CONSTRUCTION OF 3D CLAY THICKNESS MODELS OF TURKU FOR URBAN PLANNING AND INFRASTRUCTURE

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Suomen etelä- ja länsiosat ovat olleet enimmäkseen veden alla Itämeren altaan eri kehitysvaiheissa. Tästä syystä erityisesti Suomen rannikkoalueilla on koettu suolaisia ja murtovesivaiheita, jotka ovat vaikuttaneet sedimentaatio-olosuhteisiin. Aiemmat tutkimukset Itämeren ja sen rannikkoalueiden laskeumaympäristöistä kertovat, että merenpohjan pinnanmuodot ja olosuhteet ovat keskeisessä asemassa hienorakeisten maalajien sedimentoitumisessa ja niiden ominaisuuksissa. Hienorakeiset sedimentit kaupunkien alueilla haastavat yhdyskuntatekniikkaa, kun väkiluvun kasvamisen myötä kaupunkeja joudutaan laajentamaan maankäytön kannalta epäsuotuisille alueille. Erityisesti Turun kaltaisissa rannikkokaupungeissa saviset kerrostumat luovat haastavat olosuhteet rakentamiselle. Tässä tutkimuksessa esitetään Turun alueen savikoiden esiintymisalueet ja niiden paksuudet, tuottamalla kaupunkisuunnittelua ja -rakentamista palvelevia kolmiulotteisia geologisia malleja. Luomalla alueesta muinaisen Itämeren altaan paleotopografiset mallit i) jääkauden jälkeen sekä ii) Litorinameren aikana, voitiin alue luokitella yksityiskohtaisesti topografisten ominaisuuksien mukaisesti. Yhdistämällä topografiset luokitukset savenpaksuus-malliin pystyttiin laatimaan havainnollistava malli Turun alueen sedimenttikerrostumista. Lähes 60 % tutkimusalueesta sisältää hienorakeisia sedimenttejä, joista paksuimmat kerrostumat sijaitsevat pääasiassa murroslaaksoissa Aurajoen varrella sekä satama-alueella. Lukuun ottamatta suurimpia murroslaaksoja, alueen savisedimentit ovat topografialtaan hyvin pienipiirteisiä, sisältäen paljon pieniä painanteita, kohoumia ja rinteitä. Lisäksi tässä tutkimuksessa on tarkasteltu edellytyksiä mallintaa potentiaalisia happamien sulfaattimaiden alueita havainnollistettujen savikerrosten perusteella. Tämän tutkimuksen tuloksia voidaan hyödyntää Turun alueen rakennushankkeiden ja aluesuunnittelun tukena sekä suuntaa antavana paikkatietomallina rakennuspohjan esiintymisestä ja koostumuksesta. Tutkimuksessa käytettyjä menetelmiä voidaan soveltaa vastaavanlaisille hienorakeisten sedimenttien alueilla tehtäville samanlaisille tutkimuksille Itämeren rannikoilla.

Avainsanat: Paleotopografinen luokittelu, hienorakeiset sedimentit, kerrostumisympäristöt, Benthic Terrain Modeler (BTM), maankäyttö, Turku

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The southern and western parts of Finland have been mostly submerged during the different phases of development of the Baltic Sea Basin. For this reason, these areas have experienced saline and brackish water phases, which has affected the sedimentation settings. Based on the previous studies of Baltic Sea and its deposition environments in onshore areas, the conditions and the seabed topography have a major role in the deposition of fine-grained sediments and their properties. Areas of fine-grained sediments challenges the community engineers, as the population in cities are growing and the urban expansion requires more unfavorable areas for land use. Especially in coastal cities like Turku, the fine-grained deposits create challenging conditions for construction. This study provides a characterization of fine-grained sedimental deposits in the Turku area by producing three-dimensional geological models for urban planning and construction. Paleotopographic models for the ancient Baltic Sea Basin in the Turku area i) after deglaciation and ii) during the Litorina transgression were built and classified into bathymetric zones and structures. Combining the topographic classifications with the thickness of fine-grained sediments, it was possible to produce a demonstration of the characteristics of sedimentary environments in the Turku area. Nearly 60% of the research area contains fine-grained sediments, where the thickest deposits are mainly located in depressions and joint valleys along the Aurajoki river and around the harbor area. Except for the biggest joint valleys, the topography of fine-grained sediments in the area has very small features with lots of smaller depressions, hills, and slopes. In addition, this study sidelines the possibility to predict and model potential areas that contain acid sulphate soils with characterization of fine-grained sediments. This study increases knowledge about Turku areas surficial deposits and can be used as a support for construction and urban planning in the Turku region or as a spatial information model guide on the presence and composition of building foundations. The methodology used in this study can be utilized in similar areas on the coasts of Baltic Sea to study fine-grained sediments.

Key words: Paleotopographic classification, fine-graines sediments, depositional environments, Benthic Terrain Modeler (BTM), land use, Turku

Content

1. Introduction

Modern life is affected a lot by urbanization, this demands new untypical building areas for increasing population in the city regions and therefore also new solutions for construction. One of the main objectives of land use planning is regional structure compaction, which means new construction regions cannot always be selected from the perspective of structural capacity. Land use planning of a difficult area, for example fine-grained sediments, requires proper background studies and plans to avoid problems due to surficial deposits possible weak characteristics. It is also necessary to bear in mind the higher construction costs caused by more challenging founding conditions.

Turku is one of the biggest cities in Finland with the population of 195 000 (kuntaliitto.fi, visited 07/2022) and yet growing. Turku is located the coastal area of south-west Finland, where the surficial deposits composition is being influenced by the formation history of the Baltic Sea Basin. This means that the Turku area has experienced saline and brackish water phases during its history and contains mostly fine-grained sediments (Gardemeister, 1975). These sediments can be found mainly in bedrock depressions, but their exact spatial distribution and thickness variations are poorly defined and modelled in the Turku region. Nearly 40% of the surface in Turku is fine-grained sediments, which is not so ideal for construction because its poorer geotechnical properties. Fine-grained sediments are usually featured with frost susceptibility, low load capacity and large depression (Turun kaupunki, 2013).

