this, the Geological Survey of Sweden (Sveriges geologiska undersökning, SGU), have been granted additional resources in order to expand and target groundwater related issues in particular. SGU, in collaboration with Kalmar County Administrative Board and Mörbylånga municipality are now approaching the issue on several fronts, ranging from the drilling of new wells and performing SkyTEM investigations, to the construction of a seawater desalination plant. This master's thesis, which is written in collaboration with SGU, constitutes one of the many parts in the collective efforts for the improvement of future groundwater management on Öland.

## 1.1 Aim and purpose of the study

In order to assure satisfactory drinking water quality, Mörbylånga municipality samples both groundwater and end-user drinking water on a quarterly basis. The samples are analyzed for chemical, physical and microbiological content by accredited laboratory Eurofins Sweden AB and results are then compared to current guidelines and regulations. In addition, private well owners in Mörbylånga have been encouraged to have the quality of their drinking water analyzed, resulting in a large number of analyzed samples over the last decade. The main purpose of this study is to process water chemistry data collected over the last 8–10 year period in order to create a comprehensive overview of the groundwater chemistry in Mörbylånga. To achieve this, all

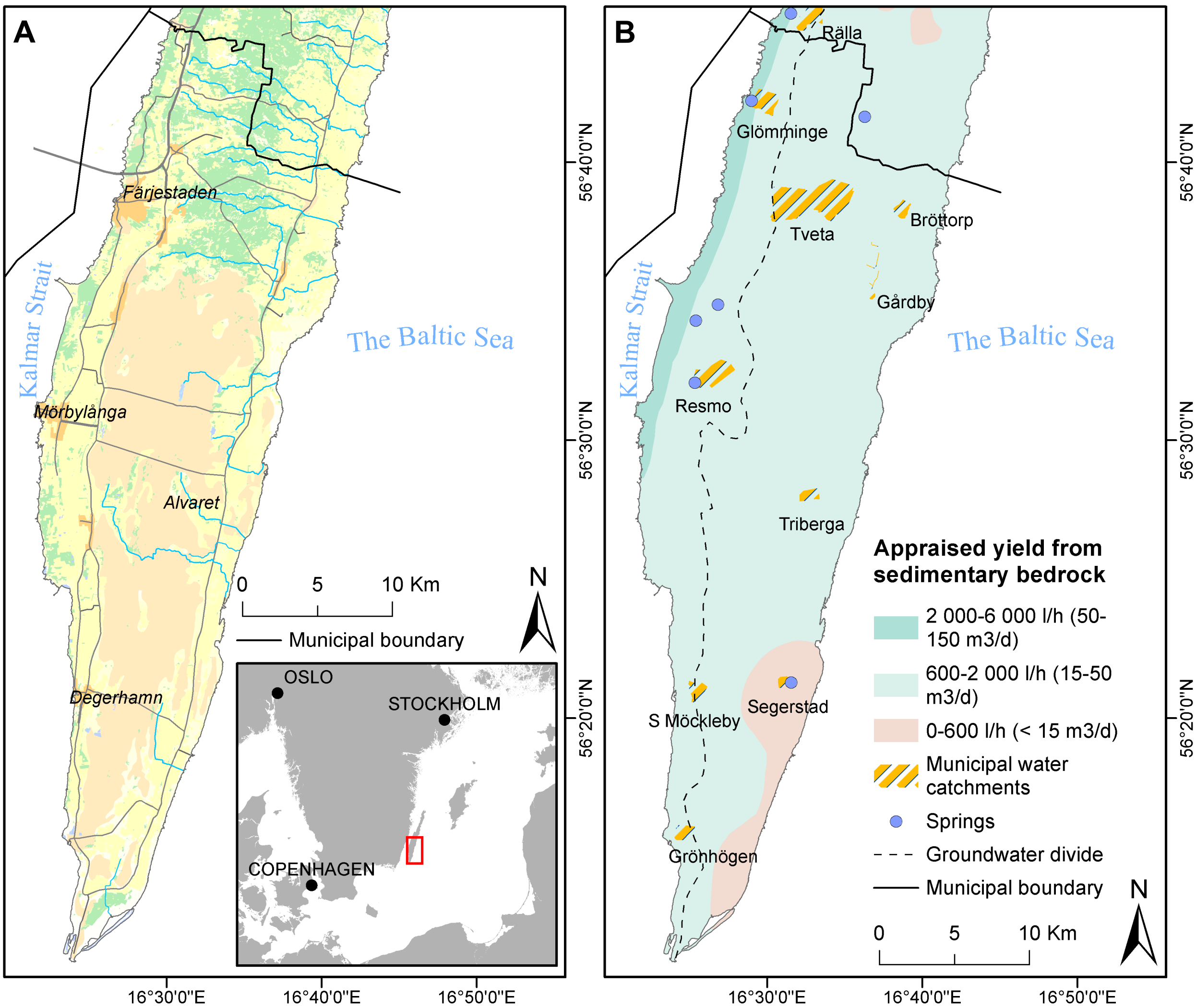



*Fig. 1*. Maps showing **A**. Mörbylånga Municipality and its regional position, created with data from GSD-Översiktskartan © Lantmäteriet, and **B**. hydrogeological setting in the sedimentary bedrock, created with data from SGU Grundvatten, 1:1 000 000 © SGU.

parameters have been categorized on a basis of current guidelines (see chapter 1.2). Furthermore, maps, graphs and tables are created to reveal trends and make them available for interpretation.

Additionally, spatial geo-data collected by means of mapping, sampling and remote sensing, have over the past decades accumulated in significant volumes. Traditionally, this data is reviewed and interpreted individually and later compared with different datasets. A growing number of studies, however, incorporate datasets from multiple disciplines to solve multi-criteria problems and for suitability modeling. Therefore, an additional goal of this study is to make use of available spatial data to create maps of hydrogeological importance, covering Mörbylånga municipality.

More specifically, the aim of this thesis is to answer the following questions:

- How does the groundwater quality vary across the municipality and how does it compare to current guidelines?

- What is the spatial distribution and concentration of analyzed groundwater chemistry parameters?

- Which of the analyzed parameters can be linked to geological circumstances and / or anthropogenic activities? Are there any elements present in hazardous concentrations?

- Can existing spatial data be used to narrow down the search area for untapped groundwater resources within the municipality?

### 1.2 Guidelines and environmental objectives

The World Health Organization (WHO) has worked out guideline values for physiochemical and microbiological parameters to ensure a water quality safe for consumption. These guidelines are elaborated in consideration of those at greatest risk of waterborne illnesses, such as infants, elderly and debilitated people, over a lifetime of consumption. The guidelines are described as "*reasonable minimum requirements*" (WHO, 2011, p. 2), implying stricter values could be adopted by individual states in order to better reflect current conditions and encourage continued improvement. The National Food Agency (Livsmedelsverket) is the responsible authority for issuing provisions regarding drinking water guidelines in Sweden. Although certain values are set at the same concentration when comparing the WHO and Livsmedelsverket guidelines, values enforced by Livsmedelsverket are generally found at stricter concentrations (SLVFS 2001:30 ; LIFSFS 2017:2).

Sweden's ongoing commitment for environmental improvements, known as the Swedish Environmental Objectives, consists of the Generation goal, sixteen Environmental quality objectives and milestone targets. The Generation goal is formulated as follows: "*The overall goal of environmental policy is to hand over to the next generation a society in which the major environmental problems have been solved, without increasing environmental and health problems outside Sweden's borders.*" (Naturvårdsverket, 2016, p. 3). The Environmental Protection Agency of Sweden (Naturvårdsverket) is the responsible authority of the generation goal. Responsibility for the Environmental quality objectives, however, is shared and monitored among appropriate authorities. SGU, for instance, is responsible for the quality objective Good-quality groundwater. As part of SGU's mission to ensure good-quality groundwater in Sweden, a comprehensive report with guideline values have been created (SGU 2013a). In addition to health effects, the report also addresses geological circumstances and environmental impact. Therefore, in regard to health and environmental impact, guideline values are subdivided into five classes: 1 – very low, 2 – low, 3 – medium, 4 – high, 5 – very high. In many cases, guideline values, as specified by Livsmedelsverket, fall between class 4 and 5 in the SGU groundwater quality criteria report, indicating values 4 and below, as suitable in terms of drinking water. Concentrations falling within class 5 are generally unsuitable for consumption.

Groundwater is a vital source for drinking water in Sweden, as is the case on Öland. At the time of writing, Mörbylånga municipality receives its drinking water from nine groundwater production plants (Fig. 1B). Because the results in this report are based on groundwater chemistry data, the SGU groundwater quality criteria report and its presented guideline values represent a central role in this study. All results presented here will be compared to that report, in its current state and at the time of writing.

## 2 Background and geological setting

### 2.1 Previous studies

During the 1940s the alum shale on Öland was investigated to evaluate its economic importance (Westergård 1944, 1947). The studies showed, however, that only low quantities of oil could be obtained by distillation of the shale and hence the formation was found to be of little economic interest.

Pousette and Möller (1972) conducted extensive investigations of the hydrogeological setting of Öland, evaluating the water-bearing properties of the bedrock and soil based on data from numerous wells. Pousette (1972, 1974) conducted further groundwater studies in the Great Alvar area of Öland, an area characterized by exposed karst and flat topography with little to no soil cover.

In more recent times Falk et al., (2006) studied metal mobility in the alum shale from Öland, finding correlation between low pH and release of metals. Vöks (2010) investigated the distribution of natural springs and their water chemical status on southern Öland. Calner et al. (2014) analyzed the Ordovician part of a drill core from northeastern Öland for carbon isotope geochemistry, presenting new results useful for

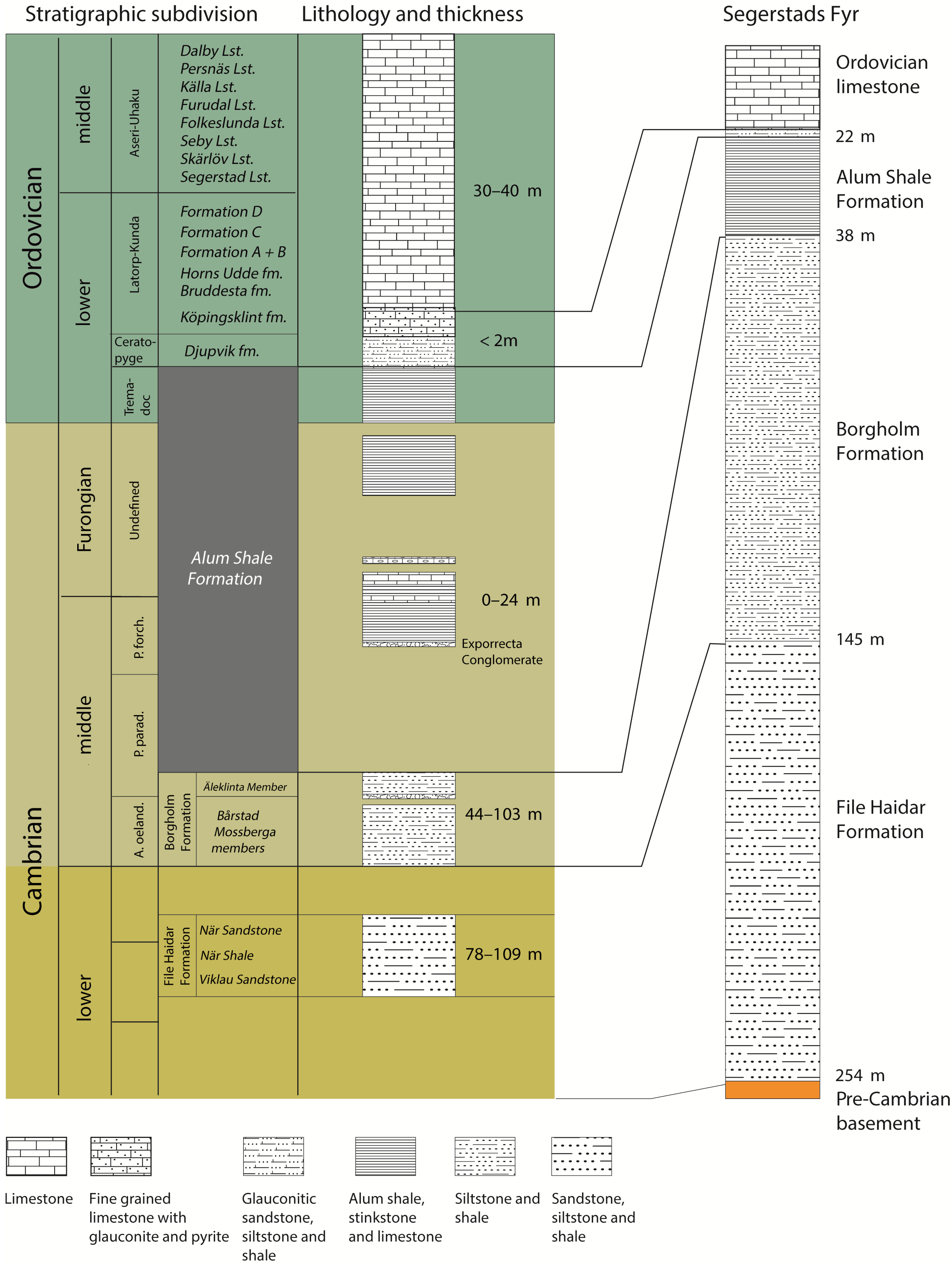



*Fig. 2*. Stratigraphic subdivision, lithology and thickness of sedimentary successions from the SGU drill core at Segerstads Fyr, southeastern Öland. Location of Segerstads Fyr is shown on Fig. 3. Modified and used with permission from Erlström (2016).

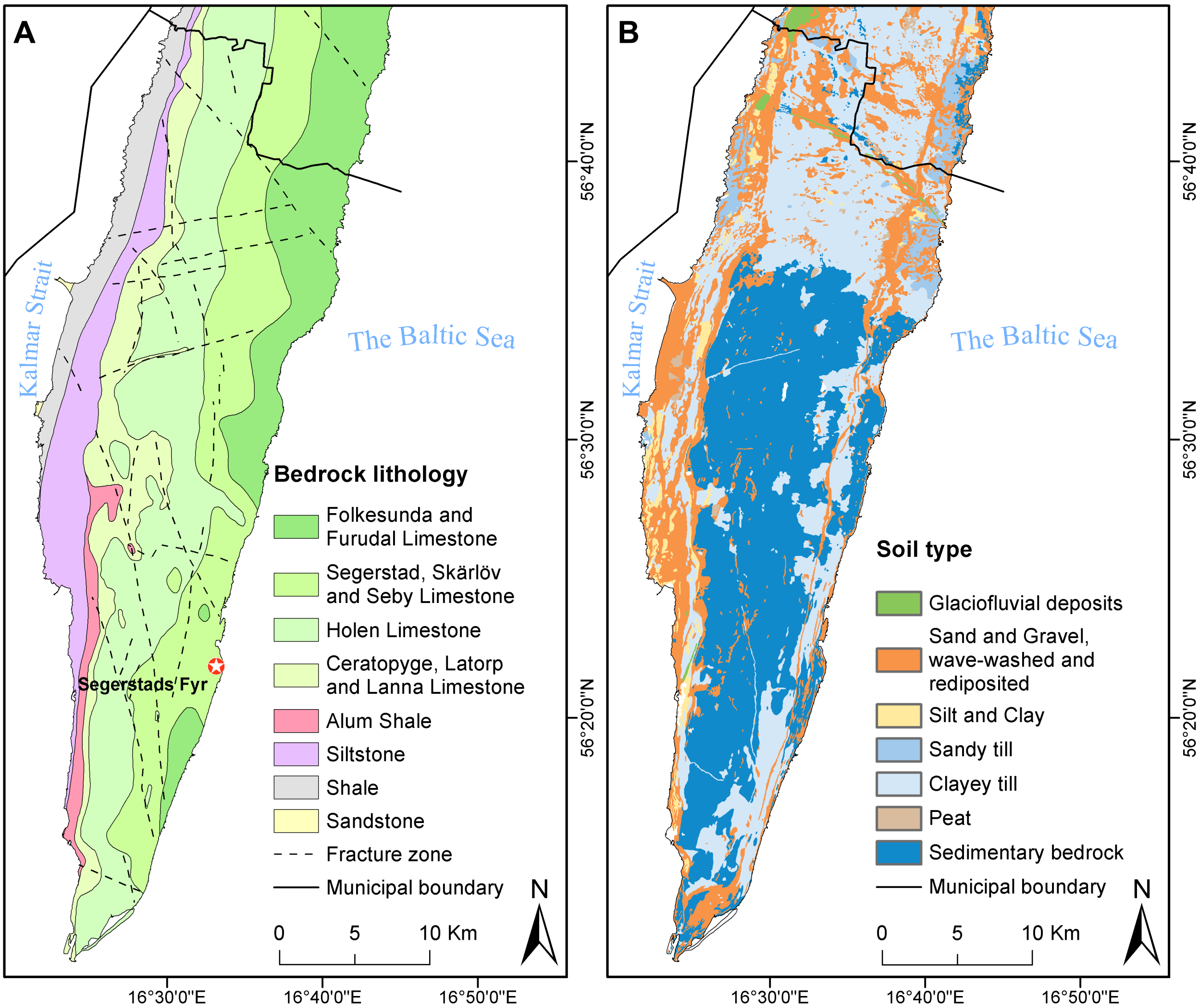



*Fig. 3*. Maps showing **A**. major lithological units of the bedrock and location of SGU drill core at Segerstads Fyr from Fig. 2, created with data from SGU Bergarter, 1:1 000 000 © SGU and SGU Grundvatten, 1:250 000 © SGU, and **B**. soil types in Mörbylånga municipality, created with data from SGU Jordarter, 1:25 000 – 1:100 000 © SGU.

intercontinental correlation purposes. Swierz (2016), in a study similar to this one, evaluated the groundwater chemical status of private wells in Borgholm municipality, northern Öland. Erlström (2016) investigated a drill core in the Grönhögen water catchment using X-ray fluorescence to describe the geochemistry of the sedimentary succession.

## 2.2 Development and evolution of the Baltic Basin

Öland is situated in the northwestern part of the Baltic Basin (also known as the Baltic Syneclise). The Baltic Basin developed as an intracratonic basin on the Proterozoic Baltic shield (BABEL Working Group, 1990). Sedimentation commenced in late Ediacaran to early Cambrian time. During late Ordovician and middle Silurian, extensional tectonics caused major subsidence of the basin. However, during late Silurian to early Devonian, the Baltic Basin was instead characterized by a compressional regime (Harff et al., 2011). Towards the Permian, the tectonic activities came to a halt with only minor faulting occurring during the Mesozoic. Instead, development of the Mesozoic Danish and Polish basins commenced to the southwest, leaving the Baltic Basin relatively unaffected for most of the Mesozoic era. However, towards late Cretaceous, inversion tectonics along the Sorgenfrei-Tornquist Zone and Teysseyre-Torniquist zone affected the southwestern margin of the Baltic Basin (Erlström et al., 1997; Sopher et al., 2016). During the Cenozoic, the most recent geological events to affect the basin are those of glacial erosion. Today the sedimentary basin reaches its maximum depth of 4000 meters in its southern parts, extending over northern Poland. It is here that reservoir formations are found with economically important occurrences of oil and gas (Harff et al., 2011).

## 2.3 The sedimentary bedrock of Öland

The sedimentary deposits on Öland cover the time period of early Cambrian to middle Ordovician. The bottommost units are the lower Cambrian sandstone (File Haidar Formation), which is superposed by siltstone and shale (Borgholm Formation) of middle Cambrian age. They are in turn superposed by alum shale of Furongian and lower Ordovician age. Limestone formations of lower and middle Ordovician age constitute the uppermost units (Fig. 2), and measures as

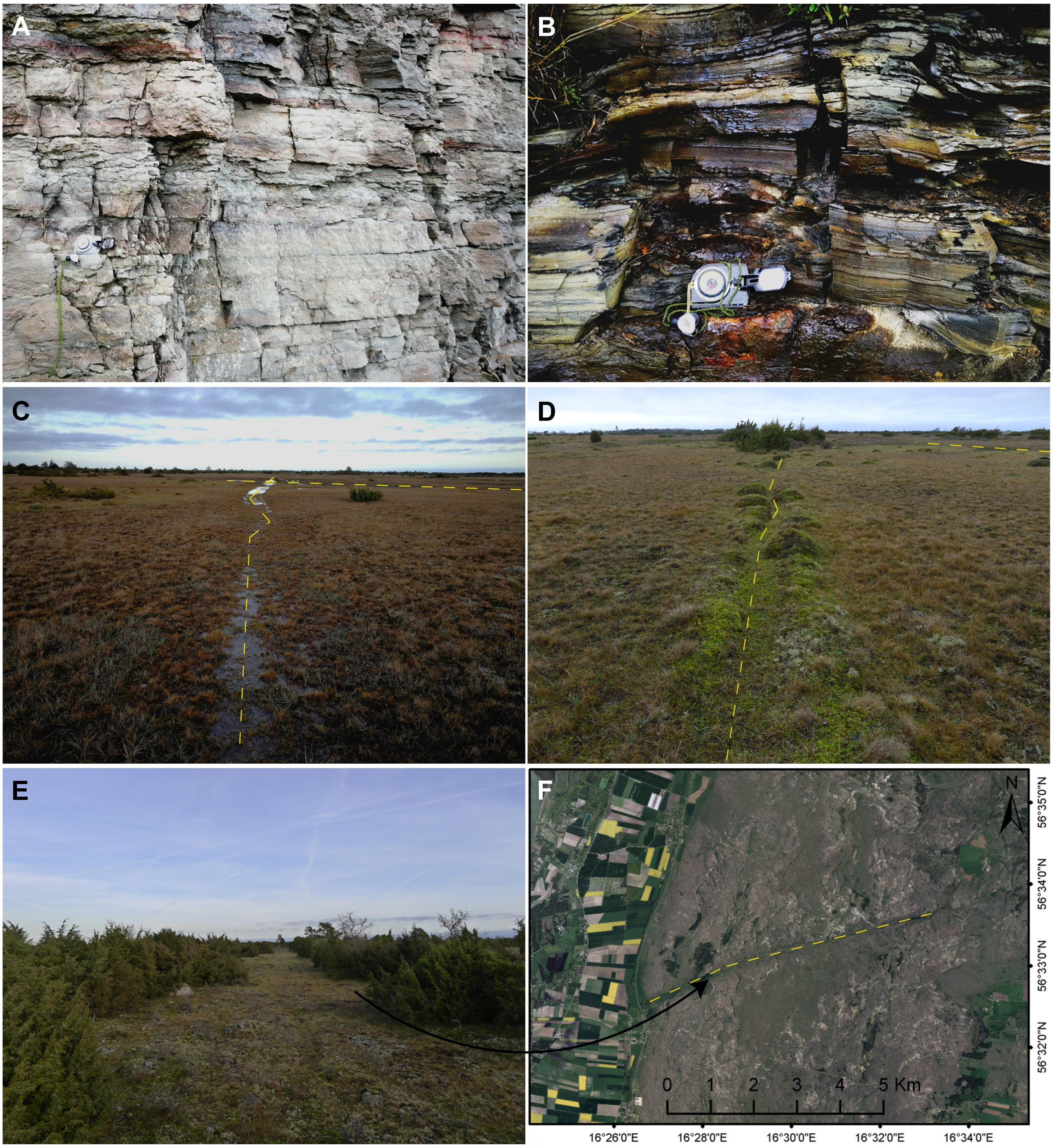



*Fig. 4*. Detail of **A**. Limestone outcrop in Albrunna kalkbrott and **B**. alum shale outcrop near Degerhamn. Visible signs of leaching on a lens of stinkstone on which the compass is resting. **C**–**D**. Photos of fissures visible at surface in the Great Alvar east of Resmo, and **E**. The Resmo Fissure (*Resmosprickan*) at surface in the Great Alvar, facing ENE. **F**. Aerial photo of the Resmo Fissure, created with data from GSD-Ortofoto25 © Lantmäteriet. Arrow showing approximate location of E. Yellow dashed line highlights the fissures. Photographs A–E © Nikolás Benavides Höglund.

thick as 30 to 40 meters on the southeastern part of the island (Erlström, 2016), up to 40 to 50 meters on the northeastern part (Calner et al., 2014).