Engineering-geological properties of fine-grained sediments in coastal areas in Finland have previously been studied for example by Gardemeister (1975) all over Finland, by Ojala et al. (2018, 2021) and Saresma (2021) in the capital region and generally their spatial distribution has been mapped by Geological Survey of Finland (GTK). The results of these studies show general characteristics of fine-grained deposits in relation to challenges that fine-grained sediments bring to land use and urban planning. Most of these studies are focused on the Helsinki metropolitan area, which is, however, geologically quite like the Turku region. In 2016, Laura Pirilä did a study focusing on the characteristics of the clays, variations in their thickness and history of origin in the Turku region (Pirilä, 2016).

The morphometric characterization of sedimentary depositional environments during the Baltic Sea phases brings benefit to land use and urban planning in the areas of fine-grained sediments such as Turku. Based on the data available it is possible to create a more detailed model of the bedrock surface and the sedimentary deposits on top of it, or in other words the topography of the basin. Identifying the range, thickness, and elevation level (meters above sea level) of fine-grained sediments advances sorting out different layers in the sedimentary deposits, such as acidic sulphate soils. The geotechnical properties of fine-grained acid sulphate soils are poor in general like, because they are usually soft and massive horizons with impervious of water, they are originally structureless with no aggregates and have very low bearing capacity (Yli-Halla, 2022). According to instructions from the Ministry of the Environment, any acidic sulphate soils in the region should be taken into consideration in land use planning (Suikkanen et al. 2018). In most cases acid sulphate soils are considered as an environmental risk. When exposed to oxidizing conditions, acidification of acid sulphate soils is inevitable. As a result, the underground concrete and steel structures may become corroded. In addition, heavy metals may be dissolved in the water from excavated soil masses (Autiola et al. 2022).

This study will apply and update the previous investigation by Pirilä (2016) with the focus on mapping of areas covered by fine-grained sediments in the Turku region and their thickness variations. The overall goal of this study was to develop a 3D-model of fine-grained sediments for urban planning and land use purposes. The specific aims of the study are: (i) how fine-grained sediments and their thickness vary spatially in the area, and (ii) is it possible to recognize their variability in relation to bedrock topography and surface exposures. In order to understand why engineering-geological properties of clayey deposits vary spatially, it is essential to analyze different sedimentary deposition environments. By classifying different types of sedimental environments, it is aimed to increase understanding of fine-grained sediment for land-use and construction purposes and to predict and model potential areas that contain acid sulphate soils.

2. Study area

This study's focus is on Turku region, which is located on the southwest coast of Finland (Figure 1). The urban region of Turku covers the municipalities of Kaarina, Lieto, Masku, Mynämäki, Naantali, Nousiainen, Paimio, Raisio, Rusko, Sauvo and Turku. Urban region has surface area of 2 590 km^2 and total population of 337 000 in 2021 (Tilastokeskuksen maksuttomat tietokannat, 07/2022).

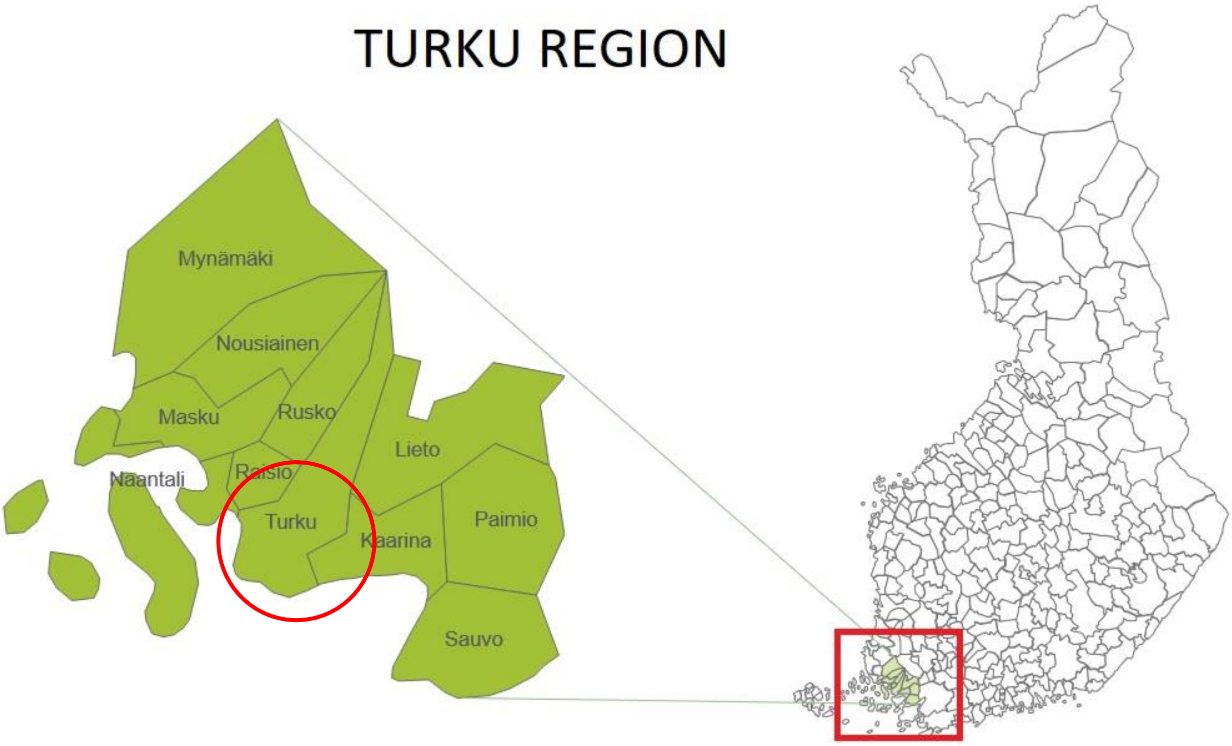
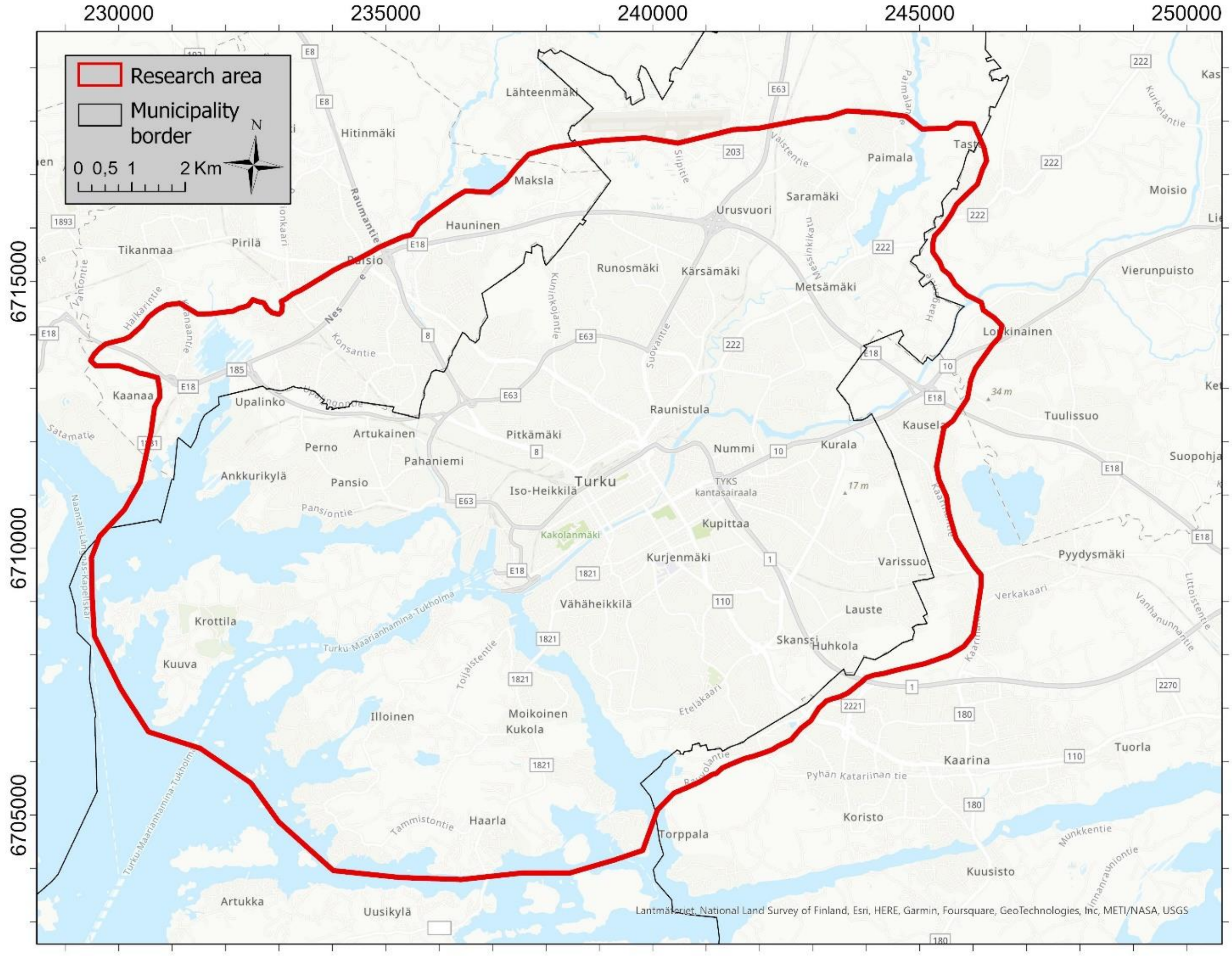


Figure 1. Overview of the Turku region in map of Finland (Tilastokeskus.fi, 07/2022). Study area marked in red circle.

The Turku region is described as hilly terrain with elevation variation of 20-50 meters. Apart from coastal and archipelago areas, there are only a few freshwater bodies in the region. Topographical general features in the area can be graded as fractured bedrock with valleys, depressions, and banks. These features are most visible especially in the coastal areas. The height ratio in the region is quite low with absolute height being under 80 meters. This is the result of late rising from the sea. The average height of the terrain rises when moving from the coastal areas to northeast (Lounais-Suomen Seutukaavaliitto, 1966).

The research area covers a total surface area of 177 km^2 and consists of parts of Turku, Raisio and Kaarina municipalities with the main concentration in Turku (Figure 2). Outer limits of the research area were mainly determined to follow bedrock outcrops and sedimentary deposits. Dimensions of the research area was also based on the data availability and coverage of geotechnical drilling information. That is why parts of the Raisio, and Kaarina municipalities were added to the research area. The northern part of the Turku municipality is mostly a sparsely populated area with lots of agricultural fields compared to the rest of the Turku and was therefore left out. The cropping was done on the south side of the Turku airport because the airport area has been under construction a lot, which has made the geotechnical data of the area very tangled.



Lantmäteriet, National Land Survey of Finland, Esri, HERE, Garmin, Foursquare, GeoTechnologies, Inc, METI/NASA, USGS

Figure 2. The study area. Bold black lines marking the municipality borders of Turku and the red line marking the study area.

2.1. History of Turku region

Turku is one of the oldest cities in Finland, formed along the river of Aurajoki. The name “Turku” was probably first mentioned in the 1150s (Lappalainen, 1999), and along the 1200s the city began to develop with trading places, villages of the Aurajoki valley and fortresses (Turun kaupunki, 2013). According to Lehtonen (1997) there are signs of human activity from 7 000 years ago in the cultural landscape of Aurajoki-valley. Prehistoric relics found in the area suggest that the settlements had been continuous since the Iron Age. And no wonder, because the living conditions in the Aurajoki-valley area have always been beneficial; sheltered location for shipping and fishing, favorable climate to live and cultivate, nutritious soil and good transport connections in sea and in land.

Traces of the first settlements are approximately from 5 000 years ago, when the sea level was 38 m higher in the Aurajoki-valley compared with the present-day sea level. At that time most of the now-known Turku was under water and the settlements were higher up along the river. As a result of isostatic land uplifting (Kakkuri, 2012), the sea level was regressive (Glückert, 1977), which meant that the water line moved further away from the settlement and the waterfront was getting too shallow for the boats to approach trade places. Therefore, the settlements moved closer to the mouth of the river by the sea along time (Kivikoski & Gardberg, 1971).

It is believed that in AD 1229, Turku was declared as the first city in Finland, when the episcopal seat was placed in Koroinen. When the Turku Cathedral was built in AD 1300 as a physical and symbolic sign of the church’s status, the cathedral area formed the core of the city with permanent settlement until the 1400’s (Turun kaupunki, 2013). In AD 1318, a fire broke out and torn down almost the entire city and the Cathedral. During the reconstruction work, the core area of the city was expanded with the town planning (Kivikoski & Gardberg, 1971). And the city started to expand even more to west side of the river after the first bridge across the river was built in AD 1414. People started to talk about “the small side and the big side”. The city of Turku was the most important trading city in Finland to the end of 1500’s (Turun kaupunki, 2013).