In the northwestern part of the Baltic Basin, the sedimentary units are dipping gently towards east-southeast by approximately 0.2–0.3 degrees, implying that the sedimentary cover becomes thicker towards southeast. This is true on Öland, where the depth to the crystalline basement in its deepest part is measured to 254 meters (Fig. 2, 3A), compared to approximately 160 meters in the shallower parts (Pousette and Möller, 1972; Erlström, 2016).

## 2.4 Hydrogeological setting of Öland

Knowledge of the hydrogeological setting on Öland is largely derived from investigations performed by Pousette and Möller (1972), Pousette (1972; 1974) and unpublished reports from consultant firms undertaken on behalf of SGU and the Mörbylånga municipal office. Recent SkyTEM investigations performed on behalf of SGU (unpublished at the time of writing) will likely constitute the foundation for future groundwater studies on Öland.

The Quaternary deposits on Öland for the most part consist of clayey till or wave-washed and redeposited sand and gravel (Fig. 3B). From a hydrogeological perspective, the sand and gravel deposits can, under favorable conditions, yield large volumes of water. In many cases on Öland however, the sand and gravel deposits are located on topographical highs and often lack necessary enclosures for water to accumulate in significant volumes (Pousette and Möller., 1972). In general, and in contrast to many parts of mainland Sweden, the fractured sedimentary bedrock is of higher hydrogeological importance than the relatively thin soil cover on Öland. Although certain glaciofluvial- and gravel deposits locally constitute important aquifers, Pousette (1972) emphasizes fractures in the sedimentary bedrock as the main factor in terms of groundwater storability and extractability.

Runoff and drainage is first and foremost controlled by topography. The Western Ridge (*Västra landborgen*) is a topographical highpoint stretching in an N to S orientation and rainfall to the west of the ridge will be drained towards Kalmar strait, whereas rainfall to the east of the ridge is drained towards the Baltic Sea (Pousette and Möller 1972). Although the groundwater divide is usually located slightly to the east of the Western Ridge crest, groundwater is drained towards the same two E to W oriented drainage basins. Results presented in this thesis, based on spatial analysis of LiDAR data, provide a more detailed overview of the watershed distributions and their drainage pathways throughout the municipality.

Because the Ordovician limestone successions are fairly consolidated, groundwater infiltrates the bedrock through fissures and karstic weathered cavities, rather than through intergranular porosity. Additionally, because the Ordovician limestone successions are the most prevalent bedrock on Öland, fractures of varying scale can be clearly observed, especially in the Great Alvar area, where the soil cover is particularly thin (Fig. 4). Effective porosity in the limestone have been found to vary from 0.2–0.5 percent under normal conditions, to 0.5–1 percent in more fractured areas (Pousette and Möller, 1972). This is significantly lower than the porosity in some of the aquifers constituted by unconsolidated deposits currently in use, where the porosity averages around 7 percent (Norconsult, 2012). In a recent investigation in the Triberga area, measurements of the hydraulic conductivity in the bedrock were found to vary from $5.67 \cdot 10^{-4}$ m/s to $1.38 \cdot 10^{-5}$ m/s (Structor, 2016), which is on par with the grain size fraction of fine sand (Talme and Almén, 1978). The borings in this investigation extended into the alum shale. This is usually the case on Öland, because of the favorable water bearing properties of the highly fractured shale (Pousette and Möller, 1972). However, the suitability of the alum shale as a reservoir rock for drinking water is often questioned (e.g. Pousette & Möller, 1972; Falk et al., 2006; SGU 2013a), because of its tendency to leach metals into the groundwater, thus lowering the quality of the water significantly.

# 3 Materials and methods

## 3.1 Materials

In order to obtain the results presented in this paper, a collection of datasets from multiple authorities was downloaded, analyzed and processed.

The Swedish University of Agricultural Science (SLU) has created the Geodata Extraction Tool (GET), a service that enable researchers and students connected to a Swedish university to download and use geodata from several authorities (SLU 2017). This tool was used extensively in this study and the datasets downloaded from the GET, as well as the authorities that owns and collects the data, are presented below in section 3.1.3. A summary of the material used in this study is shown in table 1.

### 3.1.1 Groundwater chemistry data

The groundwater chemistry data used in this study is collected by the technical administration of Mörbylånga municipality and analyzed by accredited laboratory Eurofins Environment Testing Sweden AB. For downloading of the data, access to the laboratory database was granted.

#### *3.1.1.1 Municipal water catchments*

Each well contributing to the municipal water supply is monitored for physiochemical and microbiological parameters on a quarterly basis. Furthermore, samples collected at randomly selected end-users are analyzed for an extended set of physiochemical parameters, as well as for pesticides and organic content. The end-user samples are to be viewed as the product of all contributing wells within a specific water catchment, after treatment in the municipal water plant.

#### *3.1.1.2 Private wells*

Property owners in Mörbylånga commonly have drilled or dug wells for private use. The municipal office allows property owners with private wells opportunity to have their water tested, where, in collaboration with Eurofins, three different analysis packages are available. It is the decision of each property owner which product to purchase, and therefore the water chemistry data from private wells in this study contains varying sets of parameters. Furthermore, the protocols do not specify where on the property the sampling is performed and is therefore assumed to be collected from the tap.

### 3.1.2 Climate data

The Swedish Meteorological and Hydrological Institute (SMHI) is the authority responsible for collecting climate data. Part of their mission involves collecting rainfall data from monitoring stations across the country. In this study, rainfall data from six monitoring stations in Kalmar County, was downloaded from the

SMHI database in order to create a rainfall map for use in the overlay analysis (see 3.2.3).

### 3.1.3 Datasets downloaded from the SLU GET

#### *3.1.3.1 Aerial photos*

Aerial photo mosaics at 0.25 m resolution are collected by Lantmäteriet, the Swedish mapping, cadastral and land registration authority. The dataset is a multipurpose project collected for use in map creation, community planning, environmental monitoring, etc. The data undergoes geometric correction to show a true representation of the land.

Aerial photos were used in this study to assist in mapping of geologic lineaments not already included in the lithology data provided by SGU and for the creation of the Lineament Density map used in the GIS overlay analysis (explained in 3.2.3).

#### *3.1.3.2 Land cover data*

Land cover data is collected and managed by Lantmäteriet. The data, available in raster and vector format, was downloaded and processed to create the overview map (Fig. 1A), as well as the drainage density map used in the overlay analysis (see 3.2.3.7).

#### *3.1.3.3 Soil and lithology data*

Soil and lithology data is based on mapping performed by SGU and is available in both raster and vector format. The datasets were imported to ArcGIS to create a hydrogeological map (Fig. 1B), lithology map (Fig. 3A) and a soil type map (Fig. 3B) of the municipality, as well as the soil- and bedrock lithology map used in the overlay analysis (explained in 3.2.3.4 and 3.2.3.5).

#### *3.1.3.4 LiDAR data*

The light detection and ranging (LiDAR) data, used for multiple purposes in this study, was collected by Lantmäteriet as part of the *National Elevation Model*, a program commissioned by the Swedish government in 2009. In this study LiDAR data was used to create a slope map (explained in 3.2.3.3), a watershed model (Appendix 5) and a map showing depth to the alum shale (Appendix 6).

## 3.2 Methods

### 3.2.1 Digital processing of water chemistry data

The data was downloaded and processed in Microsoft Excel to calculate maximum-, minimum-, mean-, median– and standard deviation values for each of the physiochemical and microbiological parameters. The results were also compared to guideline values from SGU 2013:01 to create stacked charts showing the distribution of each parameter in relation to the SGU 2013:01 classification system. Also shown, for comparison purposes, are the guideline values from SLV 2001:30. Groundwater quality in municipal and private wells is evaluated separately and differences are compared and discussed.

### 3.2.2 Processing of private well data into maps

In order to create maps showing the water chemical status across the municipality, the data must be georeferenced. Specified on the analysis result protocols provided by the laboratory, are the property IDs from every property where a sample was collected. Because Lantmäteriet provide shapefiles containing real estate data for every property in Sweden, each sample can be joined with its respective property ID, thus creating a database where water chemistry data is georeferenced.

After processing and excluding uncertain entries, such as analysis protocols that could not, with confidence, be tied together with a specific property, the database contains 578 georeferenced samples tested for up to 27 parameters. Multiple maps were created from this database, showing the water chemical status of each parameter. In certain cases where multiple samples are collected from the same property, the highest measured concentration of a parameter is shown on the map. This is done to highlight areas that could be associated with problematic levels of certain elements or microbiological occurrences.

### 3.2.3 GIS overlay analysis

Geographic Information System (GIS) is a tool that enable digital processing of large amounts of spatial data in a more efficient and accurate manner than if

*Table 1*. Summary and description of data used in this study

| Data products | Responsible authority | Description / Notes |
|---|---|---|
| Water chemistry data | Mörbylånga Municipality | Downloaded from the Eurofins database |
| Nederbörd, dygnsvärde | SMHI | Precipitation data |
| GSD-Ortofoto25 | Lantmäteriet | 0.25m resolution aerial photos |
| GSD-Terrängkartan | Lantmäteriet | Land cover data |
| GSD-Översiktskartan | Lantmäteriet | Land cover data |
| GSD-Höjddata grid2+ | Lantmäteriet | 2m resolution LIDAR data |
| GSD-Fastighetskartan | Lantmäteriet | Used for georeferencing water chemistry data |
| Jordarter 1:25 000 – 1:100 000 | SGU | Soil data |
| Bergarter 1:1 000 000 | SGU | Bedrock lithology data |
| Grundvatten 1:50 000 | SGU | Geologic lineaments |

performed manually. One such operation is an overlay analysis (Fig. 5). An overlay analysis can be performed to solve multi-criteria problems and model suitability. The operation integrates multiple datasets and is performed in two steps:

1. Processing and preparation of datasets

2. Assigning weight to control influence of each dataset in the multi-criteria analysis

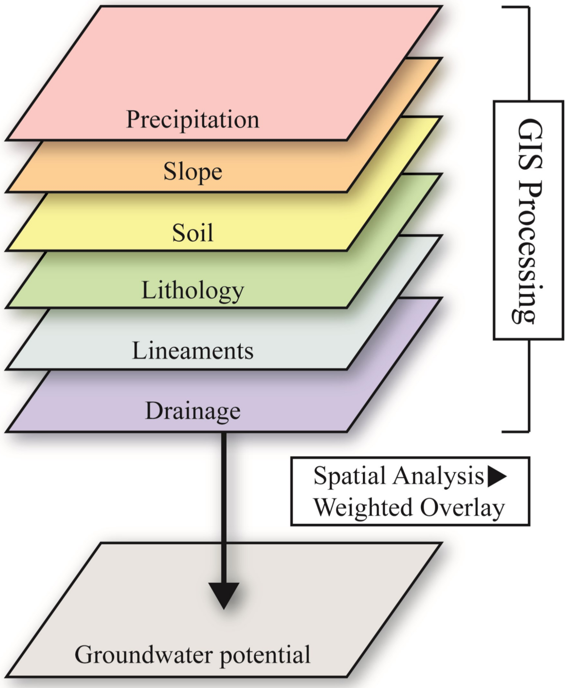



*Fig. 5*. Conceptual model of the overlay analysis method and the resulting suitability map. In this method, datasets are integrated and weighed according to their relative importance in relation to the groundwater formation process. This figure is based on information in Hsin-Fu et al., (2009).

Depending on what problem needs to be solved, datasets relevant to that problem will be selected for integration in the analysis. First, entries in the datasets are reclassified to numerical values (e.g. the soil class '*sand*' is assigned the number '5') and then scored according to an evaluation scale based on their relevance to the problem (see 3.2.3.8). Finally, each dataset is assigned a weight. This is done to control how much influence each dataset will have on the product of the analysis.

#### *3.2.3.1 Defining what problems to solve*

Two increasingly common types of GIS studies in natural science is locating sites suitable for groundwater extraction, i.e. *groundwater potential* (e.g. Hsin-Fu et al., 2009; Karami et al., 2016), as well as sites suitable for constructing artificial groundwater recharge (e.g. Singh et al., 2013; Satapathy and Syed, 2015). The aim of this exercise is to model groundwater potential in Mörbylånga municipality using datasets downloaded from the GET. Each dataset represent factors with influence on groundwater recharge and are explained further below.

#### *3.2.3.2 Precipitation*

Considering the hydrologic equation, where *Inflow* = *Outflow* ± *Changes in storage* (Fetter, 2001), precipitation in the form of rainfall constitutes a major contributor to the input of water into an area. Other factors that may contribute to the inflow (or outflow) of water to an area include surface water flow (discussed in 3.2.3.7) and groundwater flow.

In order to create the precipitation map used in the overlay analysis, rainfall data for the period December 2006 – December 2016 was downloaded from the SMHI database for six monitoring stations in Kalmar County. Annual means were then calculated for each monitoring station using Microsoft Excel and later georeferenced using ArcGIS. Finally, the data was interpolated using the Kriging method to create the final precipitation map (Fig. 6A).

#### *3.2.3.3 Slope gradient*

The slope gradient affects at which ratio rainfall will infiltrate the ground and reach the saturated zone or become surface runoff. Therefore, a low slope gradient is optimal in terms of infiltration. Furthermore, as the water table in porous media generally tends to mimic surface topography (Fetter, 2001), one can assume a higher potential for groundwater accumulation in areas of low slope gradient. Even though the topography of Öland is generally flat, reliable slope data (Fig. 6B) was derived through processing of high resolution LiDAR data.

#### *3.2.3.4 Soil class*

The groundwater potential of an area can vary greatly depending on what soil type is present at the site. Particle size, fabric, sorting and packing influence both porosity and the hydraulic conductivity of the soil, factors that in turn control how much water can be stored and effectively extracted from an aquifer (Fetter, 2001).

For groundwater extraction purposes, a well sorted, coarse grained soil type is favored over cohesive, clay rich sediments. This is because a coarser grained soil has a greater hydraulic conductivity that allows a more efficient water extraction. Because particle size and sorting has a high impact on whether or not a soil type is favorable, the SGU soil map has been modified and condensed on a basis of particle size and sorting for use in the overlay analysis (Fig. 7A).

#### *3.2.3.5 Bedrock lithology*

Storability and extractability of water in the bedrock varies greatly depending on factors such as rock type and grade of weathering and fracturing. The sedimentary successions of Öland include several sedimentary rock types of varying hydrogeological importance.

Karstic weathering is prevalent in the shallow limestone and fractures are clearly observable in field (e.g. Fig. 4) as well as on aerial photos. The underlying alum shale, although fine-grained, is associated with a relatively high yield due to a high abundance of fractures. The alum shale rests atop a dense siltstone and mudstone of low hydrogeological importance. Finally, resting atop the Precambrian quartzite, is the lower Cambrian sandstone of relatively high porosity (Pousette and Möller, 1972).

It should be stated that certain successions are associated with groundwater of poor quality in terms of chemical status. High salinities have been observed in wells extending into the Cambrian sandstone and smell of hydrocarbons and hydrogen sulfide are associated with the alum shale (Pousette and Möller, 1972). However, because the aim of the overlay analysis is formulated to model groundwater potential, chemical quality of the water is not integrated as a factor in the analysis. This is instead discussed further below.

The lithology map (Fig. 7B) used in the overlay analysis is modified from the SGU lithology map (compare with Fig. 3A), where several limestone units are condensed into a single unit.

### *3.2.3.6 Lineament density*

Secondary permeability, in contrast to primary permeability, is developed after the rock is already formed. Tectonic movements can cause brittle deformation of the bedrock with fracture zones as a result. The fractures, especially in sedimentary bedrock, can in turn be enlarged through dissolution from meteoric flushing, thus increasing the secondary permeability further (Fetter, 2001). Lineament density is a measurement of how frequently fractures are occurring within an area. This is an important factor because significant volumes of water may be stored in, and extracted from fractured bedrock.

The lineament density map used in this study (Fig. 7C), was created in two steps. First, fracture zones already mapped by SGU were extracted from the dataset '*Grundvatten, 1:250 000*' into a new dataset.

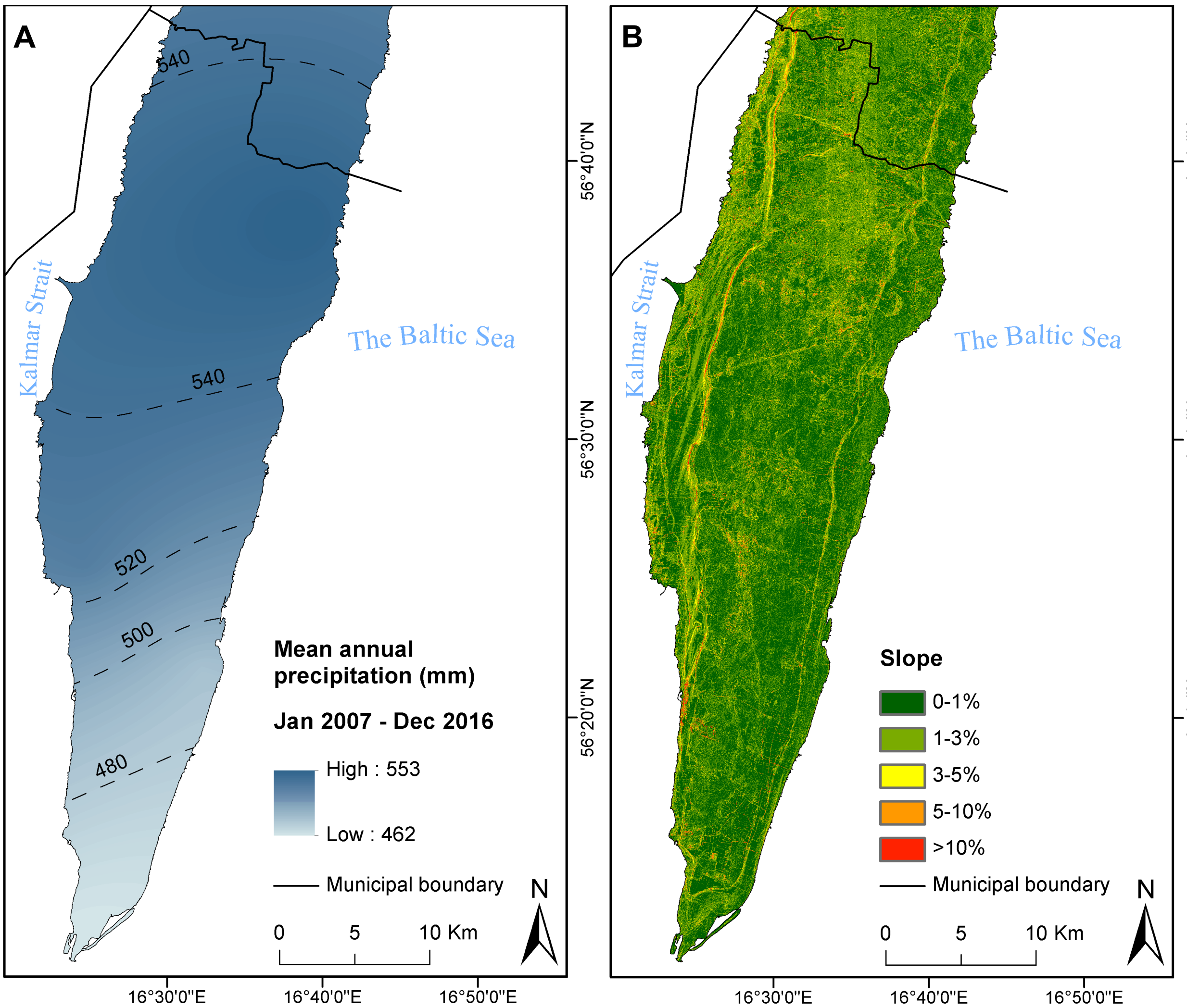



*Fig. 6*. Maps showing **A**. Mean annual precipitation in millimeters for Mörbylånga Municipality, created with data acquired from SMHI under the SMHI Open Data License, and **B**. Slope in percent, created with LIDAR data from GSD-Höjddata, grid 2+ © Lantmäteriet.