In Figure 3, can be seen the different phases of Turku's site plan. Black plots are around AD 1300, striped plots are first half of the 1300's, dotted plots are AD 1380-1520 and plank plots are AD 1520-1634 (Kivikoski & Gardberg, 1971).

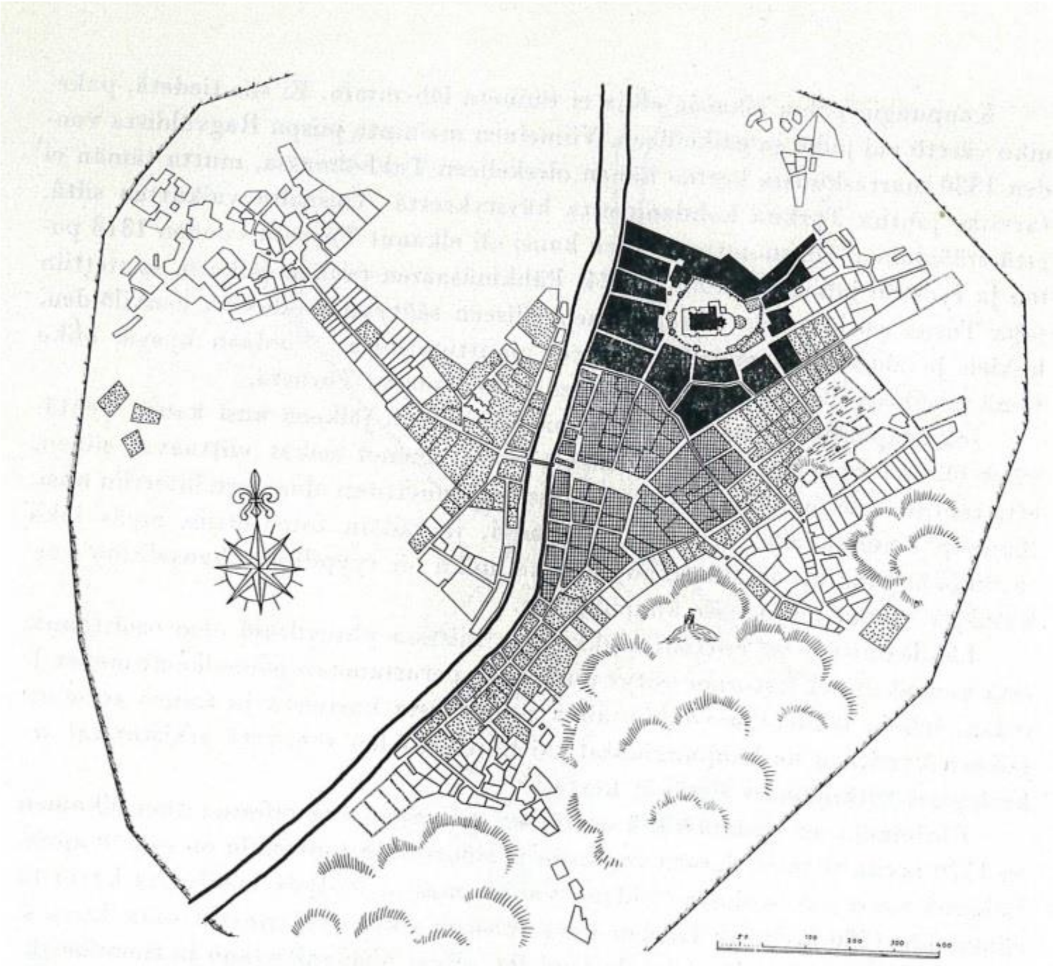
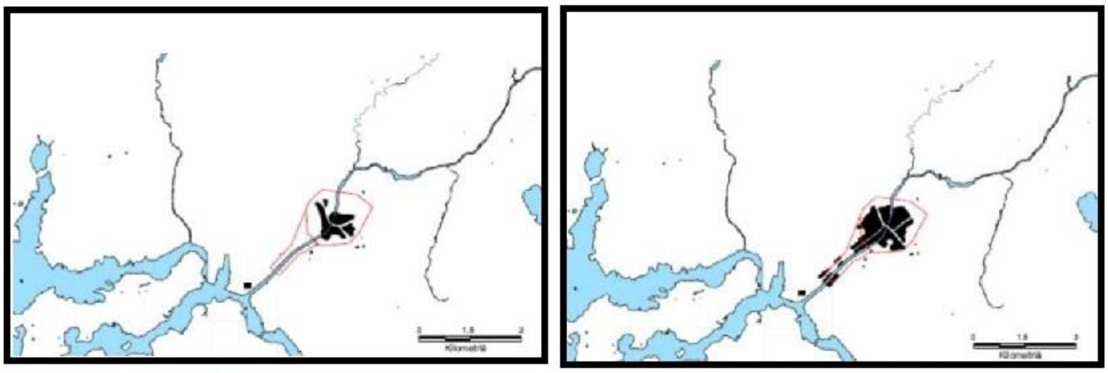


Figure 3. Development of Turku's site plan during AD 1300-1650 (Kivikoski & Gardberg, 1971).

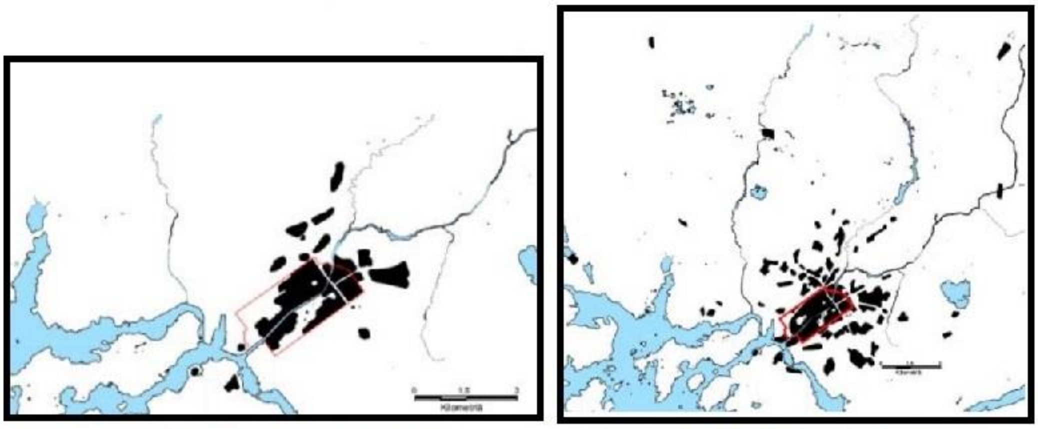
The heyday of Turku was in the 1600's, when it became the second largest city in the Swedish kingdom after Stockholm. And in addition to, the Head of Finland, governor general, was positioned in Turku, the Court of Appeal was established, the first university in Finland was founded, and the population of Turku was 3 000. In the 1700's city of Turku started to industrialize, and it is said that in Turku started the Finnish industries of tobacco, textile, and sugar. Later, started the shipyard industry and in the end of the 1700's the first features of an industrial city began to take shape with established factories along the banks of the Aurajoki river (Turun kaupunki, 2013).