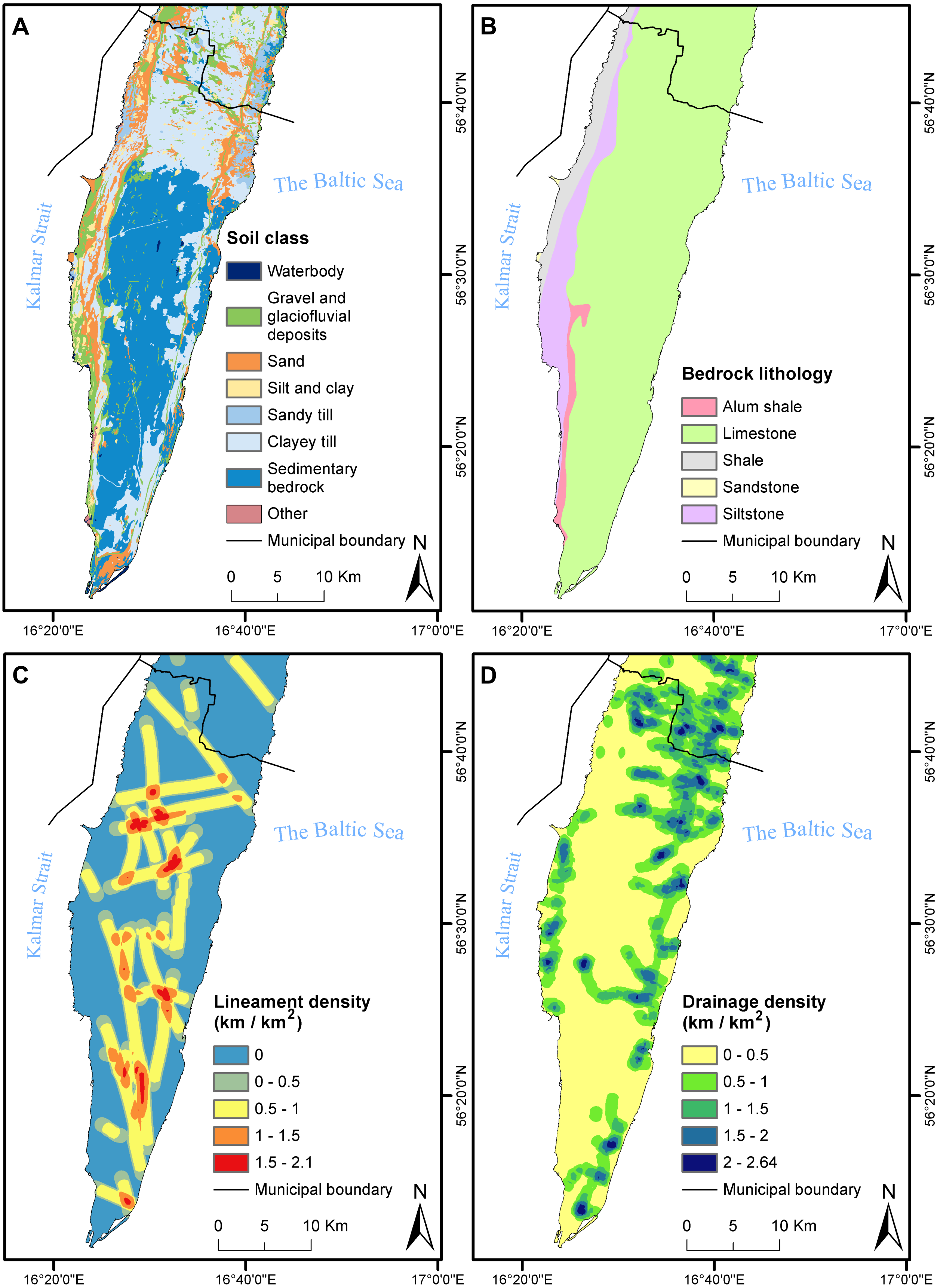



*Fig. 7*. Maps showing **A**. Soil types, created with data from SGU Jordarter, 1:25 000 – 1:100 000 © SGU., **B**. major lithological bedrock units, created with data from SGU Bergarter, 1:1 000 000 © SGU., **C**. tectonic fractures expressed as lineament density, created with data from SGU Grundvatten, 1:250 000 © SGU and **D**. drainage density, created with data from GSD-Terrängkartan © Lantmäteriet.

Secondly, additional fracture zones not already mapped by SGU were added to the new dataset by means of manual mapping with assistance of aerial photos and LiDAR data. The final map for use in the overlay analysis was created using the *Spatial Analyst* tools in ArcGIS.

#### *3.2.3.7 Drainage density*

Drainage infers the movement of water from one area (or watershed) into an adjacent area, thus decreasing the water volume of the initial area. Drainage systems occur naturally as streams and artificially as constructed dikes for agricultural purposes, and are fed by surface runoff and from discharge of groundwater. Although streams can periodically, during flooding events, as well as in arid regions, recharge the groundwater, they are generally associated with groundwater discharge, i.e. the loss of groundwater (Fetter, 2001). It is therefore important, when modeling groundwater potential, to take in consideration adjacent drainage systems and their delimiting effects on the groundwater recharge potential of an area (Edet et al., 1998; Hsin-Fu et al., 2009).

By extracting streams and dikes from the dataset '*GSD-Terrängkartan*' and importing them to a new dataset, the drainage density map (Fig. 7D) used in the overlay analysis could be created using the *Spatial Analyst* tools in ArcGIS.

#### *3.2.3.8 Scoring and weighing of parameters with influence on groundwater recharge*

The datasets were prepared by subdividing values into ranges or units. The units were then assigned a score from 0–100 according to their influence on groundwater recharge potential, where < 50 represents a negative influence, 50 a neutral, or no influence and > 50 a positive influence (Table 2). Each dataset was then assigned a weight according to their relative influence on groundwater recharge potential, where the sum of all weights equals one hundred percent (see Table 9 in Results, next chapter). Also, in order to demonstrate how alternate weights impact the final analysis result, two more analyses were run with slightly altered weights (Appendix 4).

### 3.2.4 Watershed delineation and mapping depth to alum shale

In addition to the GIS overlay analysis, two other maps were created using the *Spatial Analyst* tools on LiDAR data in ArcGIS.

The watersheds map was created using the *Spatial Analyst: Basins* tool. This tool runs automated watershed delineation analyses on digital elevation models by computing flow direction for all cells in a raster dataset. This way, every cell in a raster dataset will form part of a watershed, small or large. Watersheds > 1 km$^2$ are highlighted in the map (Appendix 5).

SGU provided for this study a raster dataset showing the top surface of the alum shale formation on Öland in meters above sea level (SGU 2013b, unpublished report). By subtracting this dataset from the LiDAR data in the ArcGIS raster calculator accordingly, a new raster dataset was created, showing the depth to the alum shale top surface in meters below ground level (Appendix 6). Contour lines for every five meters below ground level were added to the map. Due to the high resolution of the LiDAR data, the lines were jagged and hampered the usability of the map. To counter this, the contour lines were smoothened out with the *Focal Statistics* tool, using mean values.

*Table. 2.* Categorization and scoring of factors with influence on groundwater recharge potential.

| Factor | Range or unit | Score |
|---|---|---|
| Precipitation (mm) | | |
| | 462 — 480 | 80 |
| | 480 — 500 | 85 |
| | 500 — 520 | 90 |
| | 520 — 540 | 95 |
| | 540 — 553 | 100 |
| Slope (%) | | |
| | 0 — 1 | 100 |
| | 1 — 3 | 85 |
| | 3 — 5 | 65 |
| | 5 — 10 | 50 |
| | > 10 | 20 |
| Soil | | |
| | Waterbody | 100 |
| | Gravel and glaciofluvial deposits | 70 |
| | Sand | 65 |
| | Silt and clay | 10 |
| | Sandy till | 50 |
| | Clayey till | 20 |
| | Sedimentary bedrock | 50 |
| | Other | 50 |
| Bedrock lithology | | |
| | Alum shale | 40 |
| | Limestone | 70 |
| | Shale | 40 |
| | Sandstone | 50 |
| | Siltstone | 40 |
| Lineament density (km / km$^2$) | | |
| | 0 | 50 |
| | 0 — 0.5 | 60 |
| | 0.5 — 1 | 70 |
| | 1 — 1.5 | 80 |
| | 1.5 — 2.1 | 90 |
| Drainage density (km / km$^2$) | | |
| | 0 — 0.5 | 90 |
| | 0.5 — 1 | 70 |
| | 1 — 1.5 | 50 |
| | 1.5 — 2 | 40 |
| | 2 — 2.64 | 30 |

# 4 Results

## 4.1 Groundwater quality in the municipal water catchments

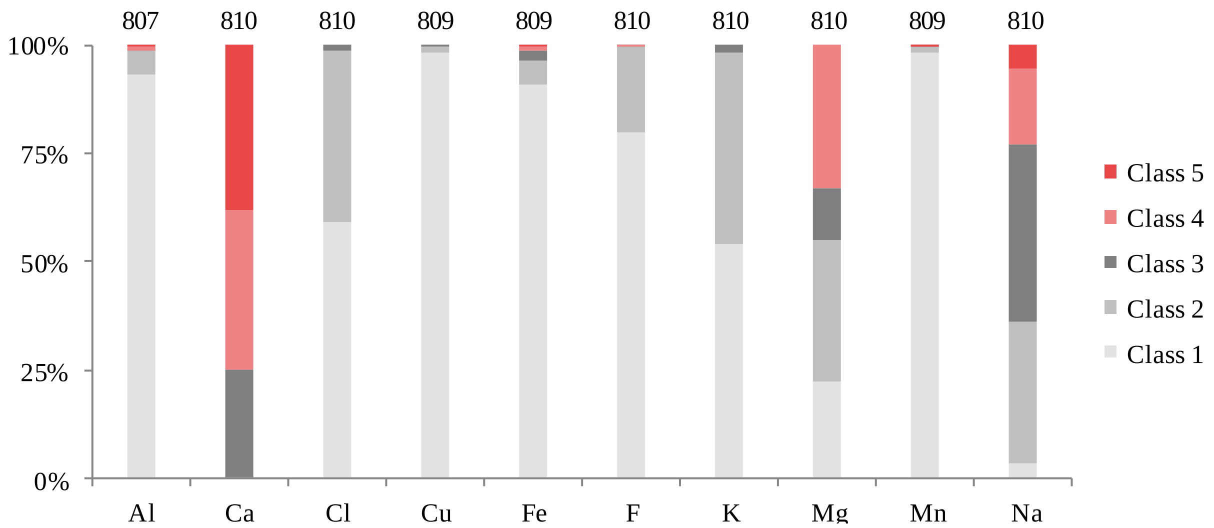
Approximately 800 groundwater chemical analyses have been processed and concentrations for 25 physio-chemical and microbiological parameters are presented in tables 3–5. Each parameter is shown with a maximum, minimum, mean, median and standard deviation value. In addition, for the purpose of comparison, guideline values from SGU 2013:01 are shown beneath each parameter respectively. Also shown, where applicable, are guideline values from SLVFS 2001:30.

Below each table is a stacked chart, showing the distribution of measured concentrations for each parameter according to the SGU 2013:01 classification system. The charts show the amount of samples included in the statistics and how many of the samples, in percent, that falls in each of the classes defined in SGU 2013:01.

Furthermore, concentrations of uranium, lead, arsenic, boron and nickel in end-user collection samples are shown in the graphs attached in appendix 1. These graphs show measured concentrations over the studied

*Table 3*. Groundwater chemical parameters from Mörbylånga municipal water catchments and their relation to the classification system presented in SGU 2013:01. Sample period from January 2008 – February 2017. Below is a stacked chart showing the distribution of chemical parameters according to guideline values in SGU 2013:01. Numbers above each stack represents amount of samples for each parameter. *SLVFS 2001:30 guideline values.

| | Al mg/l | Ca mg/l | Cl mg/l | Cu mg/l | Fe mg/l | F mg/l | K mg/l | Mg mg/l | Mn mg/l | Na mg/l |
|---|---|---|---|---|---|---|---|---|---|---|
| Maximum | 1 | 190 | 91 | 0.81 | 2.2 | 3.5 | 7.9 | 21 | 0.55 | 240 |
| Minimum | < 0.001 | < 0.2 | 3.5 | < 0.02 | < 0.02 | < 0.2 | 1 | < 0.5 | < 0.01 | < 0.5 |
| Mean | 0.015 | 89 | 20 | 0.021 | 0.054 | 0.28 | 2.9 | 6.7 | 0.015 | 31 |
| Median | < 0.001 | 87 | 17 | < 0.02 | < 0.02 | < 0.2 | 2.7 | 2.8 | < 0.01 | 15 |
| Std. Dev. | 0.061 | 37 | 10 | 0.028 | 0.12 | 0.17 | 1.7 | 5.8 | 0.024 | 34 |
| Error range | 20% | 10% | 10% | 10% | 10% | 10% | 10% | 15% | 15% | 15% |
| Number of samples | 807 | 810 | 810 | 809 | 809 | 810 | 810 | 810 | 809 | 810 |
| SLVFS* | 0.1 | 100 | 100 | 2 | 0.2 | 1.5 | | 30 | 0.05 | 100 |
| SGU Class | | | | | | | | | | |
| 1 | < 0.01 | < 10 | < 20 | < 0.02 | < 0.1 | < 0,4 | < 3 | < 2 | < 0.05 | < 5 |
| 2 | 0.01–0.05 | 10–20 | 20–50 | 0.02-0.2 | 0.1–0.2 | 0.4–0.8 | 3–6 | 2–5 | 0.05-0.1 | 5–10 |
| 3 | 0.05–0.1 | 20–60 | 50–100 | 0.2–1 | 0.2–0.5 | 0.8–1.5 | 6–12 | 5–10 | 0.1–0.3 | 10–50 |
| 4 | 0.1– 0.5 | 60–100 | 100-300 | 1–2 | 0.5–1 | 1.5–4 | 12–50 | 10–30 | 0.3–0.4 | 50–100 |
| 5 | ≥ 0.5 | ≥ 100 | ≥ 300 | ≥ 2 | ≥ 1 | ≥ 4 | ≥ 50 | ≥ 30 | ≥ 0.4 | ≥ 100 |
| SGU 2013:01 | | | | | | | | | | |



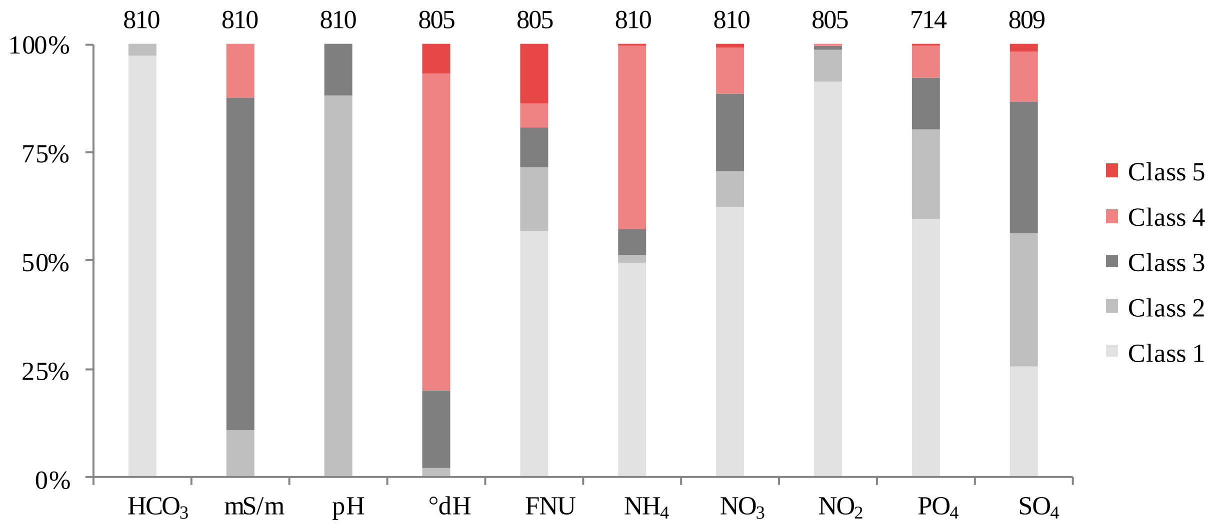
period, for the six greatest municipal water catchments. Also shown, in appendix 2, are the 28 different types of pesticides analyzed in end-user collection samples, of which none was found above detection limit.

Significant concentrations of calcium, magnesium and sodium (Table 3) are detected in the groundwater. Ammonium, nitrate, phosphate and sulfate (Table 4) occurrences are detected in notable concentrations. Microorganisms (Table 5) are found in more than half of the analyzed samples. Although occurrences of microorganisms are quite common, coliform bacteria are rarely encountered. Total hardness is in general high, nearly all samples show values above 4,9 °dH (Class 3 –5, Table 4). Conductivity (Table 4) of the water and Chemical oxygen demand ($COD_{Mn}$, Table 5) is over all moderate. Concentrations of the remaining analyzed elements are low.

Analyses of end-user drinking water (Appendix 1) reveal low, but detectable concentrations of uranium in Tveta, Resmo, S Möckleby and Grönhögen water catchments. Lead concentrations are occasionally high

*Table 4*. Groundwater physiochemical parameters from Mörbylånga municipal water catchments and their relation to the classification system presented in SGU 2013:01. Sample period from January 2008 – February 2017. Below is a stacked chart showing the distribution of physiochemical parameters according to guideline values in SGU 2013:01. Numbers above each stack represents amount of samples for each parameter.*SLVFS 2001:30 guideline values.

| | **Alkalinity mg $HCO_3$/l** | **Conductivity mS/m** | **pH** | **Total hardness, °dH** | **Turbidity FNU** | **$NH_4$ mg/l** | **$NO_3$ mg/l** | **$NO_2$ mg/l** | **$PO_4$ mg/l** | **$SO_4$ mg/l** |
|---|---|---|---|---|---|---|---|---|---|---|
| Maximum | 830 | 130 | 8.5 | 27 | 160 | 1.5 | 62 | 0.29 | 0.6 | 200 |
| Minimum | 110 | < 2 | 7 | < 0.5 | < 0.1 | < 0.01 | < 0.44 | < 0.007 | < 0.02 | < 1 |
| Mean | 326 | 62 | 7.9 | 14 | 3.9 | 33 | 6.36 | 0.009 | 0.035 | 27.9 |
| Median | 330 | 62 | 8 | 15 | 0.32 | 0.07 | < 0.44 | < 0.007 | < 0.02 | 21 |
| Std. Dev. | 72 | 11 | 0.3 | 4.7 | 11 | 0.35 | 10.7 | 0.014 | 0.039 | 26.2 |
| Error range | 10% | 10% | 0.2 | | 20% | 15% | 20% | 15% | 30% | 15% |
| Number of samples | 810 | 810 | 810 | 805 | 805 | 810 | 810 | 805 | 714 | 809 |
| SLVFS* | | 250 | | | 1.5 | 0.5 | 50 | 0.5 | | 100 |
| Class | | | | | | | | | | |
| 1 | > 180 | < 25 | > 8.5 | < 2.1 | < 0.5 | < 0.05 | < 2 | < 0.01 | < 0.02 | < 10 |
| 2 | 60–180 | 25–50 | 7.5–8.5 | 2.1–4.9 | 0.5–1.5 | 0.05–0.1 | 2–5 | 0.01-0.05 | 0.02-0.04 | 10–25 |
| 3 | 30–60 | 50–75 | 6.5–7.5 | 4.9–9.8 | 1.5–3 | 0.1–0.5 | 5–20 | 0.05–0.1 | 0.04–0.1 | 25–50 |
| 4 | 10–30 | 75–150 | 5.5–6.5 | 9.8–21 | 3–6 | 0.5–1.5 | 20–50 | 0.1–0.5 | 0.1–0.6 | 50–100 |
| 5 | ≤ 10 | ≥ 150 | ≤ 5.5 | ≥ 21 | ≥ 6 | ≥ 1.5 | ≥ 50 | ≥ 0.5 | ≥ 0.6 | ≥ 100 |
| SGU 2013:01 | | | | | | | | | | |



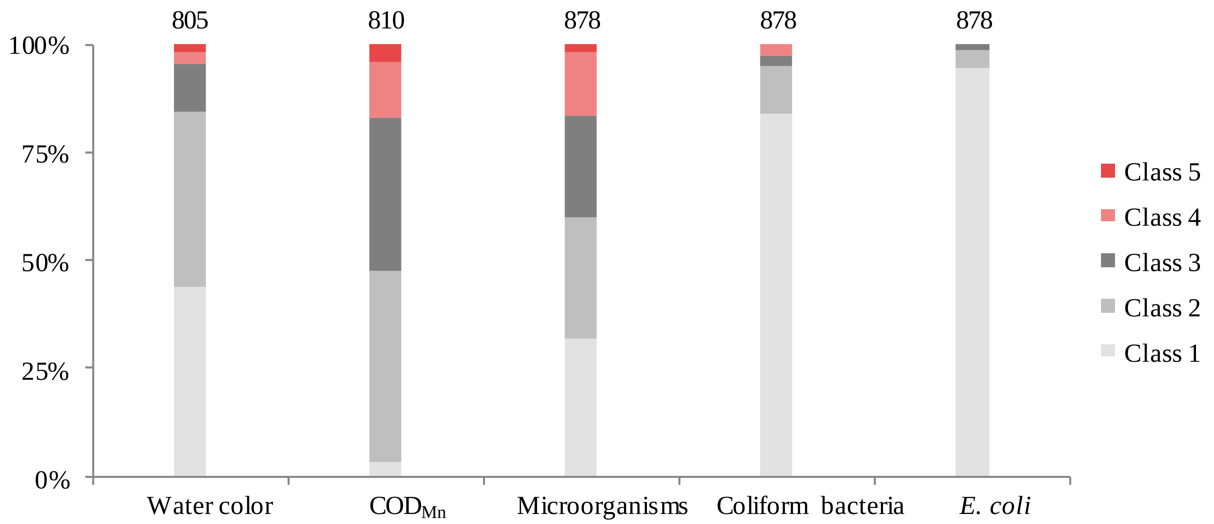
in Tveta water catchment. The other five municipal water catchments show low lead concentrations for the studied period. However, in S Möckleby anomalously high lead concentrations were detected in April 2016 when compared to earlier samples. Arsenic concentrations are generally below detection limit, although a temporary increase in concentrations occurred in Tveta during 2014. Boron is found in notable concentrations in water catchments Grönhögen, S Möckleby and Segerstad. The measured boron concentrations are generally following a stable pattern throughout the studied period. However, a significant decrease in concentration compared to previous measurements was recorded in Grönhögen in October 2016. Nickel was detected occasionally during the studied period in Tveta water catchment, with concentrations reaching as high as 13 µg/l (Class 4) in December 2015 (although still below the SLVFS 2001:30 guideline value of 20 µg/l for drinking water).