The 1800’s was downhill for Turku. In AD 1809, Finland was annexed to Russia and Turku was declared the capital of autonomous Finland. Three years later the capital was moved to Helsinki. And the last straw was in AD 1827, when the Great Fire of Turku happened and destroyed the city. After that, rest of the state administration moved to Helsinki as well, leaving Turku with trading and industry. In the end of the 1800’s, industrialization and urbanization brought modern municipal engineering with water and sewage plants, waste management, electricity, and gas for the people. After the world wars, in the mid-1900’s, the population of Turku started to grow, when people moved from primary production in the countryside to industry and service occupations in the city. Because of the negligible expansion possibilities in the bank of Aurajoki river, the factories moved away from the city center. During the 1900’s, city of Turku expanded considerably, when new residential areas were built outside the city and new areas were added to Turku (Turun kaupunki, 2013). In Figure 4 can be seen the expansion of the land use and plan area in the Turku region from AD 1650 to AD 1950.



Land use and plan area boundary in AD 1650

Land use in AD 1800 and plan area boundary in AD 1650



Land use in AD 1900 and plan area boundary in AD 1828

Land use in AD 1950 and plan area boundary in AD 1828

Figure 4. Land use in Turku region from 1650 to 1950. (Turun kaupunki, 2013 / Asemakaava 2020).

Most of the cultural landscape in Aurajoki-valley is molded by human activity, such as field cultivation since the 1500's. Until the 1700's, the landscape was mostly fields with a few churches in the middle and the settlements in Aurajoki-valley were focused on the main roads of ancient times, such as Hämeen Härkätie and Varkaantie. After the mid-1800's, urban areas were built with schools, shops, and municipal and industrial buildings. In the middle of the 1900's, industrialization made also agriculture mechanized, which meant the population of cities grew rapidly and a need to have new land area for new residential areas (Lehtonen, 1997).

In the last 50 years, the population of Turku has been increasing and decreasing alternately. After the eager migration flow in the beginning of the 70's, the population started to decline after the mid-70's. Until in the 90's it turned up again and started to grow steadily. The development of the population can be seen in the Figure 5 (Turun kaupunki, 2013).

The total surface area of Turku is 306,4 km^2. In 1970, the town plan area was 60,5 km^2 and in 40 years, it has grown around 60%. In 2012, 97 km^2 of Turku surface area was covered in urban area development plan (Turun kaupunki, 2013).

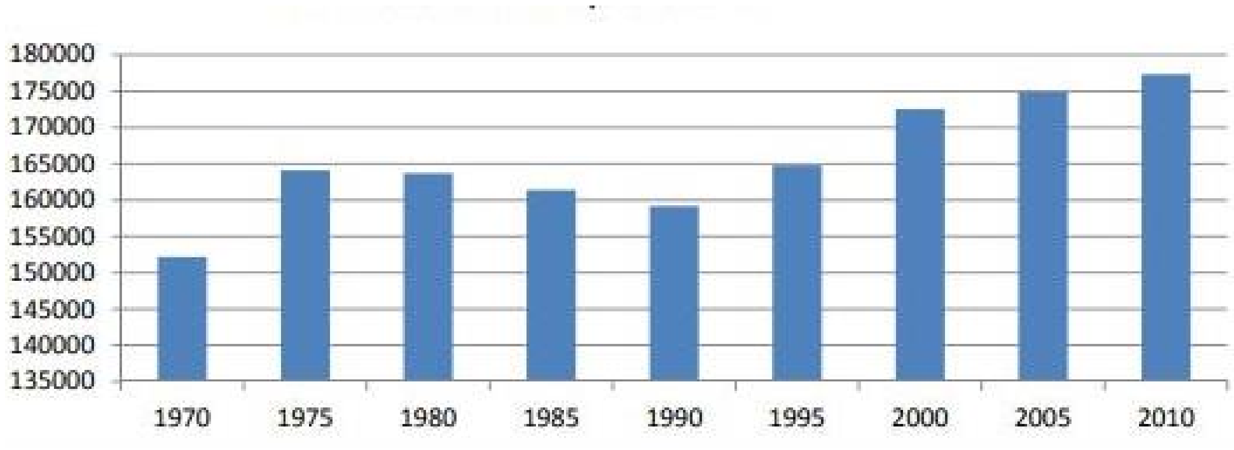


Figure 5. The development of the population in Turku from AD 1970 to 2010 (Turun kaupunki, 2013).

2.2. Geological characteristics

The ground surface in Finland consists of two main geological units that are separated by unconformity and have significant difference in age and in characteristics. The bottom unit is the Precambrian crystalline bedrock that topped with an upper layer of Quaternary sediments. Elsewhere in the world this type of geological setting is very uncommon which makes the Finnish ground surface special. The lower lying bedrock is part of the Fennoscandian Shield, which belongs to wider section of Northern and Eastern European bedrock. Most of the Finnish bedrock originates from 3000 – 1,500 Ma ago when the mountain range started to foliate (Niini, et al. 2007). The surficial deposits in Finland are developed in the recent geological times mostly during the Quaternary period. Most Quaternary deposits in Finland represent the end of the latest glaciation period, which started about 2,5 Ma ago, and beyond (Salonen et al., 2002). As stated by Andrén et al. (2011) the location of the Baltic Sea Basin in high northern latitude makes it sensitive to glaciations and gives the area a very dynamic development during its geological history. According to Haavisto-Hyvärinen & Kutvonen (2007) Finland is mostly covered by surficial deposits with some exposed Precambrian bedrock in places. The surficial deposits are mainly developed during the youngest quaternary period, in the last 100 000 years or after it. Since the Earth’s crust was embedded by the influence of the ice sheets during the glaciation, after the Weichselian ice age when the ice sheet was melted, over half of Finland was submerged under Baltic Sea.

2.2.1. Bedrock

According to Eklund et al (2007) the bedrock in the South-West Finland formed 1900 – 1765 Ma ago during the Svecofennian orogenesis. It has been molded by repeated ice ages since then, but the sediments on top of the bedrock have formed mostly during the latest glaciation, Weichelian, the deglaciation and post glaciation. Generally, in Finland approximately 3% of the bedrock are visible outcrops in the surface area while rest of the area is encrusted with different surficial deposits formed during or after the withdraw of the glaciers (Niini, et al. 2007). Besides the traces of the ice age, the bedrock has experienced the transitions of the earth’s crust, which has caused local tectonic changes such as folding, lamination, fractioning, and cleavage.

In the Turku region, around 35% of surface area is composed of bedrock outcrops (Turun kaupunki, 2013). It is based on the old bedrock with abundance of mica schists and mica gneisses observed in the north, whereas granites and granodiorites are found in the south. Also, east-west-directional zones of amphibolitegneiss can be found in the area (Lounais-Suomen Seutukaavaliitto, 1966). A more detailed map of the lithological rock units in Turku is found in Figure 6.

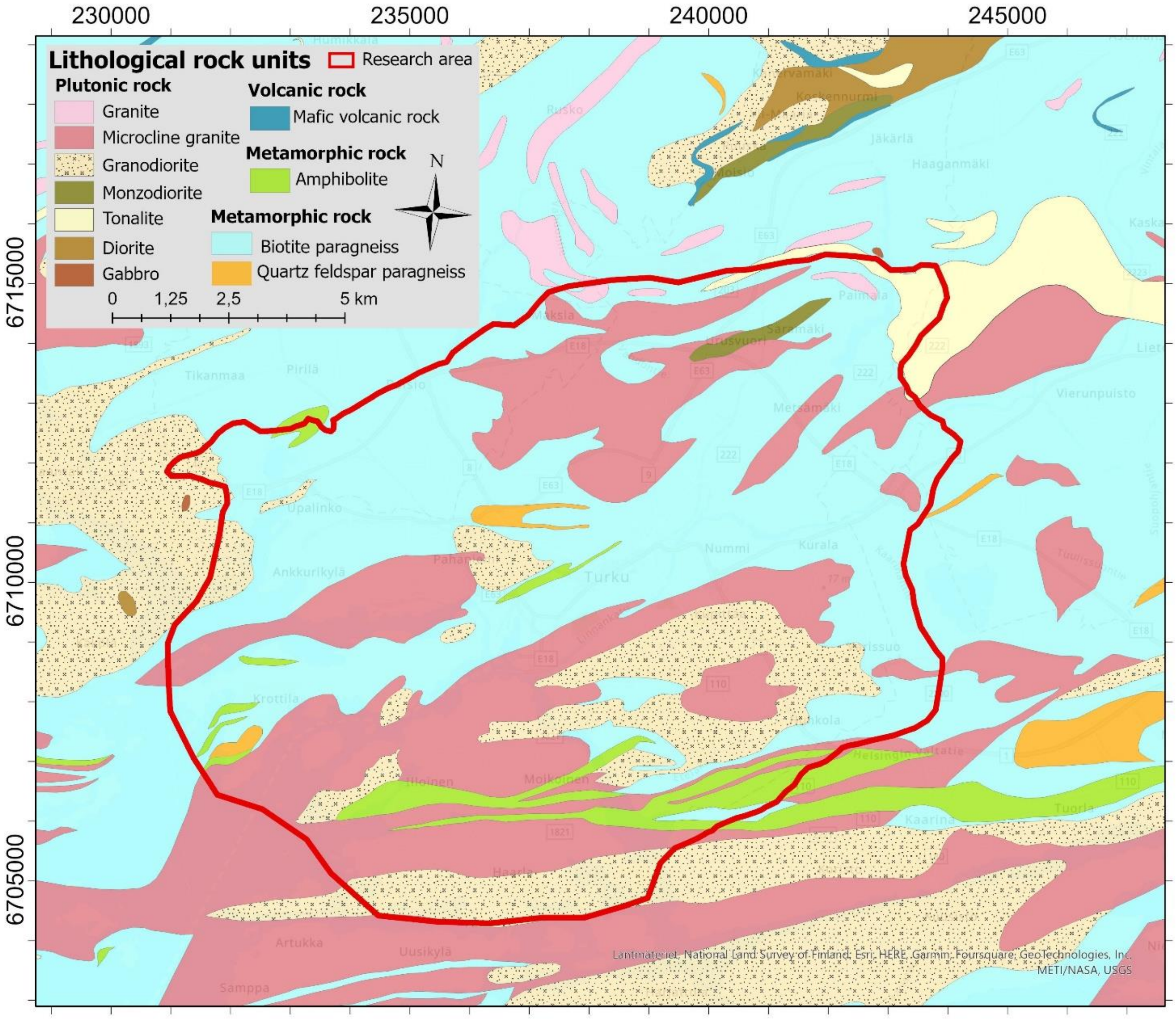


Figure 6. Lithological rock units in Turku area. (GTK bedrock of Finland 1:200 000).

In the following is a description of Pre-Quaternary rocks of the Iniö and Turku map-sheet areas by Karhunen (2004). Based on the summary, the oldest rocks in Turku region are Svecofennian supracrustal rocks which have deposited into sediments and vulcanites on the seabed and on the earth's surface. Most widely represented are mica gneisses, but also rocks like quartz-feldspar-paragneisses and volcanic amphibolites are found in the area. Large continuous areas of mica gneiss can be found in the region, with heterogenous features and partly migmatitic rocks ranging from fine-grained mica schists to coarse-grained veined gneisses. By dividing mica gneisses into two main groups by mineralogically, they can be categorized as 1) biotite-plagioclase mica gneisses, with fine- to medium-grained and main minerals such as plagioclase, K-feldspar, quartz, and biotite and 2) garnet-cordierite mica gneisses (kinzigites) with slightly coarser grained and main minerals such as plagioclase, quartz, biotite, and garnet and/or cordierite.