## 4.2 Groundwater quality in private wells

Data from approximately 650 analyses have been processed for 27 different parameters and are presented in the tables below (Table 6–8). Note that certain param-

*Table 5*. Groundwater physiochemical and microbiologial parameters from Mörbylånga municipal water catchments and their relation to the classification system presented in SGU 2013:01. Sample period from January 2008 – February 2017. Below is a stacked chart showing the distribution of physiochemical and microbiological parameters according to guideline values in SGU 2013:01. Numbers above each stack represents amount of samples for each parameter. *SLVFS 2001:30 guideline values.

| | **Color mg Pt/l** | **$COD_{Mn}$ mg $O_2$/l** | **Microorganisms cfu/100 ml** | **Coliform bacteria cfu/100 ml** | ***E.coli* cfu/100 ml** |
|---|---|---|---|---|---|
| Maximum | 310 | 12 | 1700 | 85 | 34 |
| Minimum | < 5 | < 0.24 | < 1 | < 1 | < 1 |
| Mean | 11 | 2.6 | 44 | 2.6 | 1.3 |
| Median | 6 | 2 | 5 | 1 | < 1 |
| Std. Dev. | 17.6 | 1.9 | 143 | 7 | 2,3 |
| Error range | 20% | 20% | | | |
| Number of samples | 805 | 810 | 878 | 878 | 878 |
| SLVFS* | | | 100 | 10 | 1 |
| Class | | | | | |
| 1 | < 5 | < 0.5 | < 1 | < 1 | < 1 |
| 2 | 5–15 | 0.5–2 | 1–10 | 1–10 | 1–10 |
| 3 | 15–30 | 2–4 | 10–100 | 10–50 | 10–20 |
| 4 | 30–60 | 4–8 | 100–1000 | 50–500 | 20–100 |
| 5 | ≥ 60 | ≥ 8 | ≥ 1000 | ≥ 500 | ≥ 100 |
| SGU 2013:01 | | | | | |



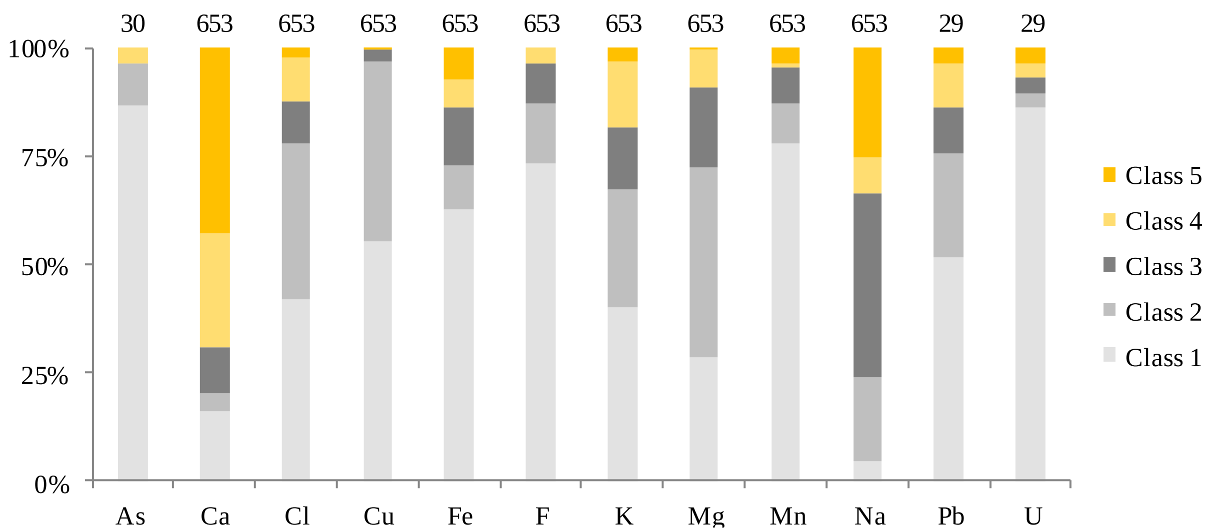
eters analyzed for in the private well data (e.g. arsenic and lead) are not found in tables 3–5 for the municipal well data. The municipal office of Mörbylånga instead analyzes these parameters on end-user drinking water (as shown in appendix 1).

Additionally, the data collected from private wells was georeferenced in this study for the purpose of creating maps showing concentration and distribution of physiochemical and microbiological parameters in the municipality. The data forms the base of 26 maps created in ArcGIS and is, due to the amount of maps created, presented in appendix 3.

High concentrations of calcium and sodium were detected, as well as notable concentrations of potassium, magnesium, lead (Table 6), ammonium, nitrate, phosphate and sulfate (Table 7). Significant concentrations of microorganisms and coliform bacteria were also detected. Microorganisms were found in nearly all samples and coliform bacteria were found in 70 percent of the samples (Table 8). In 20 percent of the samples concentrations of coliform bacteria exceeded the 500 cfu/100ml guideline value (Class 5). Although absent in most of the samples, concentrations of *Esch-*

*Table 6*. Groundwater chemical parameters from private wells and their relation to the classification system presented in SGU 2013:01. Sample period from January 2008 – February 2017. Below is a stacked chart showing the distribution of chemical parameters according to guideline values in SGU 2013:01. Numbers above each stack represents amount of samples for each parameter. *SLVFS 2001:30 guideline values.

| | **As µg/l** | **Ca mg/l** | **Cl mg/l** | **Cu mg/l** | **Fe mg/l** | **F mg/l** | **K mg/l** | **Mg mg/l** | **Mn mg/l** | **Na mg/l** | **Pb µg/l** | **U µg/l** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Maximum | 5.2 | 310 | 1900 | 3.4 | 9.7 | 3.9 | 190 | 51 | 5.5 | 880 | 18 | 32 |
| Minimum | < 0.2 | < 0.2 | 2.2 | < 0.02 | < 0.02 | < 0.2 | < 1 | < 0.5 | < 0.01 | 2.2 | < 0.05 | < 0.01 |
| Mean | 0.66 | 82 | 51 | 0.055 | 0.30 | 0.41 | 9.05 | 4.30 | 0.08 | 64 | 1.5 | 3.29 |
| Median | 0.23 | 94 | 24 | < 0.02 | 0.036 | 0.2 | 3.9 | 3.1 | 0.01 | 23 | 0.42 | 0.82 |
| Std. Dev. | 0.95 | 51 | 105 | 0.168 | 0.83 | 0.41 | 16.29 | 4.36 | 0.33 | 86 | 3.65 | 6.95 |
| Error range | 15% | 10% | 10% | 10% | 10% | 10% | 10% | 15% | 15% | 15% | 20 | 20% |
| Number of samples | 30 | 653 | 653 | 653 | 653 | 653 | 653 | 653 | 653 | 653 | 29 | 29 |
| SLVFS* | 10 | 100 | 100 | 2 | 0.2 | 1.5 | | 30 | 0.05 | 100 | 10 | |
| Class | | | | | | | | | | | | |
| 1 | < 1 | < 10 | < 20 | < 0.02 | < 0.1 | < 0.4 | < 3 | < 2 | < 0.05 | < 5 | < 0,5 | < 5 |
| 2 | 1–2 | 10–20 | 20–50 | 0.02-0.2 | 0.1–0.2 | 0.4–0.8 | 3–6 | 2–5 | 0.05-0.1 | 5–10 | 0.5–1 | 5–10 |
| 3 | 2–5 | 20–60 | 50–100 | 0.2–1 | 0.2–0.5 | 0.8–1.5 | 6–12 | 5–10 | 0.1–0.3 | 10–50 | 1–2 | 10–15 |
| 4 | 5–10 | 60–100 | 100-300 | 1–2 | 0.5–1 | 1.5–4 | 12–50 | 10–30 | 0.3–0.4 | 50–100 | 2–10 | 15–30 |
| 5 | ≥ 10 | ≥ 100 | ≥ 300 | ≥ 2 | ≥ 1 | ≥ 4 | ≥ 50 | ≥ 30 | ≥ 0.4 | ≥ 100 | ≥10 | ≥ 30 |
| SGU 2013:01 | | | | | | | | | | | | |



*erichia coli*, well above the SLVFS 2001:30 guideline values, was encountered occasionally (Table 8).

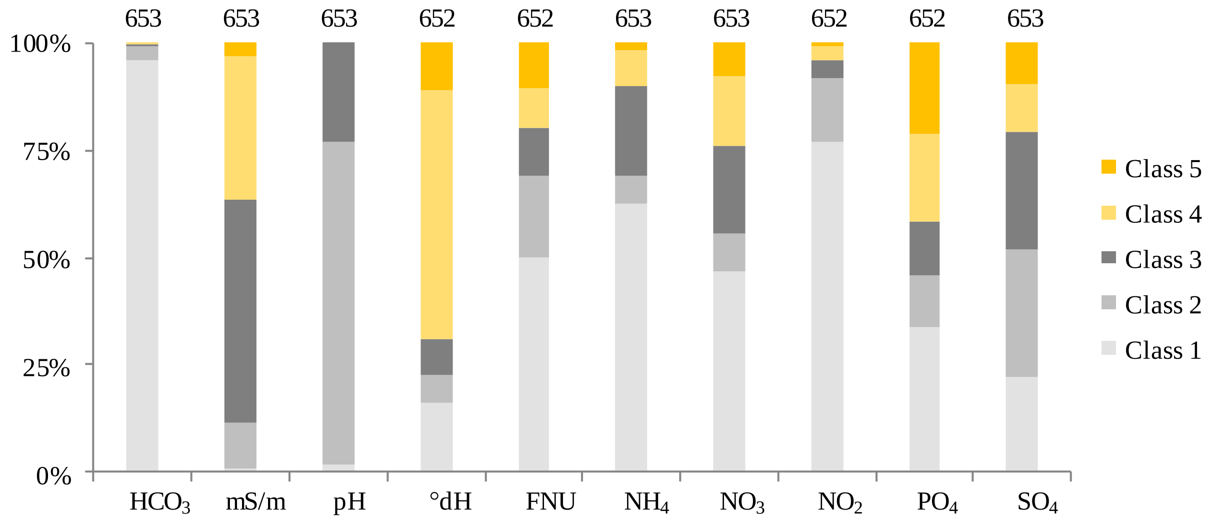
The total hardness is slightly lower than water hardness in municipal wells, although still high (Table 7). Chemical oxygen demand is on par with $COD_{Mn}$ in municipal wells (Table 8). Conductivity of the water is slightly higher in private wells compared to municipal wells (Class 3–5).

Compared to the groundwater quality in municipal wells, concentrations of calcium, magnesium and ammonium are lower in private wells. Concentrations of sodium, nitrate, nitrite, phosphate and sulfate, as well as microorganisms, are higher in private wells compared to municipal wells.

Concentration and spatial distribution of sodium, chloride, sulfate, calcium, magnesium, iron, and ammonium are uniform across the municipality (Appendix 3). Concentrations of nitrate, nitrite, phosphate and potassium, as well as COD, are generally higher in the northern and eastern parts of Mörbylånga. Microorganisms, including coliform bacteria, have been encountered in high concentrations all across the studied area.

*Table 7*. Groundwater physiochemical parameters from private wells and their relation to the classification system presented in SGU 2013:01. Sample period from January 2008 – February 2017. Below is a stacked chart showing the distribution of physiochemical parameters according to guidelines in SGU 2013:01. Numbers above each stack represents amount of samples for each parameter. *SLVFS 2001:30 guideline values.

| | **Alkalinity mg $HCO_3$/L** | **Conductivity mS/m** | **pH** | **Total hardness, °dH** | **Turbidity FNU** | **$NH_4$ mg/l** | **$NO_3$ mg/l** | **$NO_2$ mg/l** | **$PO_4$ mg/l** | **$SO_4$ mg/l** |
|---|---|---|---|---|---|---|---|---|---|---|
| Maximum | 760 | 590 | 9.8 | 47 | 250 | 31 | 490 | 4.3 | 23 | 440 |
| Minimum | 23 | 2 | 6.6 | 0.14 | < 0.1 | < 0.01 | < 0.44 | < 0.007 | < 0.02 | < 1 |
| Mean | 318 | 75 | 7.8 | 12.4 | 3.3 | 0.23 | 15 | 0.03 | 1 | 37 |
| Median | 320 | 68 | 7.8 | 14 | 0.49 | 0.014 | 3.1 | < 0.007 | 0.0535 | 23 |
| Std. Dev. | 89 | 37 | 0.36 | 7.5 | 12.8 | 1.31 | 31 | 0.19 | 2.7 | 46 |
| Error range | 10% | 10% | 0.2 | | 20% | 15% | 20% | 15% | 30% | 15% |
| Number of samples | 653 | 653 | 653 | 652 | 652 | 653 | 653 | 652 | 652 | 653 |
| SLVFS* | | 250 | | | 1.5 | 0.5 | 50 | 0.5 | | 100 |
| Class | | | | | | | | | | |
| 1 | > 180 | < 25 | > 8.5 | < 2.1 | < 0.5 | < 0.05 | < 2 | < 0.01 | < 0.02 | < 10 |
| 2 | 60–180 | 25–50 | 7.5–8.5 | 2.1–4.9 | 0.5–1.5 | 0.05–0.1 | 2–5 | 0.01-0.05 | 0.02-0.04 | 10–25 |
| 3 | 30–60 | 50–75 | 6.5–7.5 | 4.9–9.8 | 1.5–3 | 0.1–0.5 | 5–20 | 0.05–0.1 | 0.04–0.1 | 25–50 |
| 4 | 10–30 | 75–150 | 5.5–6.5 | 9.8–21 | 3–6 | 0.5–1.5 | 20–50 | 0.1–0.5 | 0.1–0.6 | 50–100 |
| 5 | ≤ 10 | ≥ 150 | ≤ 5.5 | ≥ 21 | ≥ 6 | ≥ 1.5 | ≥ 50 | ≥ 0.5 | ≥ 0.6 | ≥ 100 |
| SGU 2013:01 | | | | | | | | | | |



## 4.3 Overlay analyses and other GIS results

As a result of the GIS overlay analysis, a map showing the estimated groundwater potential of Mörbylånga (Fig. 8), was created after scoring and weighing of parameters as described in 3.2.3. The effective weight of each thematic layer is shown in table 9. Two additional groundwater potential maps were also created, with slightly altered weights of influence (Appendix 4). According to the analysis, the maps reveal one area in particular, where the groundwater potential is better than average. The area, in blue, is located on the groundwater divide between Tveta and Resmo municipal water catchments (Fig. 8) and covers approximately 2.5 km$^2$.

Two additional maps, based on LiDAR data, were created in ArcGIS. The watershed map (Appendix 5) shows watersheds 1 km$^2$ and larger, where areas in blue are drained towards Kalmar Strait to the west. Areas in green are drained towards the Baltic Sea to the east. The second map (Appendix 6) shows depth to the alum shale in meters below ground level.

*Table 8*. Groundwater physiochemical and microbiological parameters from private wells and their relation to the classification system presented in SGU 2013:01. Sample period from January 2008 – February 2017. Below is a stacked chart showing the distribution of physiochemical and microbiological parameters according to guidelines in SGU 2013:01 classification system. Numbers above each stack represents amount of samples for each parameter. *SLVFS 2001:30 guideline values.

| | **Color mg Pt/l** | **$COD_{Mn}$ mg $O_2$/l** | **Microorganisms cfu/100 ml** | **Coliform bacteria cfu/100 ml** | ***E.coli* cfu/100 ml** |
|---|---|---|---|---|---|
| Maximum | 270 | 53 | > 53000 | > 3600 | > 2400 |
| Minimum | < 5 | < 0.24 | < 1 | < 1 | < 1 |
| Mean | 17 | 3.11 | 804 | 528 | 32 |
| Median | 8.7 | 1.9 | 180 | 27 | < 1 |
| Std. Dev. | 27 | 3.9 | 2435 | 894 | 215 |
| Error range | 20% | 20% | | | |
| Number of samples | 652 | 653 | 634 | 630 | 632 |
| SLVFS* | | | 100 | 10 | 1 |
| Class | | | | | |
| 1 | < 5 | < 0.5 | < 1 | < 1 | < 1 |
| 2 | 5–15 | 0.5–2 | 1–10 | 1–10 | 1–10 |
| 3 | 15–30 | 2–4 | 10–100 | 10–50 | 10–20 |
| 4 | 30–60 | 4–8 | 100–1000 | 50–500 | 20–100 |
| 5 | ≥ 60 | ≥ 8 | ≥ 1000 | ≥ 500 | ≥ 100 |
| SGU 2013:01 | | | | | |

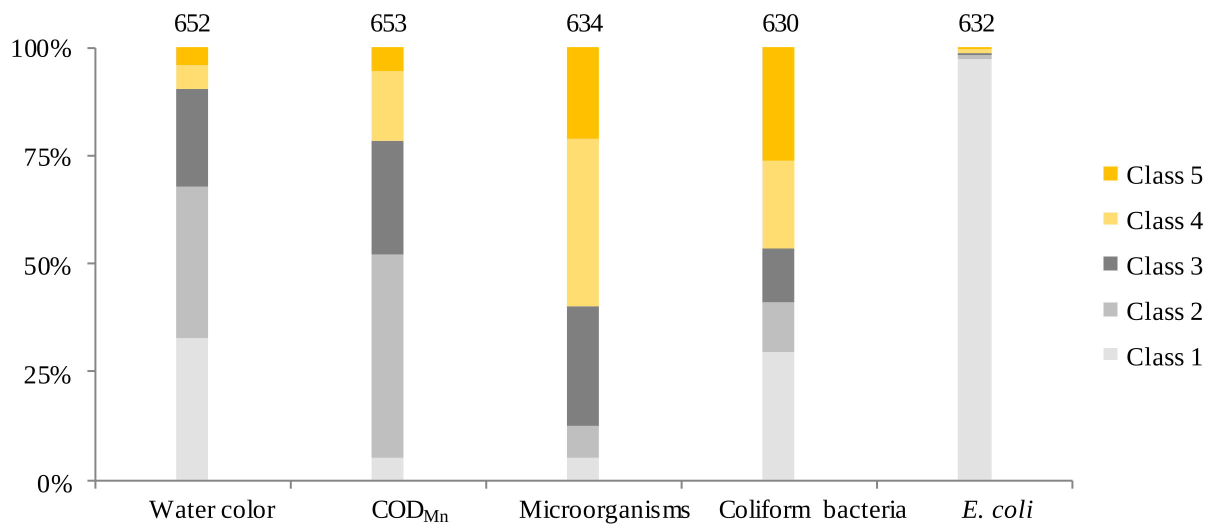


*Table. 9*. Effective weight of each thematic layer after groundwater recharge potential scores have been assigned.

| | **Factor** | | | | | |
|---|---|---|---|---|---|---|
| | Precipitation | Slope | Soil class | Lithology | Lineament density | Drainage density |
| **Weight** | 5% | 15% | 35% | 15% | 20% | 10% |

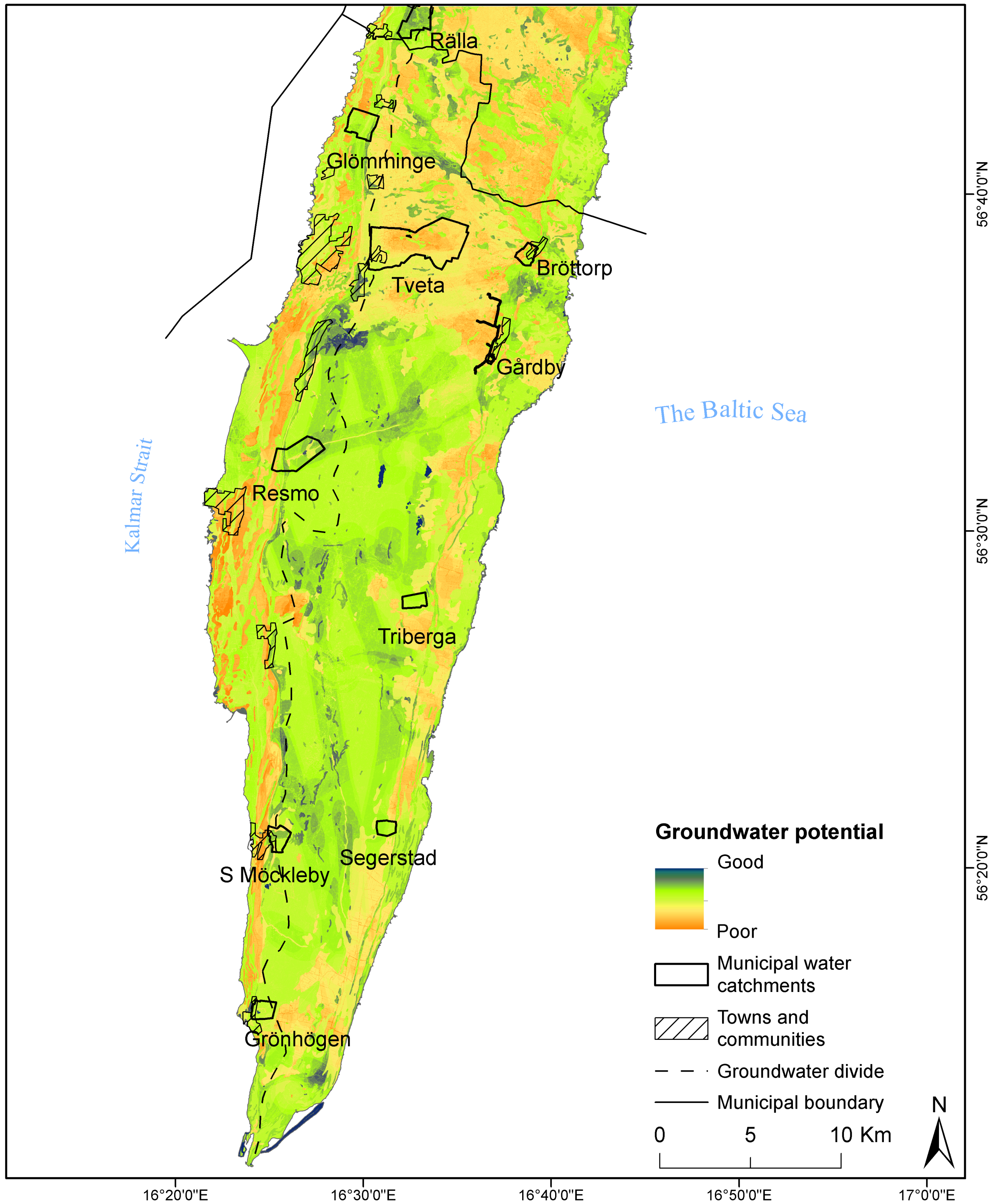



*Fig. 8*. Map showing the estimated groundwater potential of Mörbylånga. Dark blue areas represent zones where multiple positive factors coincide and are deemed the most promising in terms of groundwater recharge. For sense of spatial distribution major towns and communities of Mörbylånga, as well as existing municipal water catchments, are added to the map.

# 5 Discussion

## 5.1 Groundwater chemistry in Mörbylånga municipality

The results presented in this study show a connection between the groundwater chemistry and geological circumstances, as well as land use in Mörbylånga. In general, a better groundwater quality is found in municipal wells. This is probably because municipal wells are more frequently drilled into the sedimentary bedrock and better sealed off from inflow of surface water. This is supported by higher calcium- (Table 3) and lower microbiological (Table 5) concentrations in the municipal wells. Private wells are to a higher degree also affected by inflow of saline water (Table 6), although this could also be the case in certain municipal wells (Fig. 9). Influence from agricultural activity is present in groundwater in terms of increased levels of nitrate, nitrite and phosphate in both municipal and private wells, although private wells show higher concentrations of the nutrients (Table 7). Pesticides have not been detected in municipal end-user drinking water (Appendix 2). Although pesticide content has not been analyzed in private wells, wells located near cultivated land could possibly be at risk, especially where increased levels of nutrients have been found. Extending future analyses for selected wells, to also examine pesticide content, would provide important knowledge on whether pesticides occur in problematic concentrations or not. A suitable strategy for such an inventory may be to, in cooperation with farmers, catalogue what pesticides have been used, and to target wells where previous measurements have shown high concentrations of nutrients for extended analyses.

### 5.1.1 Characteristics and evaluation of the groundwater chemistry

The groundwater chemistry in Mörbylånga is largely influenced by geology and land use. A high microbiological presence is found in private wells and both private- and municipal wells are at risk of salt water intrusion. Geologically associated elements present in moderate to high concentrations in most wells are calcium, magnesium and sulfate. A comparison of two wells in Grönhögen water catchment reveal significant differences in sulfate concentration (Fig. 9A). Although both wells extend into the alum shale, sulfate concentrations of well #1 are steady below 10 mg/l for most of the studied period. The reason for this could possibly be due to the positioning of well #1, which is adjacent to a water filled open pit limestone quarry. This would imply that water in well #1 is to a lesser extent than well #5 in influenced by the alum shale.

Also associated with the alum shale are low to intermediate concentrations of lead, uranium and arsenic. Ammonium-, nitrate-, nitrite- and phosphate occurrences in the groundwater are associated with agriculture and other anthropogenic activity (Naturvårdsverket, 2006; SGU 2013a). Although these chemical compounds are most common in private wells, they also occur to varying degrees in municipal wells. Salt water influence is associated with high levels of sodium and chloride. Although these elements are present to some degree in most wells, few of them fall into the highest category (Class 5), where inflow of salt water from the Baltic Sea is the most likely cause of elevated salinity. The microbiological presence, as determined by the parameters microorganisms, coliform bacteria and *E. coli*, is greater in private wells than municipal wells. As stated above (5.1), municipal wells, more often than private wells, are drilled into the sedimentary bedrock and are better sealed off from surface inflow. This is supported by an almost complete absence of coliform bacteria in municipal wells, whereas in private wells, nearly half of the analyzed samples fall into class 4 or class 5, indicating leakage of surface water into the wells. Indeed, the water protection areas surrounding the municipal groundwater catchments may also have a significant impact regarding the absence of microorganisms in municipal wells. Presence of *E. coli*, found in problematic levels in a few of the private wells, can indicate inflow from a nearby damaged sewage pipe. For wells in proximity to farms where livestock is kept, occurrences of *E. coli* can also be caused by leakage of surface water and manure into the well (Krapac et al., 2002).

### 5.1.2 Geological influence on the groundwater chemistry

The groundwater chemistry on Öland is heavily influenced by the chemical composition of the main sedimentary successions. Traces of the Cambrian alum shale and the Ordovician limestone are present to varying degree in nearly every groundwater sample.

The Ordovician limestone succession, covering the major part of Öland, shows clear evidence of chemical weathering (Pousette & Möller, 1972). The weathering process of calcite and aragonite [$CaCO_3$], the main constituents of limestone, occurs in the following dissolution reaction:

$$CaCO_3 + CO_2 + H_2O \rightarrow Ca^{2+} + 2HCO_3^-$$

This reaction, over time, results in calcium enrichment in the groundwater. Weathering of dolomite [$CaMg(CO_3)_2$] and magnesium calcite ($Mg^{2+}$ substitutes $Ca^{2+}$) explains the presence of magnesium in the groundwater.

The Cambrian alum shale is associated with a wide variety of elements, including most metals found in the groundwater on Öland. Bituminous limestone (stinkstone) and kerogen is also associated with the alum shale, adding to the complexity of the groundwater chemistry caused by the alum shale.

The alum shale weathers easily, resulting in generation of $H_2SO_4$ and free metal cations (Falk et al., 2006). The sulfuric acid in turn reacts to destabilize the kerogen and silicate minerals, releasing more elements into the groundwater (Jeng, 1991, 1992). Sulfate occurrences in the groundwater are the most distinct signature of the alum shale and the measured sulfate concentration, in any well, can be seen as the amount of influence the alum shale formation plays on the groundwater chemistry of that well. Occurrences of lead, uranium, arsenic and nickel in the groundwater (Appendix 1) are also linked to the alum shale (Erlström, 2016). Weathering and leaching of old lead pipes used during the 1960's–1980's may, locally, also be a source of elevated lead concentrations in the groundwater (P. Dahlqvist, 2018, pers. comm., 16 May). Unsafe lead concentrations (Class 5) are measured in a few of the private wells. Also in municipal wells, time-series data reveal a variation in lead concentration, reaching as high as class 4 for the studied period (Appendix 1). The alum shale itself is enriched in vanadium (Westergård et al., 1944) and zink (Erlström, 2016). Although concentrations of vanadium and zinc in the groundwater were not analyzed for in this study, Falk et al. (2006) found lower metal concentrations in weathered alum shale compared to intact, un-weathered shale, suggesting leaching to and enrichment of vanadium and zinc in the groundwater. The occurrence of potassium in groundwater, although a constituent of alum $[KAl(SO_4)_2 \cdot 12H_2O]$, is more

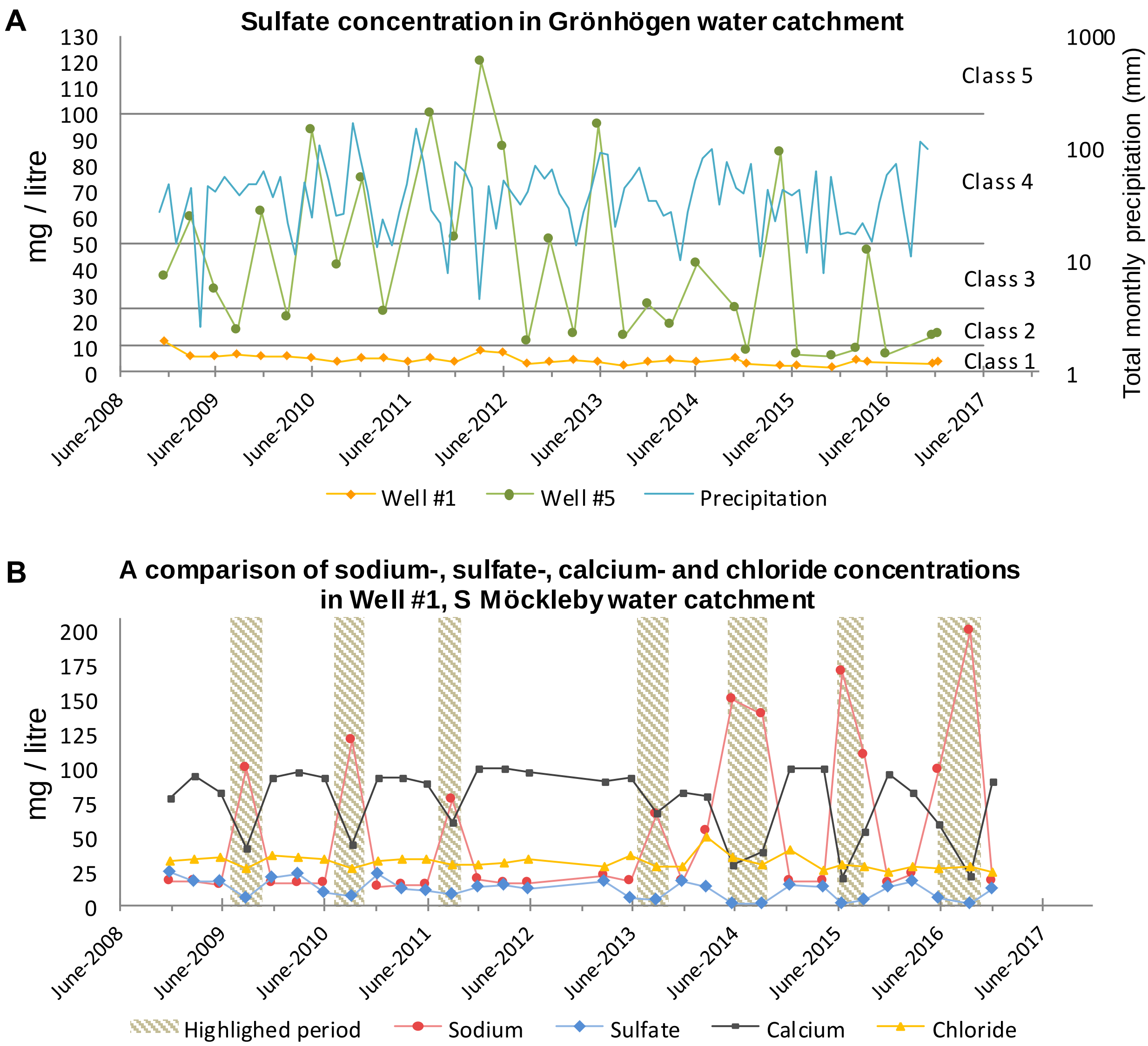



*Fig. 9.* **A**. Charts showing two distinct characteristics in the sulfate concentration sampled from separate wells within the same municipal water catchment, and **B**. a comparison of sodium-, sulfate-, calcium and chloride concentrations in well #1, S Möckleby water catchment. Sodium concentration increases significantly during summers and autumns alongside a concurrent decrease in sulfate– and calcium concentrations. In contrast, chloride concentrations remain stable for the studied period.

likely linked to the use of fertilizers from agricultural activities. This is supported by the overall higher potassium concentrations measured in private wells, compared to municipal wells. Notable boron concentrations are measured in the municipal water catchments Grönhögen, S. Möckleby and Segerstad (Appendix 1). The origin of the boron occurrences in groundwater on Öland is still up for debate. However, elevated boron concentrations have been encountered in the groundwater of similar sedimentary successions in Scania and on the island of Gotland. There, presence of boron is thought to be connected to certain marlstone successions (SGU 2013a), hence suggesting a geological source for the boron occurrences. On the other hand, recent studies have also found elevated boron concentrations to be linked with leakage of sewer water into the groundwater (Held et al., 2006). Because the municipal wells, where notable boron occurrences have been measured, does not show elevated concentrations of microorganisms or nutrients, the above mentioned circumstances clearly favor a geologic origin for the boron occurrences on Öland. However, the possibility of an anthropogenic source should not be ruled out based on these assumptions.

#### 5.1.3 Land use and distribution of associated elements

Presence of ammonium, nitrate, nitrite and phosphate in groundwater is typically associated with the use of fertilizers in agriculture (Naturvårdsverket, 2006; SGU 2013a). In Mörbylånga, rainfall or irrigation water containing dissolved ions are either discharged to the Baltic Sea or percolates into the ground, enriching the groundwater in these substances. Because farming is practiced both east and west of the main groundwater divide, the distribution of samples where a high nutrient content are found, is rather evenly spread along both coasts. However, slightly higher nutrient concentrations are found in the northern and eastern parts of the municipality (Appendix 3). Nitrate, nitrite and phosphate found in higher concentrations in private wells (Table 7) compared to municipal wells (Table 4), suggests that private wells are more often located near cultivated land than municipal wells. Ammonium, found in slightly higher concentrations in municipal wells (Table 4), and the less mobile ion of the four mentioned, can also be associated with leaking sewage water. However, this suggestion is in conflict with the low occurrences of microorganisms measured for the studied period. Why ammonium concentrations are higher in municipal wells could, instead, be because they often extend deeper than private wells and more frequently are in contact with the alum shale. The alum shale on Öland is rich in organic matter (8–9% TOC, Erlström, 2014) and anaerobic degradation of organic matter is a natural source for ammonium in groundwater (Böhlke et al., 2006).

#### 5.1.4 Saltwater contamination

Coastal areas are commonly considered at risk of saltwater intrusion (Melloul and Goldenberg, 1997). Because pumping generates a flow towards the well, salt water from the sea may be drawn into the aquifer due to a reversed groundwater gradient and reach the well through the porous rock from which freshwater is being produced. Saltwater can also be encountered in sedimentary bedrock that is no longer in contact with the sea. This occurs when fossil saltwater from a marine sedimentary environment is still present in the formation (Fransson et al., 2004). In Mörbylånga municipality, saltwater has mainly been associated with the Lower Cambrian sandstone (Pousette and Möller, 1972). However, results presented in this paper suggest that formations superposing the sandstone may also be prone to saltwater intrusion. This is especially true in times when a high demand of fresh water coincide with a net negative groundwater recharge. Data collected over time from a well in Södra Möckleby water catchment, show a sink in sulfate and calcium with concurrent peaks in sodium concentrations during late summer–early autumn for the studied period (Fig. 9B). Because calcium is associated with the limestone bedrock, and the alum shale is a known source for sulfate in groundwater (e.g. SGU 2013a), this recurring pattern could indicate an alteration in water chemistry due to salt water intrusion. Especially at times when the recharge rate in the fresh water magazine cannot keep up with the demand, such as during summers and autumns. On the contrary however, chloride concentrations, which can also be expected at high concentrations during periods of saltwater intrusion, rests fairly stable around 30–40 mg/l for the studied period. Thus, a source other than saltwater intrusion cannot be ruled out for this observation.

Given that this effect is not as pronounced in other wells within the same water catchment, the end consumer will probably not experience any problem related to elevated sodium levels, due to mixing of water from different wells. A more detailed study of wells where high sodium concentrations are measured, could contribute important knowledge when planning for future wells in coastal areas.

### 5.2 Design of the groundwater chemistry maps

An early vision for this study was to create two categories of groundwater chemistry maps: the groundwater chemistry in soil and the groundwater chemistry in sedimentary bedrock. An option to further divide the bedrock groundwater category on basis of which sedimentary succession the wells extended into was also discussed. All of the above, however, proved difficult. Upon examination, most wells were not recorded in the SGU Wells Archive. This is probably because many wells still in use today, were dug or drilled before the law on drilling records (SFS 1975:424) was passed. Only in certain cases did the records match and in few of those, more than one well were registered on the same property, thus making it problematic to know with certainty which specific well the data was collected from.

Because no reliable way of separating the groundwater chemistry data, on basis of whether it was collected from the soil or the bedrock, could be found within the timeframe of this study, the groundwater chemistry maps were created containing data from both categories. It is therefore important when reading the maps to take in consideration not only annual and seasonal variations during the studied period, but also that the data is collected from groundwater in both soil and bedrock.

With the volume of data collected, it would be possible to create groundwater chemistry maps for all four seasons, although with less data points on each map. However, because the primary goal of the maps is to show whether certain elements exist in problematic concentrations, and if so, where, it is reasonable to present the results for each parameter in its entirety.

Concerning the possibility to categorize the data on basis of whether it was collected from the soil or the bedrock, a few options can be considered for future endeavors. The more reliable alternative is performing an inventory of the wells where the data for this study was collected from. This would have to be done in collaboration with Mörbylånga municipality and require the approval of each property owner from where a sample was collected. This task would indeed be time consuming, but it would also provide valuable records for the SGU Wells Archive. The second option is using a GIS-based approach to separate the data based on assumptions. By assuming that any well in a location where the soil depth is less than two meters (or any other arbitrary depth) is drilled into the sedimentary bedrock, an SQL-query can be formulated to select and extract only those wells, together with any well already matching the SGU Wells Archive. The data can then be presented in two separate categories. However, because of how the query is formulated, the results would not be reliable. At best, they would represent an estimate rather than the actual setting.

## 5.3 Reliability of the GIS-overlay analyses

As mentioned earlier, GIS is an excellent tool for analyzing and processing large amounts of spatial data. However, when applying overlay analyses in natural sciences, caution should be practiced. It is important to recognize that processes in nature are often complex, and data often represent a simplified version of nature. Because of this, any results derived from such analysis should not be accepted as fact. The results simply indicate the *potential* for groundwater recharge in the studied area, based on whatever data was incorporated, evaluated and weighted in the analysis. This statement is needed, as results presented in previous studies, where a GIS-based approach is used, sometimes are formulated in a manner that they could be interpreted as facts. They are not. Even the LiDAR data used in this study does not represent the true topography beyond the limitation of its resolution.

Regarding what types of datasets are used when trying to solve a groundwater related problem, the literature gravitates toward the following main factors: geology (usually subdivided into loose deposits and firm bedrock), slope gradient, lineament density and drainage density (e.g. Hsin-Fu et al., 2009; Selvam et al., 2016; Panahi et al., 2017). Other factors commonly implemented are precipitation (e.g. Satapathy and Syed, 2015; Karami et al., 2016) and geomorphology (e.g. Singh et al., 2013; Senanyake et al., 2016). However, more datasets are sometimes integrated. To avoid introducing unnecessary uncertainties into the model, it is a good idea to only include datasets that contain factors with a fundamental influence on the hydrological equation. More datasets, such as slope aspect (e.g. Zeinivand and Nejad, 2018) and distance to rivers (e.g. Maity and Mandal, 2017) should therefore only be integrated if they with certainty will increase the accuracy of the model.

Indeed, the challenge, when conducting a GIS-based multi-criteria analysis to solve a hydrogeological problem, is being as accurate and precise as possible. Scoring parameters and weighing the influence of each dataset will ultimately determine the outcome. One can at best make an educated guess when translating arguments into quantified logic for the computer to process. One method commonly used for this purpose is the *Analytic Hierarchy Process* (AHP) developed by Saaty (1980). The AHP is essentially a method that decision makers can use when dealing with complex, multi-criteria problems, to find suitable solutions (Saaty, 1987). In order to show how different weighting would affect the result, two more analyses were carried out where slightly altered weights were used (Appendix 4). The results show only marginal difference and the locations of interest remain unchanged.

Assuming the analyses (Fig. 8 and Appendix 4) were carried out to the best of knowledge, the study area will be delineated on a basis of groundwater potential. The more positive criterions coinciding in an area, the higher the probability of a desirable groundwater recharge rate in that location. These locations are good starting points for field investigations and subsequent geophysical surveys, such as ERT (Electric Resistivity Tomography) and TEM (Transient Electromagnetic Method), before any well drilling is commenced. If however, the surveyed areas, after proper investigation, are deemed unfavorable in terms of groundwater recharge, the model should be revised and altered.

An important observation is although the numbers of GIS-based *groundwater potential*-studies are growing, there is little evidence supporting their reliability and accuracy. There is probably a practical reason for this, as field studies, geophysical investigations and well constructions are both time-consuming and vastly more expensive than GIS-studies. Adiat et al. (2012) investigated the reliability of a GIS-based groundwater potential study in northwestern Malaysia. Based on a comparison of predicted and actual yield from 16 boreholes in the study area, predictions from the GIS overlay analysis were 81.25 percent accurate. More studies of this nature, where results are actually tested in practice, would certainly be a valuable complement in this field of study. As earlier mentioned, SGU is at the time of writing processing SkyTEM data covering the major part of Öland. The data is to be complemented with approximately 30 well drillings across the island. When the SkyTEM data is processed and available for interpretation, as well as the experiences from the well drillings are recorded, results from GIS-analyses in this study can be evaluated.

With the increasing amount of geophysical data collected for commercial and academic purposes, the foundations for a comprehensive review on the effectiveness and reliability of GIS-based groundwater-potential studies are in place. At this point, any case study has the potential to make significant contributions for the development and refinement of the methodology used in GIS-based groundwater studies.

### 5.3.1 Implications of the GIS analyses and recommendations for Mörbylånga municipality

The results presented in this study reveal one large and few small locations with a good potential for groundwater recharge (Fig. 8 and Appendix 4). These locations could, potentially, yield significant volumes of water.

As stated above (6.3), the municipality will benefit from already acquired SkyTEM data, and can therefore examine parts of the SkyTEM data extending into and covering the favorable locations presented in this study. These locations can serve as suitable starting points when commencing the interpretation of the SkyTEM data and, if shown promising, visited in field before reaching any further decision.

# 6 Conclusions

Water chemistry data from approximately 1400 groundwater analyses form the base for the quality evaluation undertaken in this thesis. Data from municipal water catchments and private wells, were evaluated separately and later compared for differences. Results were acquired by comparing concentrations of more than 25 physiochemical and microbiological parameters, for each sample, to guideline values from SGU 2013:01 and SLVFS 2001:30. In addition, maps showing spatial distribution of concentrations of analyzed parameters were created based on georeferenced well data. The groundwater quality assessment shows that:

- Groundwater quality is generally better in municipal wells compared to private wells. This is especially true in terms of microbiological presence and nutrient concentrations. Ninety percent of samples from private wells show microorganisms in concentrations ≥ 10 cfu/100ml (SGU Class 3–5) and coliform bacteria were detected in more than half of the samples analyzed. Although microbiological presence is common, concentrations in most samples were under guideline values. Harmful bacteria can, however, represent a problem to individual well owners.

- Elements and compounds found in significant concentrations and associated to the sedimentary bedrock of Öland are calcium, magnesium and sulfate. Significant concentrations of boron and lead were also detected and are probably associated to the sedimentary bedrock. However, an anthropogenic source for these occurrences cannot yet be ruled out.

- Lead is occasionally found in concentrations well above the national average. In Tveta water catchment, concentrations in end-user drinking water have reached as high as 2.5 µg/l (SGU Class 4) for the studied period. Lead occurrences in private wells have, in certain cases, also been detected at significant concentrations and in one case even exceeded guideline values (≥ 10 µg/l). The source for lead in the groundwater is likely the alum shale, but could, locally, also be leaching of old lead pipes. Measuring lead concentrations on all wells in Tveta water catchment will help pinpoint the source.