The quartz-feldspar gneisses can be found as thin layers intercalated with mica gneisses, amphibolites and hornblende gneisses. They are usually fine-grained and banded gneisses, which seem most likely to present layering originated from depositions in shallow water.

The amphibolites in the area occur even-grained and fine- to medium-grained. They are often banded with well-preserved primary structures, i.e., pillow-lavas and pillow-breccias which indicate their volcanic origin. The largest aphibolitezones in the area are one and a half kilometers wide and several kilometers long in an east-west direction.

Synorogenic plutonic rocks, such as granodiorite and tonalite, are found in the Turku region as large continuous zones in east-west direction. They are mainly medium- to coarse-grained, pale, and often foliated. Gabbros in the Turku area are even-grained and medium- to coarse-grained. They occur as small, separate intrusions and as fragments in other plutonic rocks with diorite.

Microline granites in the area are described as red and greyish, heterogeneous, and medium- to coarse-grained. Granites in Turku are rich in garnet compared to granites in the further west. They often grade into pegmatite and their migmatized veins and irregular dykes intrude into the supracrustal rocks (Karhunen, 2004). Probably the most famous granite from the area is Kakola granite, which was quarried locally in the Kakola Central Prison by its prisons in Kakolanmäki Hill, southwest of the city center. Kakola granite was used for example in buildings, paving stones, memorial stones, and tombstones (Selonen & Ehlers, 2021).

The bedrock in the area is full of rifts and fracture topography, because of the ancient and overtime recurrent earthquake movements. Most of the joint valleys can be seen as long and wide valleys in the landscape. The bedrock in the region is described very fractured and exposed, with strong fault lines and bordered by clay. In the archipelago, the fault lines direction is typically east-west, slopes of the rock outcrops are steep, and depressions are filled with clay. More inland, the strongest fault lines are directional in south-north or in south-west and north-east. The slopes are not as steep as in the coastal areas and wide clay plains spread out at the intersection of the fault lines (Lounais-Suomen Seutukaavaliitto, 1966).

2.2.2. Surficial deposits

As stated by Salonen et al (2002) the surficial deposits in Finland are relatively thin, with the overall thickness of three to four meters. On the other hand, the entire thickness of overburden in Finland is the average of 8,6 m, and in some areas, for example in high ridge areas or clayey areas, it can get tens of meters thick. High ridge areas with over hundred meters thick layers of glacial gravel and sand can be found in Salpausselkä region e. g. in Nummelanharju, Vihti and Aurinkovuori, Asikkala in Southern Finland. Clayey areas can be tens of meters thick, but especially in Southern Finland the layers of clay are in many places 20-30 m thick. Some of the thickest clay layers in Finland have been found in the Aurajoki-river area in Turku, Southwestern Finland (approximately 50m), and near Oulu in Northern Finland with over hundred meters (Salonen, et al. 2002).

The occurrence of fine-grained clastic sediments (clay and silt) are mainly in the sub-aquatic areas in Finland (Ojala et al., 2013). Usually, the upper limit of clay deposits is approximately 20 m below the highest shore of the Baltic Sea (Salonen et al. 2002). The origin of fine-grained sediments in Finland are strongly associated with the development of Baltic Sea Basin, which make them relatively young deposits dating to the Late Weichselian and Early Holocene (e.g., Andren et al 2011). The different phases on the development of Baltic Sea Basin, post-glacial rebound and topography of the seabed have influenced what kind of clay has been formed and how much it has been deposited regionally. In Southern Finland the thickness of these fine-grained layers is average 10 m, but in South-West Finland the thickness may occur over 50 m or even 100 m (Niini et al, 2007).

Almost 40% of surface area in Turku region is covered by fine-grained sediments, while bedrock outcrops cover around 35%. From the city area, circa 10% is covered with artificial ground, which makes the original type of surficial deposits in the area unspecified. About 8% of the surface is covered by till and nearly 4% is sand and gravel (Turun kaupunki, 2013). On top of the bedrock is the second most common surficial deposit type in the area, till, with consistency of fine sand-sand, and relatively voluminous clay percentage (5-10%). Tills can be found in the area as heterogeneous thin layers in the rocky areas, rather than usual broad uniform. In the southern areas tills are generally thin strips in the southeastern slopes of rock outcrops. Glacial river deposits can be seen as fragmented series of eskers in the area, mainly scattered as small local ridges. These deposits are mostly sand and gravel with a thickness of 5-10 m. The areas clearest united series of esker is Laitilan harju ridge, which passes the research area in north with southeast-northwest direction. Shoreline landforms, which have been washed out of the moraine, are quite common in the area, but small in size. Over the till lays the fine-grained sediments, that in Turku region can be classified such as muddy clay (with 2-6% of organic material in percentage of weight) and rich clay (with over 50% of clay fraction). In the Turku area peat deposits are rare since swamps are comparatively young and thin with only 1-3 m of peat layer (Lounais-Suomen Seutukaavaliitto, 1966).