- A cyclical variation in sodium, sulfate and calcium is found in a well in Södra Möckleby water catchment. Significant increases in sodium- and concurrent decreases in sulfate- and calcium concentrations during summers and autumns, suggest that saltwater intrusion into the well could be a source for this observation. Examining the well records in Södra Möckleby may provide insight in how to decrease the risk of saltwater contamination when planning to drill new wells.

- In most cases, concentrations of analyzed parameters are uniformly distributed across Mörbylånga municipality. However, a tendency for higher nutrient concentration is found in groundwater in the northern and eastern parts of the municipality. This observation could be explained by a difference in crops grown and size of arable land. A contributing factor could also be the geomorphology of Mörbylånga. Compared to the western side, watersheds east of the groundwater divide are significantly larger, which could lead to longer residence times and enrichment of nutrients in the groundwater.

Also performed in this study was a GIS-based approach for determining groundwater potential in the municipality. The analyses were carried out using already existing spatial geo-data. In addition, a watershed map and a map showing depth to the alum shale were created using the same data. The GIS analyses show that:

- The groundwater potential is particularly promising in a 2.5 $km^2$ large area, located on the groundwater divide between Tveta and Resmo water catchments. Highly fractured bedrock superposed by gravel deposits are the main underlying reason for this area to be highlighted in the analysis. Conveniently enough, this area is also located near two of the largest towns in the municipality, Färjestaden and Mörbylånga. A unique opportunity to test the reliability of the overlay analysis method now exist thanks to recently acquired SkyTEM data, to which it can be compared with.

# 7 Acknowledgements

I would like to thank my supervisors Charlotte Sparrenbom, Peter Dahlqvist and Mattias Gustafsson for their support and for providing me with valuable insight along the way. I would also like to thank Michael Ingard and Håkan Lagesson at Mörbylånga municipal office for providing me with the data on which this thesis is based on. Lastly, I would like to thank my family for their encouragement and support.

# 8 References

Adiat, K., Nawawi, M. & Abdullah, K., 2012: Assessing the accuracy of GIS-based elementary multi criteria decision analysis as a spatial prediction - tool – A case of predicting potential zones of sustainable groundwater resources. *Journal of Hydrology 440-441*, 75 – 89.

BABEL Working Group., 1990: Evidence for early Proterozoic plate tectonics from seismic reflection profiles in the Baltic shield. *Nature 348*, 34 – 38.

Böhlke, J., Smith, R. & Miller, D., 2006: Ammonium transport and reaction in contaminated groundwater: Application of isotope tracers and isotope fractionation studies. *Water Resources Research 42*, 19 pp.

Calner, M., Lehnert, O., Wu, R., Dahlqvist, P. & Joachimski, M., 2014: δ13C chemostratigraphy in the Lower–Middle Ordovician succession of Öland (Sweden) and the global significance of the MDICE. *GFF 136*, 48 – 54.

Edet, A., Okereke, C., Teme, S. & Esu, E., 1998: Application of remote-sensing data to groundwater exploration: A case study of the Cross River State, southeastern Nigeria. *Hydrogeology Journal 6*, 394 – 404.

Erlström, M., Thomas, S., Deeks, N. & Sivhed, U., 1997: Structure and tectonic evolution of the Tornquist Zone and adjacent sedimentary basins in Scania and the southern Baltic Sea area. *Tectonophysics 271*, 191-215.

Erlström, M., 2014: *Skiffergas och biogen gas I alunskiffern I Sverige, förekomst och geologiska förutsättningar – en översikt*. Uppsala. SGU-rapport 2014:19, 28 pp.

Erlström, M., 2016: *Litologisk och geokemisk karaktärisering av berggrundsavsnitt på södra Öland*. Uppsala. SGU-rapport 2016:15, 37 pp.

Falk, H., Lavergren, U. & Bergbäck, B., 2006: Metal mobility in alum shale from Öland, Sweden. *Journal of Geochemical Exploration 90*, 157-165.

Fetter, C. W., 2001: *Applied hydrogeology*. 4th. ed. Upper Saddle River: Prentice Hall. 598 pp.

Fransson, R., Persson, K. M., Leander, B. & Anders son. O., 2004: Saltwater intrusion in the bedrock of southwest Scania. Proceedings of the 18th Salt Water Intrusion Meeting (SWIM), 533 – 550.

Harff, J., Björck, S. & Hoth, P. (eds.), 2011: *The Bal tic Sea Basin*. Berlin: Springer-Verlag. 449 pp.

Held, I., Wolf, L., Eiswirth, M. & Hötzl, H., 2006: Impacts of sewer leakage on urban groundwater. *Urban Groundwater Management and Sustainability*, 189 – 204.

Hsin-Fu, Y., Cheng-Haw, L., Kuo-Chin, H. & Po-Hsun, C., 2009: GIS for the assessment of the groundwater recharge potential zone. *Environmental Geology 58*, 185 – 195.

Jeng, A.S. 1991: Weathering of some Norwegian alum shales: I. Laboratory simulations to study acid generation and the release of sulphate and metal cations (Ca, Mg and K). *Acta Agriculturae Scandinavica 41*, 13 – 35.

Jeng, A.S., 1992: Weathering of some Norwegian alum shales: II. Laboratory simulations to study the influence of aging, acidification and liming on heavy metal release. *Acta Agriculturae Scandinavica 42*, 76 – 87.

Karami, G., Bagheri, R., & Rahimi, F., 2016: Determining the groundwater potential recharge zone and karst springs catchment area: Saldoran region, western Iran. *Hydrogeology Journal 24*, 1981 – 1992.

Krapac, I., Dey, W., Roy, W., Smyth, C., Storment, E., Sargent, S. & Steele, J., 2002: Impacts of swine manure pits on groundwater quality. *Environmental Pollution 120*, 475 – 492.

LIVSFS 2017:2. Livsmedelsverkets föreskrifter om ändring I Livsmedelsverkets föreskrifter (SLVFS 2001:30) om dricksvatten. Stockholm. Livsmedelsverket.

Maity, D.K. & Mandal, S., 2017: Identification of groundwater potential zones of the Kumari river basin, India: an RS & GIS based semi-quantitative approach. *Environment, Development and Sustainability*, 22 pp.

Melloul, A. & Goldenberg, L., 1997: Monitoring of seawater intrusion in coastal aquifers: Basics and local concerns. *Journal of Environmental Management 51*, 73 – 86.

Mörbylånga kommun, 2017: Bevattningsförbudet upphävs. https://www.morbylanga.se/kommun-politik/Press---och-informationsmaterial/Pressmeddelanden/Bevattningsforbudet-upphavs/ Received: 20/05/2018. Last updated: 29/09/2018.

Naturvårdsverket, 2006: Övergödningen av Sveriges kuster och hav. Stockholm. Naturvårdsverket rapport 5587, 39 pp.

Naturvårdsverket, 2016: *Sweden's environmental objectives – an introduction*. Bromma. 28 pp.

Norconsult, 2012: *Tveta vattentäkt*. Mörbylånga Kommun. Norconsult unpublished report, 17 pp.

Panahi, M., Mousavi, S. & Rahimzadegan, M., 2017: Delineation of groundwater potential zones using remote sensing, GIS, and AHP technique in Tehran -Karaj plain, Iran. *Environmental Earth Sciences 76*, 1 – 15.

Pousette, J. & Möller, Å., 1972: *Ölands hydrogeologi – en översikt*. Stockholm. SGU Ser. C. 670, 63 pp.

Pousette, J., 1972: Grundvattenundersökningar på Ölands Stora Alvar. Stockholm. SGU Ser. C. 675, 32 pp.

Pousette, J., 1974: Fortsatta grundvattenundersökningar på Öland. Stockholm. SGU Ser. C. 702, 72 pp.

Saaty, R., 1987: The analytic hierarchy process – what it is and how it is used. *Mathematical Modelling 9*, 161 – 176.

Saaty, T.L., 1980: *The analytic hierarchy process: planning, priority setting, resource allocation*. McGraw-Hill, New York, 287 pp.

Satapathy, I. & Syed, T., 2015: Characterization of groundwater potential and artificial recharge sites in Bokaro District, Jharkhand (India), using remote sensing and GIS-based techniques. *Environmental Earth Sciences 74*, 4215 – 4232.

Selvam, S., Dar, F., Magesh, N., Singaraja, C., Venkatramanan, S. & Chung, S., 2016: Application of remote sensing and GIS for delineating groundwater recharge potential zones of Kovilpatti Municipality, Tamil Nadu using IF technique. *Earth Science Informatics 9*, 137-150.

Senanayake, I.P, Dissanayake D.M.D.O.K., Mayadunna B.B. & Weerasekera W.L., 2016: An approach to delineate groundwater recharge potential sites in Ambalantota, Sri Lanka using GIS techniques. *Geoscience Frontiers 7*, 115 – 124.

SFS 1975:424. Lag om uppgiftsskyldighet vid grundvattentäktsundersökning och brunnsborrning. Stockholm. Näringsdepartementet.

SGU, 2013a: *Bedömningsgrunder för grundvatten*. Uppsala. SGU-rapport 2013:01, 238 pp.

SGU, 2013b: *Modellering av Ölands alunskiffer – En tredimensionell modellering baserad på data från brunnsarkivet*. SGU unpublished report, 7 pp.

SGU, 2016: Extremt låga grundvattennivåer. https://www.sgu.se/om-sgu/nyheter/2016/mars/extremt-laga-grundvattennivaer/ Recieved: 05/20/2018. Last updated: 16/03/2016.

SGU, 2018: Liten risk för vattenbrist i sommar. https://www.sgu.se/om-sgu/nyheter/2018/mars/liten-risk-for-vattenbrist-i-sommar/ Received: 20/05/2018. Last updated: 14/03/2018.

Singh, A., Panda, S., Kumar, K. & Sharma, C., 2013: Artificial groundwater recharge zones mapping using remote sensing and GIS: A case study in Indian Punjab. *Environmental Management 52*, 61 – 71.

SLU, 2017: Digital maps and geodata. https://www.slu.se/site/bibliotek/anvanda-biblioteket/soka/digitala-kartor/ Received: 20/05/2018. Last updated: 08/06/2017.

SLVFS 2001:30. Statens livsmedelsverks föreskrifter om dricksvatten. Stockholm. Livsmedelsverket.

Sopher, D., Erlström, M., Bell, N. & Juhlin, C. 2016: The structure and stratigraphy of the sedimentary succession in the Swedish sector of the Baltic Basin: new insights from vintage 2D marine seismic data. *Tectonophysics 676*, 90 – 111.

Structor, 2016: *Tveta brunnsborrning våren 2016, sammanställning*. Kalmar. Structor unpublished report, 12 pp.

Swierz, P., 2016: Utvärdering av vattenkemisk data från Borgholm kommun och dess relation till geologiska förhållanden och markanvändning. *Examensarbeten i geologi vid Lunds universitet 475*, 1 – 35.

Talme, O. and Almén, K.E. 1975. Jordartsanalys. Laboratorieanvisningar, del 1, Department of Quaternary Research, Stockholm University. 133 pp.

Westergård, A.H., 1944: *Borrningar genom alunskifferlagret på Öland och i Östergötland*. Stockholm. SGU Ser. C. 463, 22 pp.

Westergård, A.H., 1947: *Nya data rörande alunskifferlagret på Öland*. Stockholm. SGU Ser. C. 483, 12 pp.

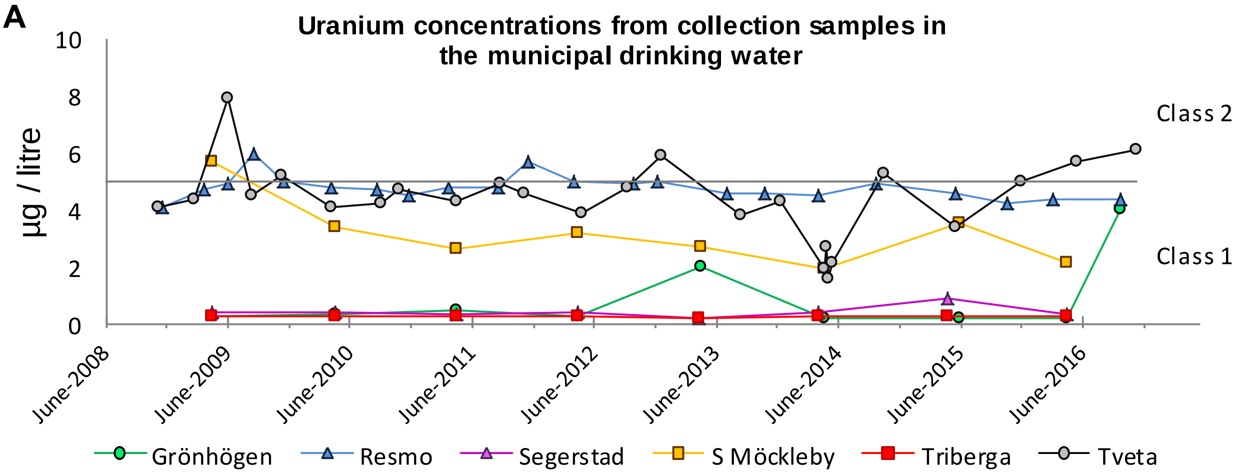
Vöks, J., 2010: Källor på södra Öland – En studie av utbredningsmönster och vattenkvalité (Dissertation). Linnéuniversitetet. 71 pp.

WHO, 2011: Guidelines for Drinking-water Quality. 4th. ed.

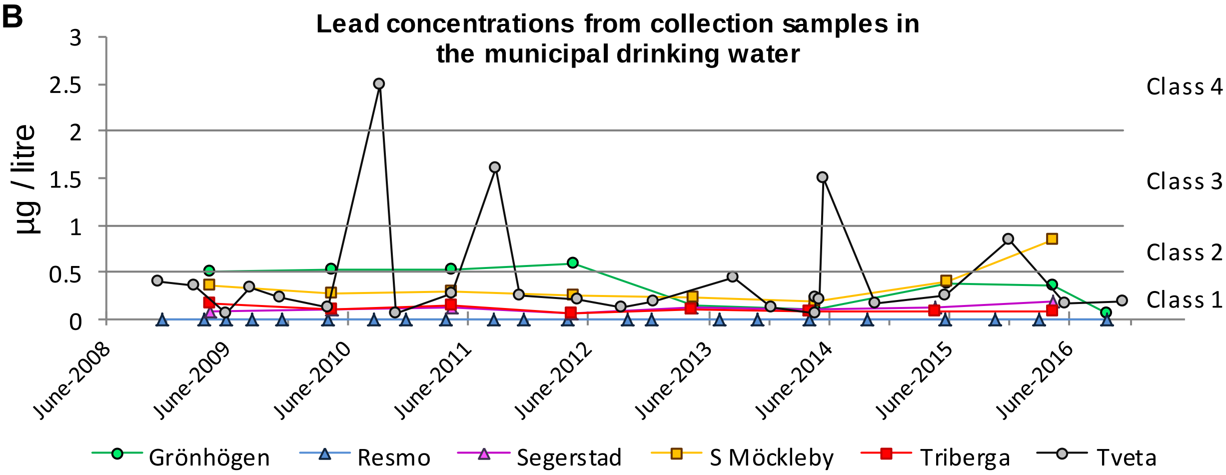
Zeinivand, H. & Ghorbani Nejad, S., 2018: Application of GIS-based data-driven models for ground water potential mapping in Kuhdasht region of Iran. *Geocarto International 33*, 651 – 666.

# Appendix 1. End-user drinking water chemical status

A




B




C

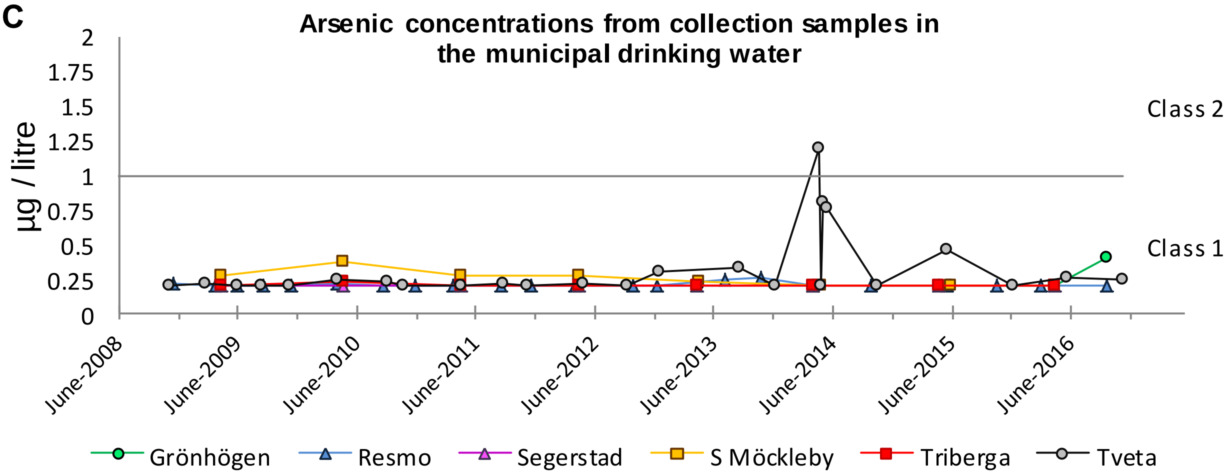



*Fig. 10*. Charts showing **A**. uranium, **B** lead, and **C**. arsenic concentrations in municipal drinking water over the eight-year sample period.

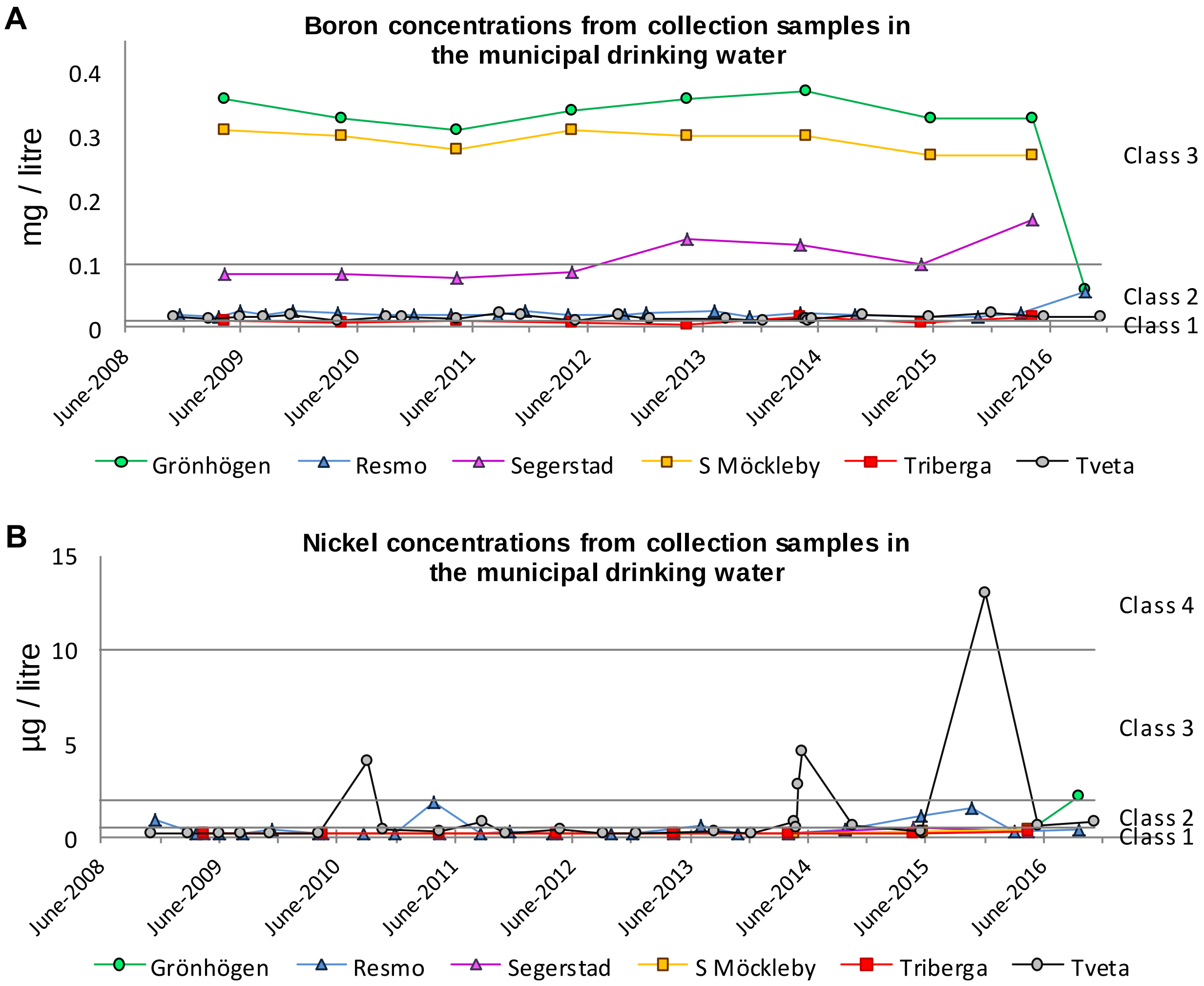



*Fig. 11*. Charts showing **A**. boron, and **B**. nickel concentration in municipal drinking water over the eight-year sample period.

# Appendix 2. Pesticide content analyzed for in municipal drinking water

*Table. 10*. Table showing pesticide parameters included in the analysis-package end-user drinking water and their minimum detection limit. Note that none of the pesticides analyzed for were detected for the studied period.

| **Parameter** | **Minimum detection limit (µg/l)** |
|---|---:|
| Aldrin | 0.03 |
| AMPA | 0.01 |
| Atrazine | 0.01 |
| Atrazine-desethyl | 0.01 |
| Atrazine-desisopropyl | 0.01 |
| Bentazone | 0.01 |
| Cyanazine | 0.01 |
| Dieldrin | 0.03 |
| Dimetoat | 0.01 |
| Etofumesat | 0.01 |
| Fenoxaprop | 0.01 |
| Fluroxypyr | 0.01 |
| Glyfosat | 0.01 |
| Heptachlorepoxide | 0.03 |
| Heptaklor | 0.03 |
| Imazapyr | 0.01 |
| Isoproturon | 0.01 |
| Klopyralid | 0.01 |
| Klorsulfuron | 0.01 |
| Kvinmerac | 0.01 |
| MCPA | 0.01 |
| Mekoprop | 0.01 |
| Metamitron | 0.01 |
| Metazaklor | 0.01 |
| Metribuzin | 0.01 |
| Metsulfuron-metyl | 0.01 |
| Simazine | 0.01 |
| Terbuthylazine | 0.01 |

# Appendix 3. Water chemical status in private wells 2008—2016

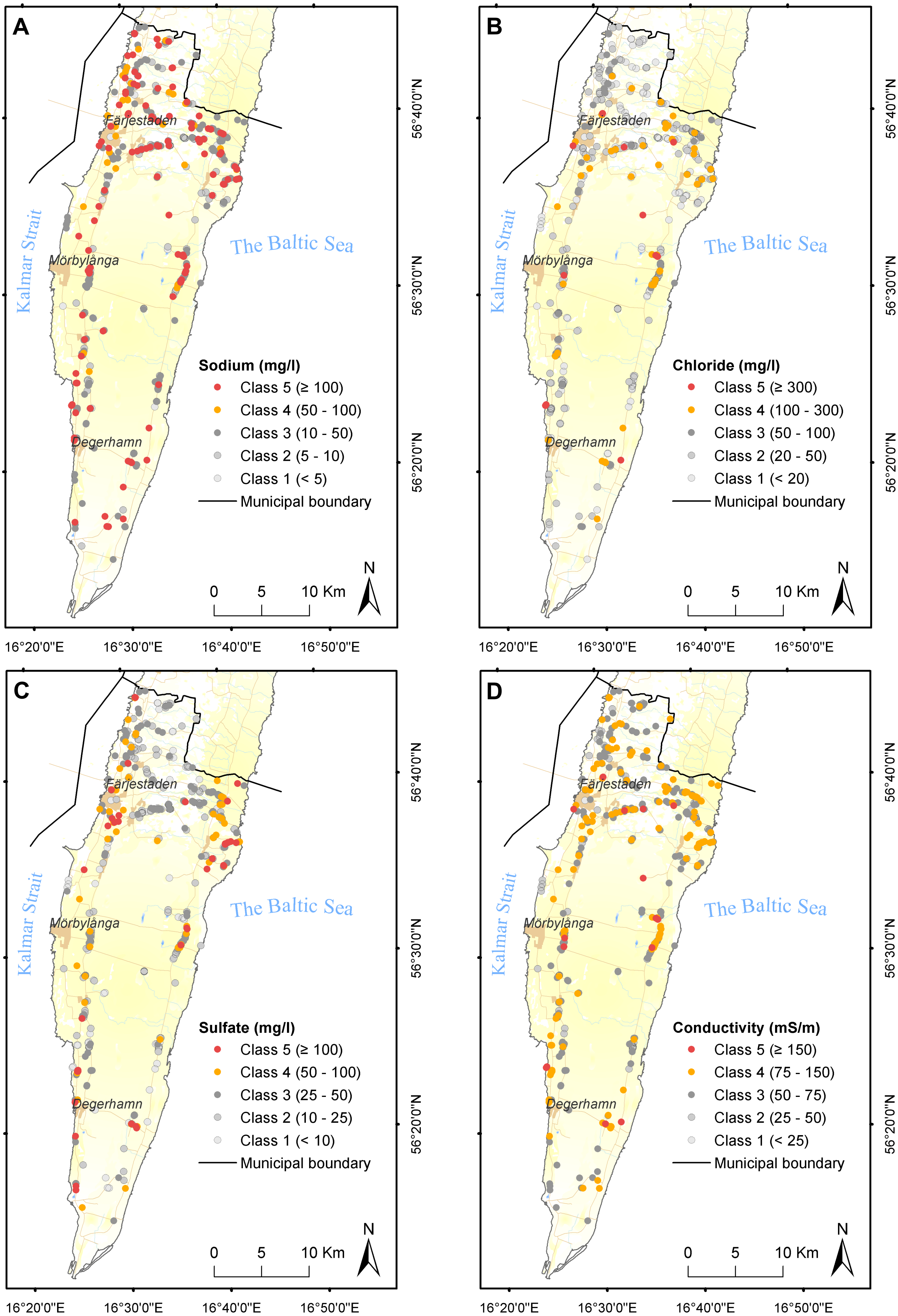



*Fig. 12* Maps showing classes and concentrations in private wells of **A**. Sodium. **B**. Chloride. **C**. Sulfate. **D**. Conductivity.

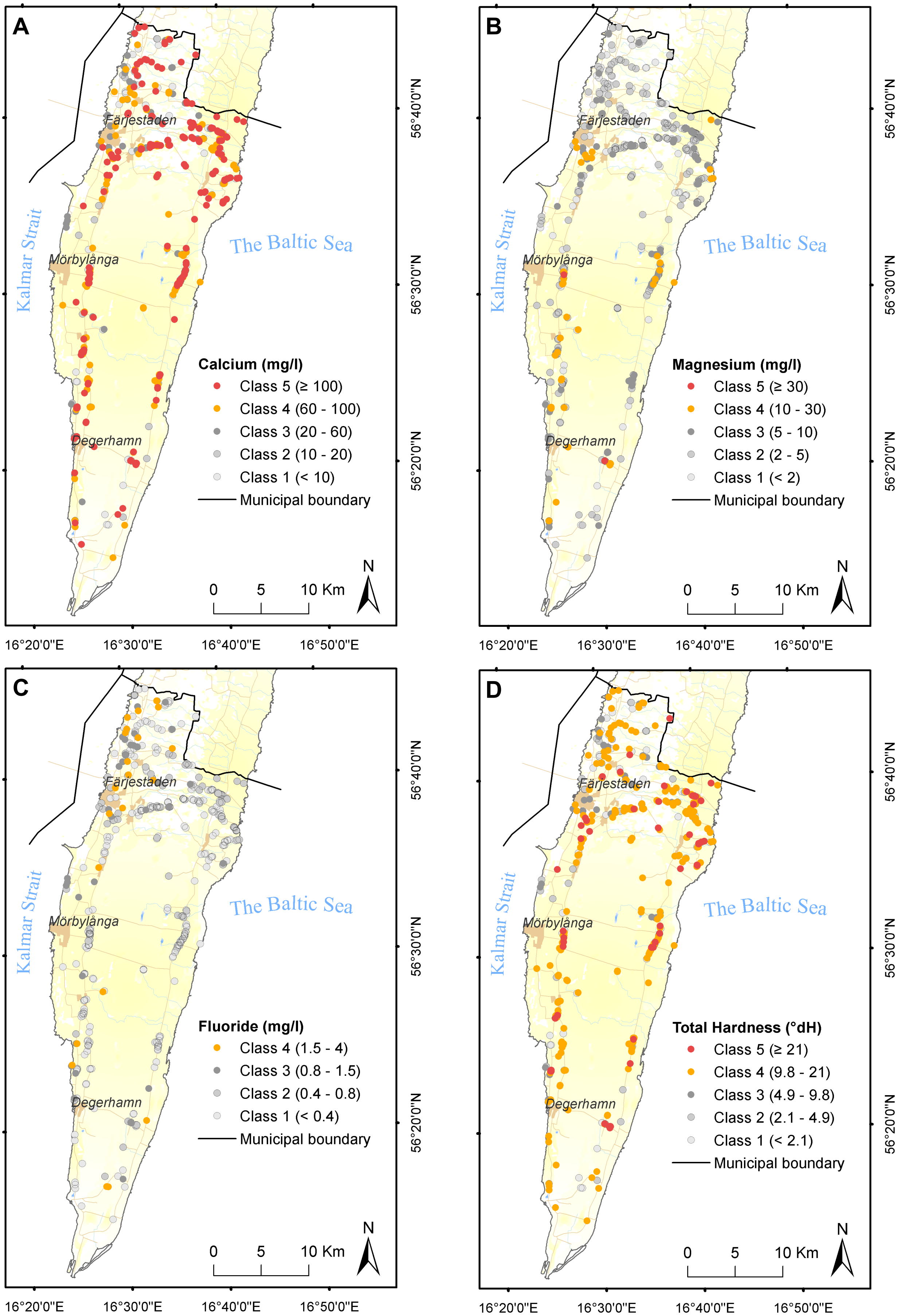



*Fig. 13.* Maps showing classes and concentrations in private wells of **A**. Calcium. **B**. Magnesium. **C**. Fluoride. **D**. Total Hardness.

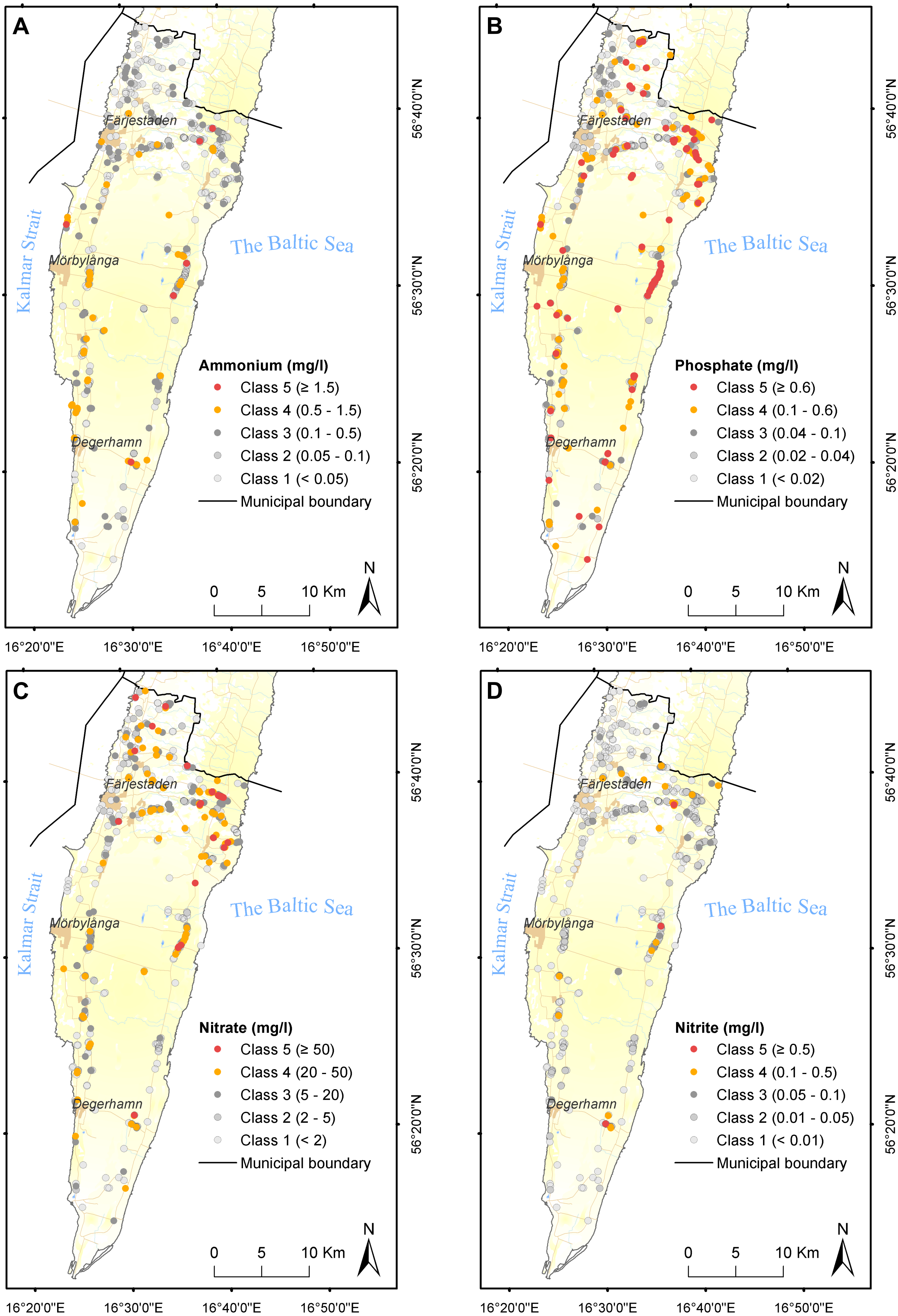



*Fig. 14*. Maps showing classes and concentrations in private wells of **A**. Ammonium. **B**. Phosphate. **C**. Nitrate. **D**. Nitrite.

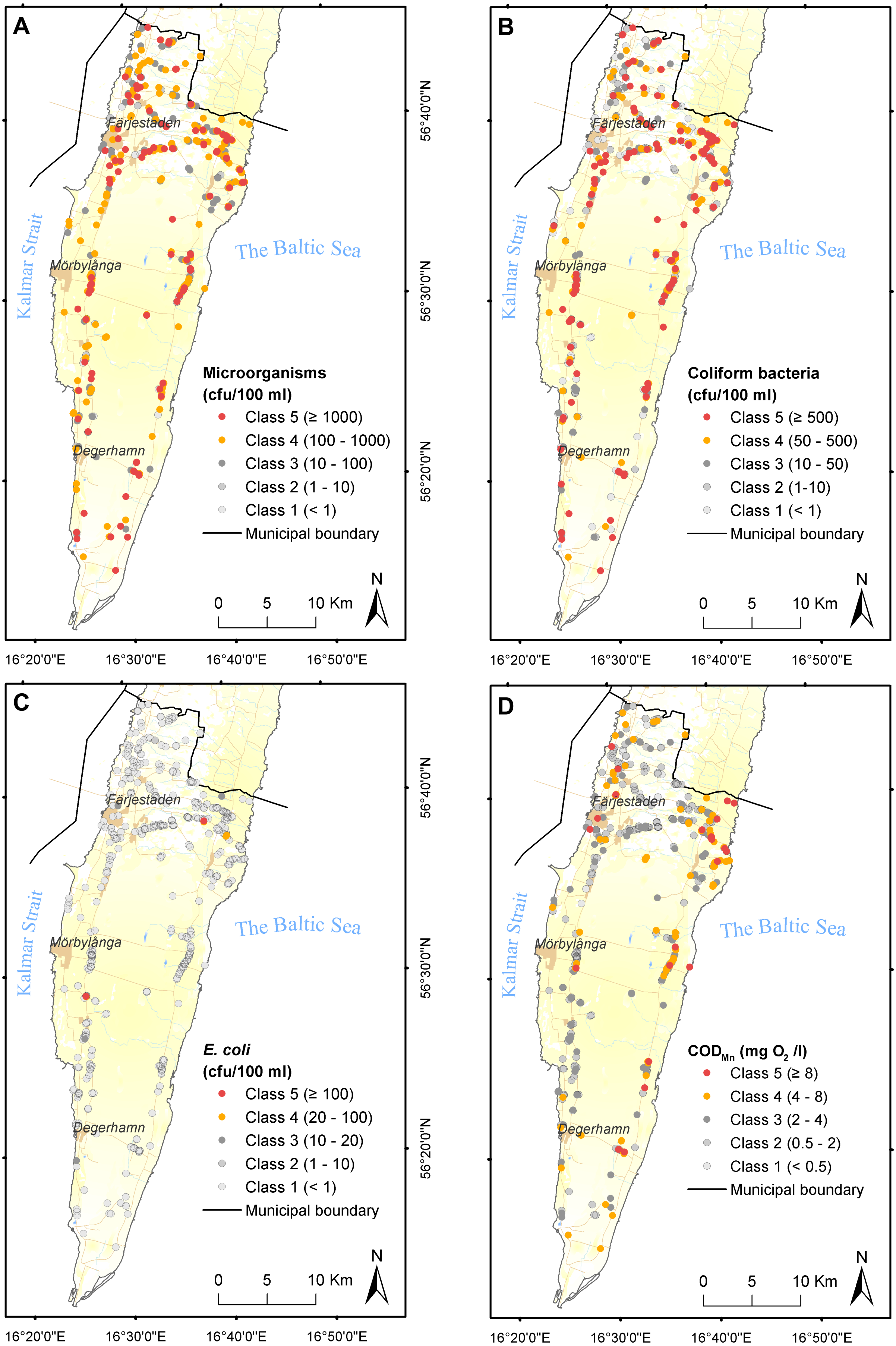



*Fig. 15.* Maps showing classes and concentrations in private wells of **A**. Microorganisms. **B**. Coliform bact. **C**. *E. Coli*. **D**. COD$_{Mn}$.

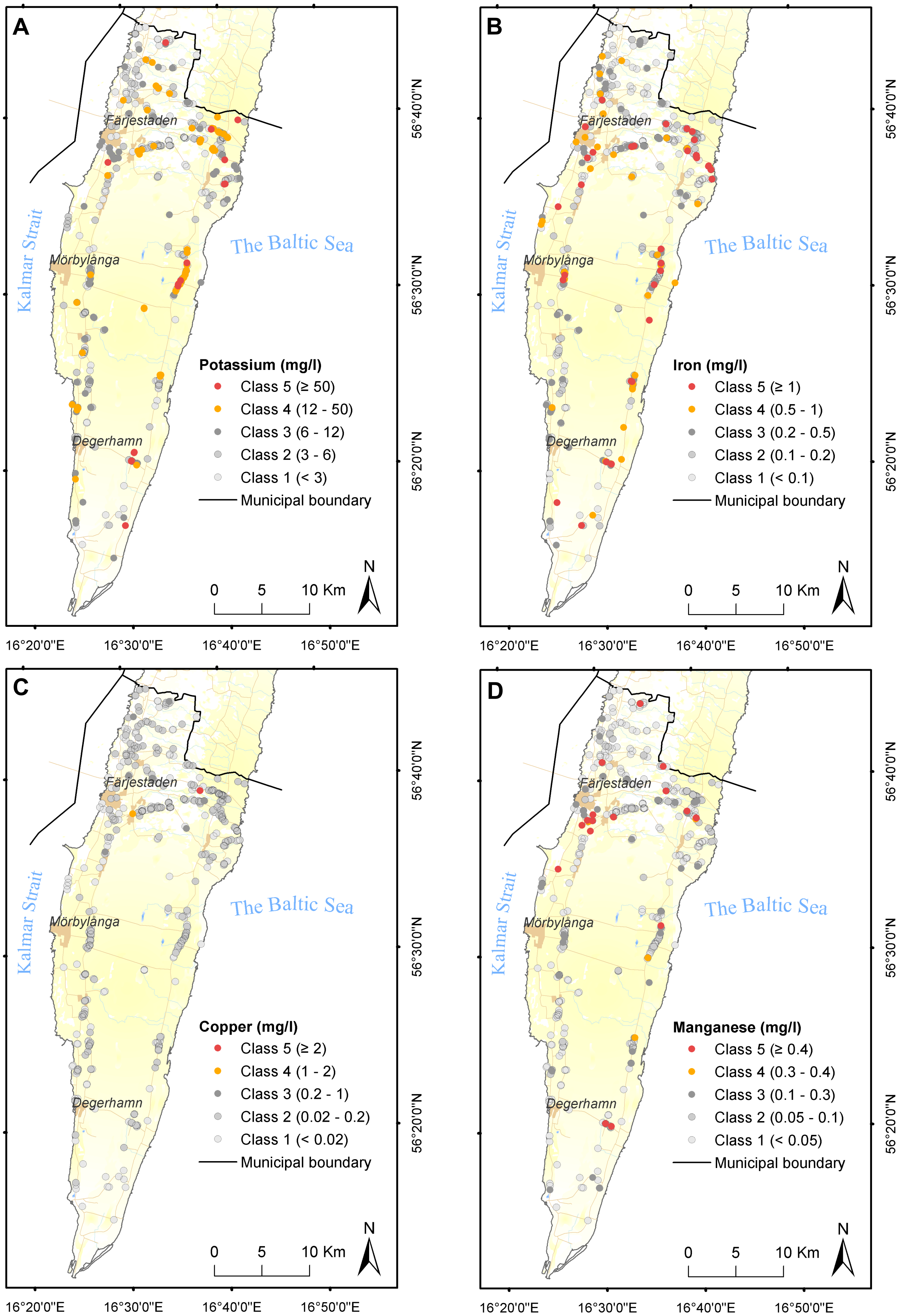



*Fig. 16.* Maps showing classes and concentrations in private wells of **A**. Potassium. **B**. Iron. **C**. Copper. **D**. Manganese

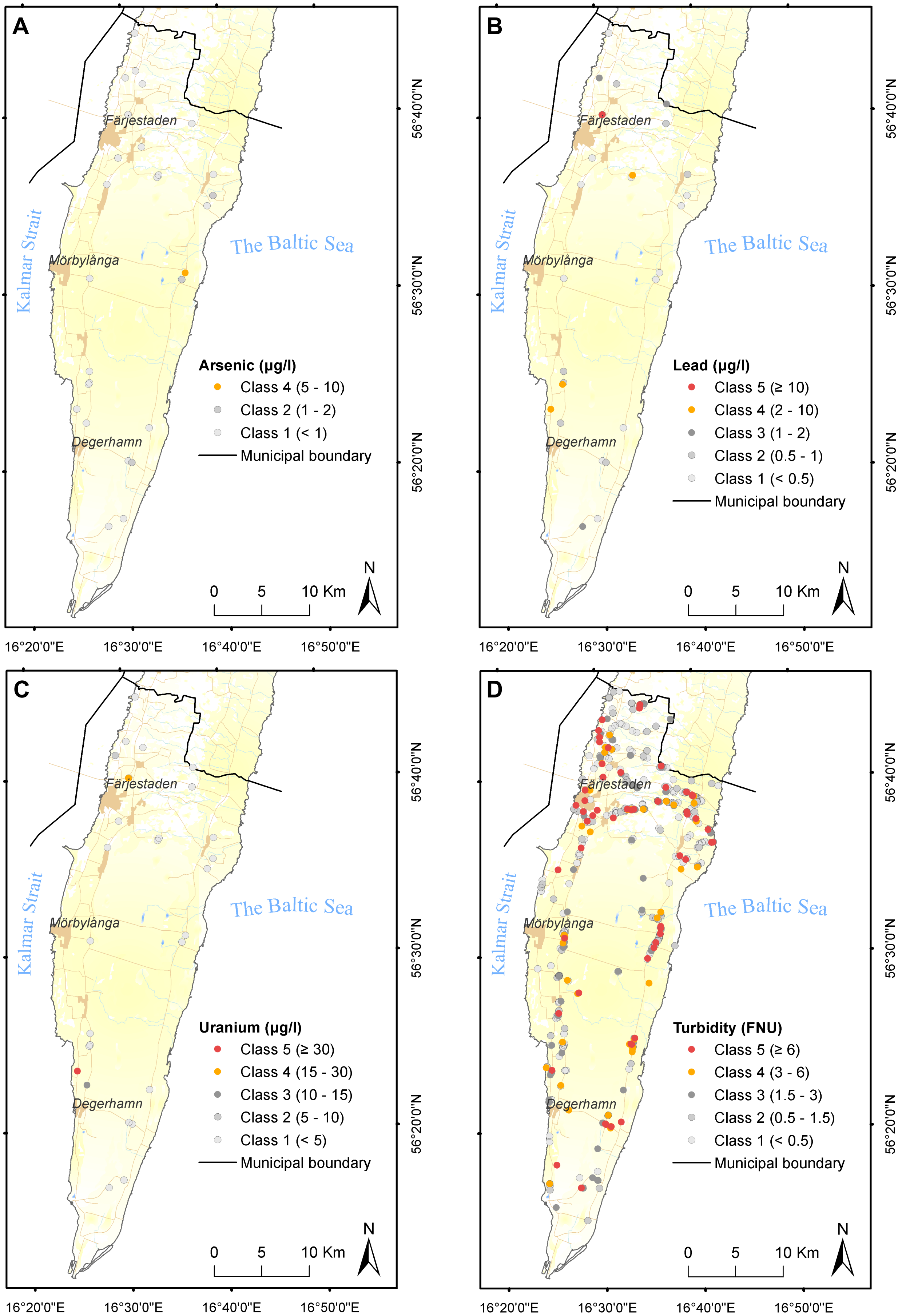



*Fig. 17*. Maps showing classes and concentrations in private wells of **A**. Arsenic. **B**. Lead. **C**. Uranium. **D**. Turbidity.

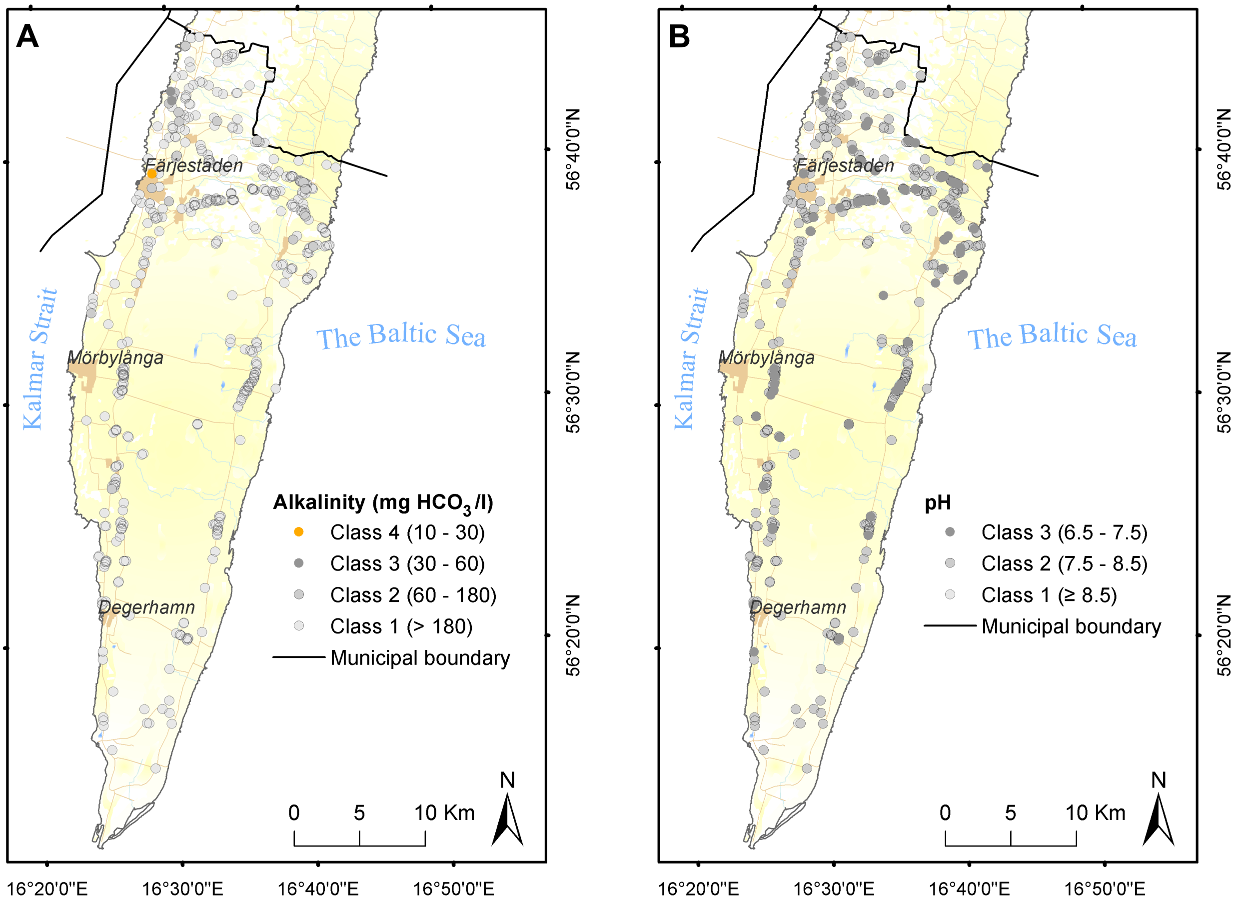



*Fig. 18*. Maps showing classes and concentrations in private wells of **A**. Alkalinity. **B**. pH.

# Appendix 4. Groundwater potential maps with altered influence

*Table. 11*. Effective weight of each thematic layer after altered groundwater recharge potential scores have been assigned.

| | Factor | | | | | |
|---|---|---|---|---|---|---|
| | Precipitation | Slope | Soil class | Lithology | Lineament density | Drainage density |
| **Weight** | 10% | 20% | 30% | 10% | 10% | 20% |

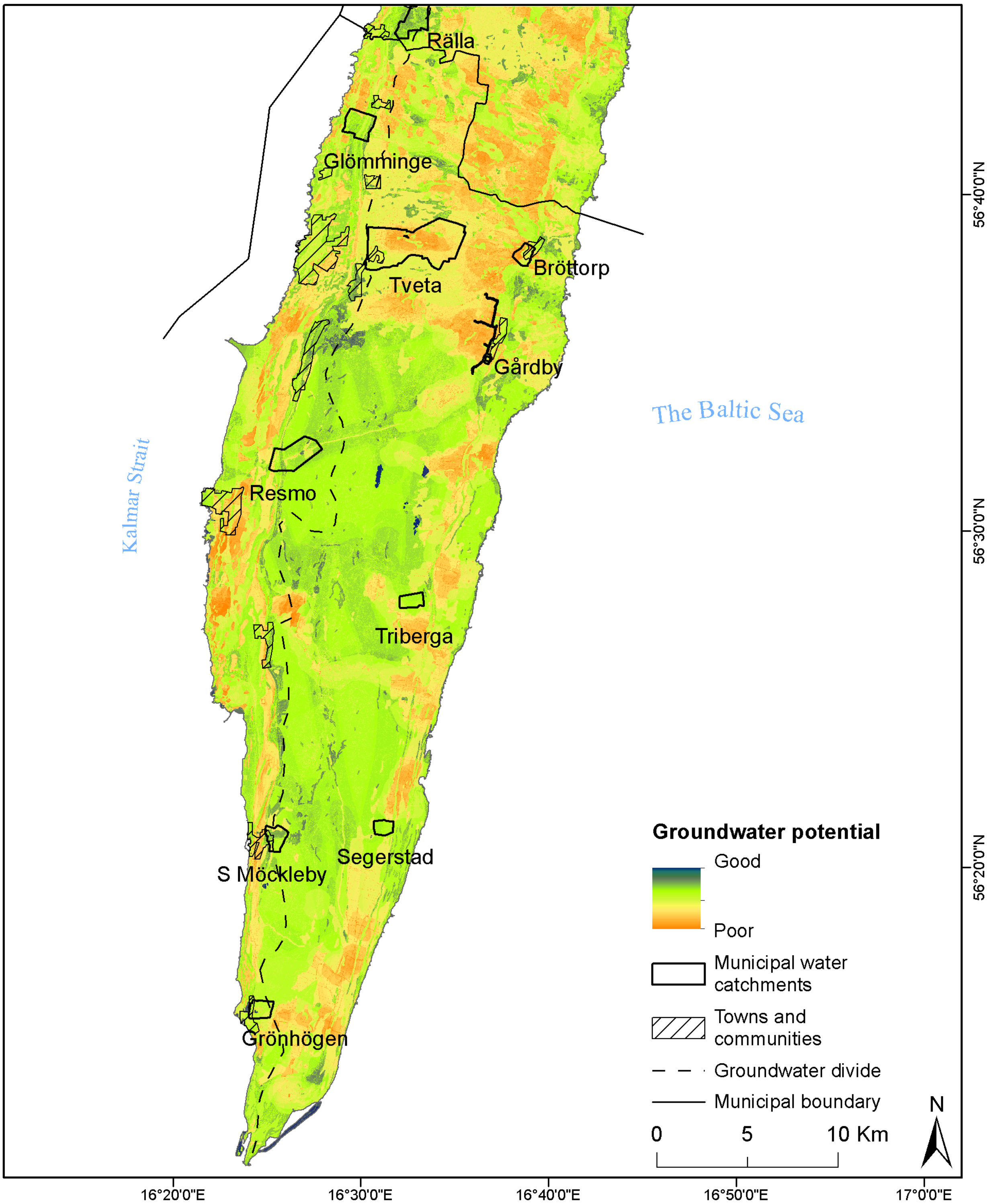



*Fig. 19*. Map showing the estimated groundwater potential of Mörbylånga. Dark blue areas represent zones where multiple positive factors coincide and are deemed the most promising in terms of groundwater recharge. For sense of spatial distribution major towns and communities of Mörbylånga, as well as existing municipal water catchments, are added to the map.

*Table. 12*. Effective weight of each thematic layer after alternate groundwater recharge potential scores have been assigned.

| | Factor | | | | | |
|---|---|---|---|---|---|---|
| | Precipitation | Slope | Soil class | Lithology | Lineament density | Drainage density |
| **Weight** | 20% | 10% | 35% | 10% | 15% | 10% |

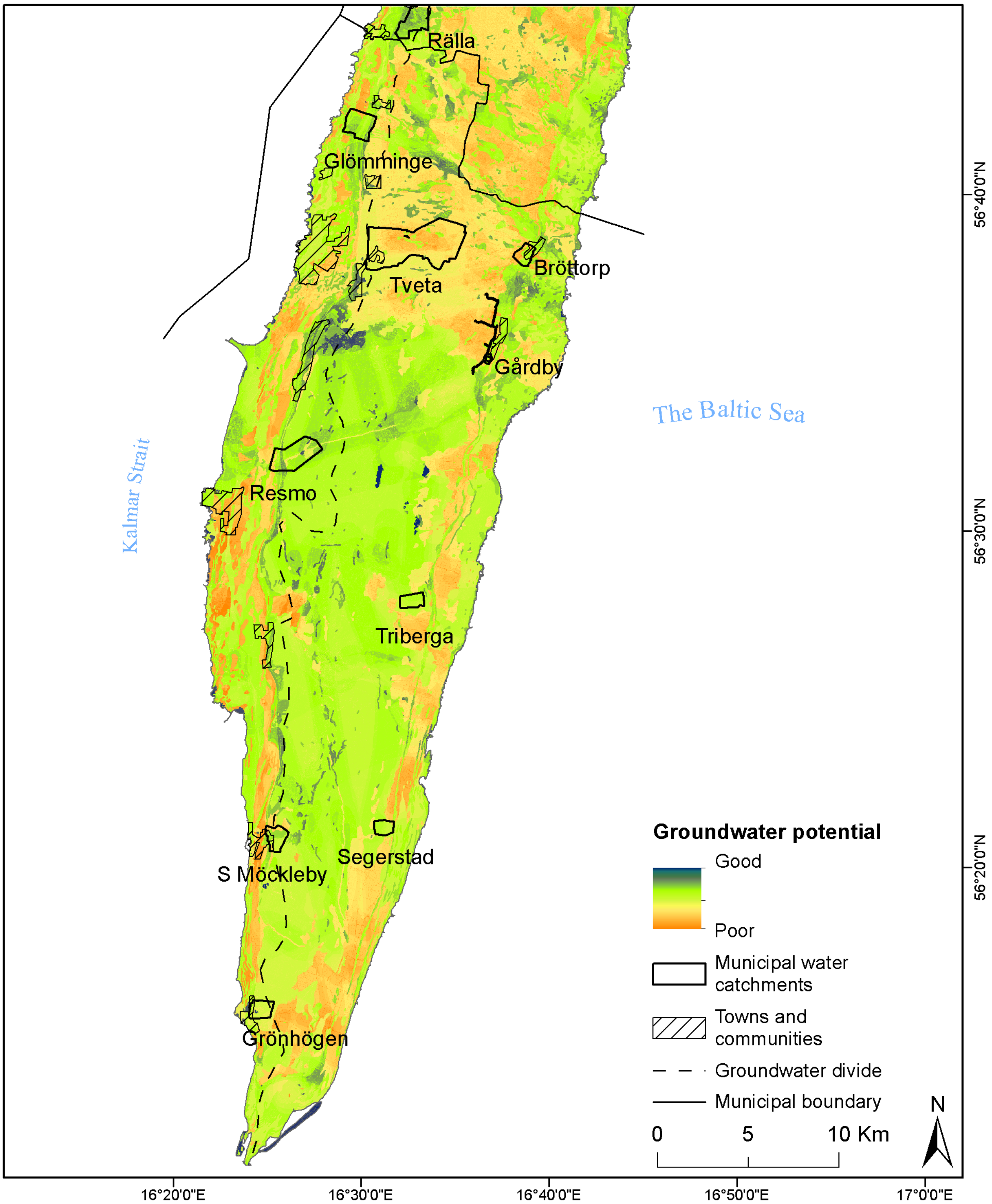



*Fig. 20*. Map showing the estimated groundwater potential of Mörbylånga. Dark blue areas represent zones where multiple positive factors coincide and are deemed the most promising in terms of groundwater recharge. For sense of spatial distribution major towns and communities of Mörbylånga, as well as existing municipal water catchments, are added to the map.

## Appendix 5. Watershed delineation of Mörbylånga municipality

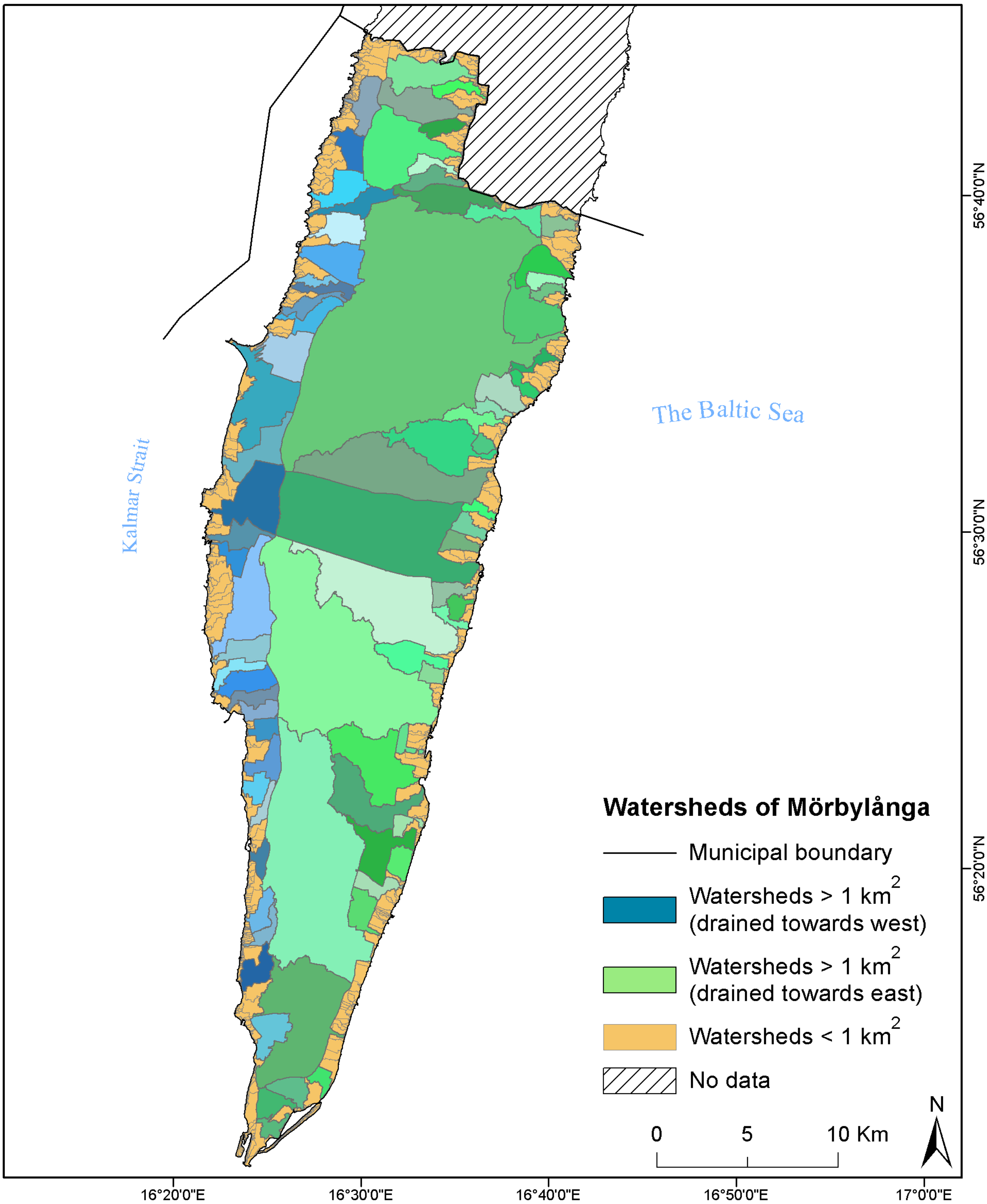



*Fig. 21*. Map showing watersheds in Mörbylånga municipality. Watersheds are subdivided into three groups on basis of extent and drainage orientation. This Map was created in ArcGIS using the *Spatial Analyst* tools. Different shades of blue and green are applied to highlight and demarcate individual watersheds.

# Appendix 6. Depth to alum shale, Mörbylånga municipality

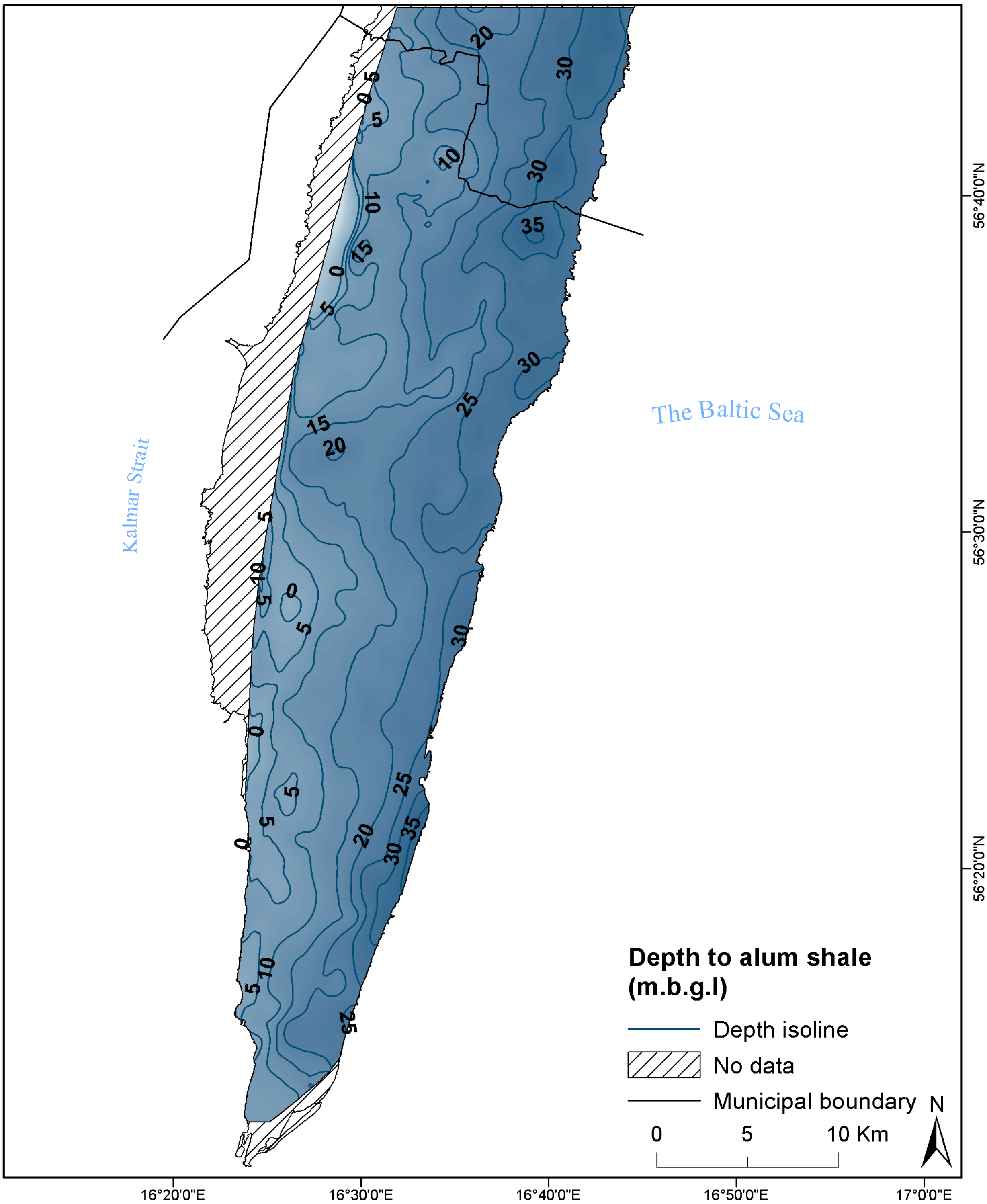



*Fig. 22.* Map showing depth from ground level (in meters) to the top of the alum shale formation in Mörbylånga Municipality. This map was created in ArcGis using the Raster Calculator tool to subtract the elevation of the alum shale top surface from the LIDAR-data.

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