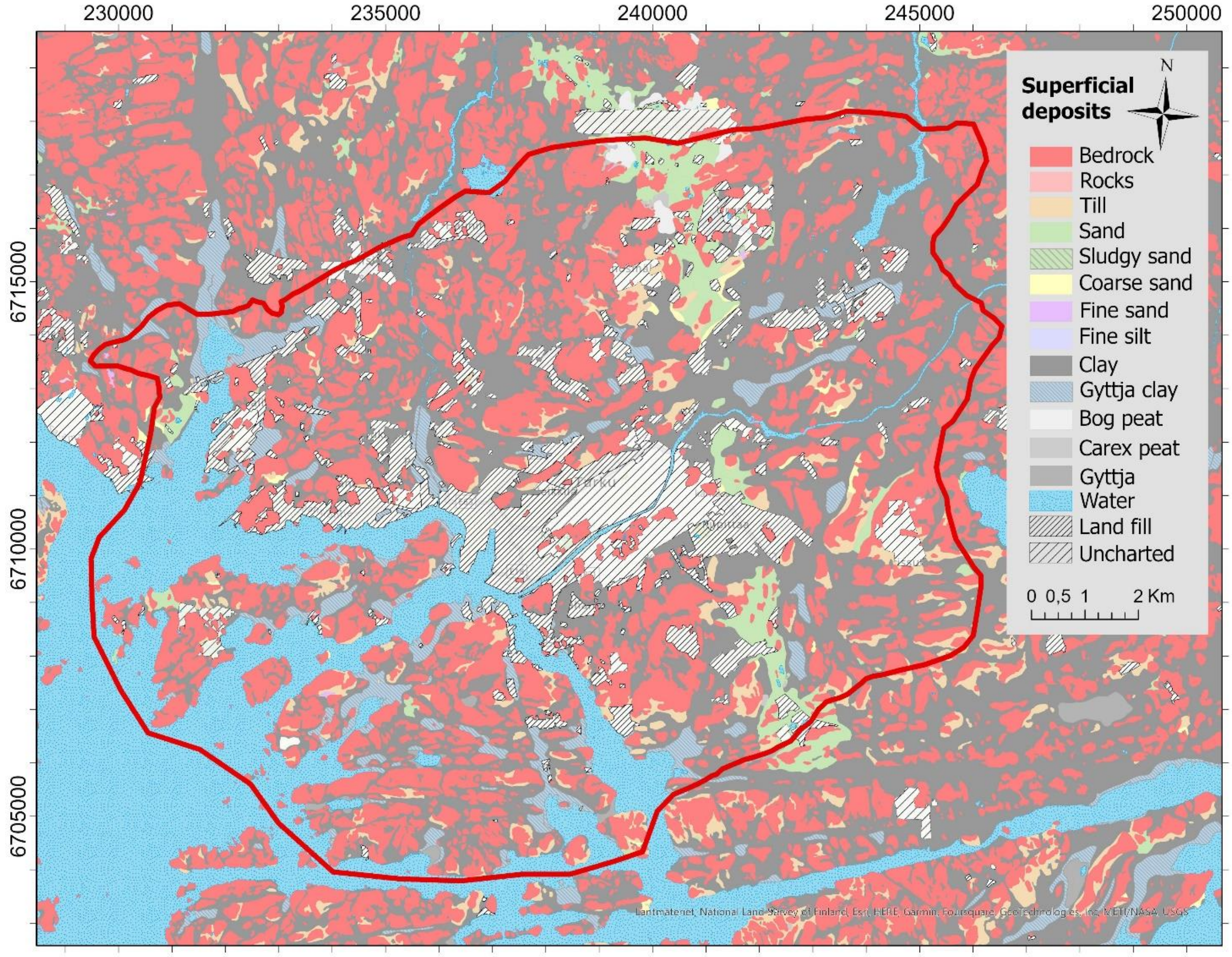


Figure 7. Surficial deposits in the Turku region (GTK Superficial deposits 1:20 000/1:50 000).

2.2.3. Development of the Baltic Sea Basin

Due to its location, the Baltic Sea Basin has gone through a lot of changes during the last glaciation, sometimes being covered by a glacier and sometimes not (Haavisto-Hyvärinen & Kutvonen, 2007). When the Quaternary ice age was at its coldest phase, during Late-Weichelian 25 000 – 11 500 years ago, a huge amount of water from the ocean was bound to the ice and because of that the ocean surface was over 120 m lower than today (Miller et al, 2020). As reported by Salonen et al (2002) the Fennoscandian Shield area was covered by up to 3 km thick ice sheet, that pushed down the Earth's crust at most 1000 m. When the ice sheet started to melt, the water bound to the glacier was released back into the hydrological cycle and the earth’s crust began to return to its former form. This caused the isostatic uplift, which already covered 600-700 m since the LGM (last glacial maximum), and which is believed to continue theoretically for the next 7000 – 12 000 years and the crust will rise another 100 – 150 m (Salonen et al, 2002).

According to Kakkuri (2012) eustatic rise is the most important factor to influence the height of the sea level. Other geophysical factors to influence it are e. g. changes in the gravity field due to continental ice melt, isostatic changes in the Earth's crust, thermal expansion of sea water, the influence of weather conditions and slow changes in the volume of the sea basin.

The retreat of an ice sheet, isostasy, melting waters and elevation changes in the water surface associated with the historical phases of the BSB left their mark to sediments and surroundings of the Baltic Sea Basin. And specially in the Southern and Southwestern Finland, the ice sheets affected a lot to the area's topography (Karhima, et al 2011).

Following the onset of deglaciation from the last glacial maximum, the Weichselian ice sheet started to melt rapidly 14 500 years ago, and in the following 2 500 years the ice sheet had withdrew over Southern Finland (Karhima et al., 2011). But a sudden turn took place, the temperature dropped again, the retreat of the ice sheet stopped, and it even started to expand a little once more. During this phase, called Younger Dryas, formed Salpausselkä I and Salpausselkä II, which pass through Southern Finland. Younger Dryas ended 11 500 years ago, when the ice age is also considered ended (Salonen et al, 2002).

After Younger Dryas, the Baltic Ice Lake (Figure 8, A) was formed by glacier meltwater and 11 600 years ago it started to discharge into Atlantic Ocean trough Billingen strait in south-central Sweden (Johnson et al, 2022). The water level in Baltic Ice Lake dropped 26-28 m and the salinity of the water started to rise. This turned the Baltic Ice Lake into the Yoldia Sea (Figure 8, B), which is the subsequent phase in development of the Baltic Sea. Since the Billingen strait started rapidly to shallow up due to tectonic uplift, the large outflow prevented saline water to enter the Baltic Sea Basin. The water level started to rise again and the Yoldia Sea transformed into a freshwater basin called the Ancylus Lake (Andrén et al. 2011).

During the Ancylus Lake (Figure 8, C), sea level started to rise when the Öresund Strait started to flood and it is believed to be the main reason for transformation into Litorina Sea. This next phase is to be said as a marked lithological change in Baltic Sea cores with its very distinct increase in organic content and abundance of brackish marine diatoms (Andrén et al, 2011). 9000-7500 years ago, when the Litorina sea-phase started, the salinity of Baltic Sea rose and the water became more brackish (Karhima, et al 2011). Litorina Sea (Figure 8, D) represents the saltiest phase in the history of the Baltic Sea, as it was more saline than Yoldia Sea and current Baltic Sea. When the Laurentide and Antarctic ice sheet started to melt and Öresund Strait started to flood, the absolute sea level rose approximately 30 m over couple of millennia.

These ice sheet melting events may be the explanation for the so-called Litorina transgression in the Baltic Sea (Andrén, et al, 2011).

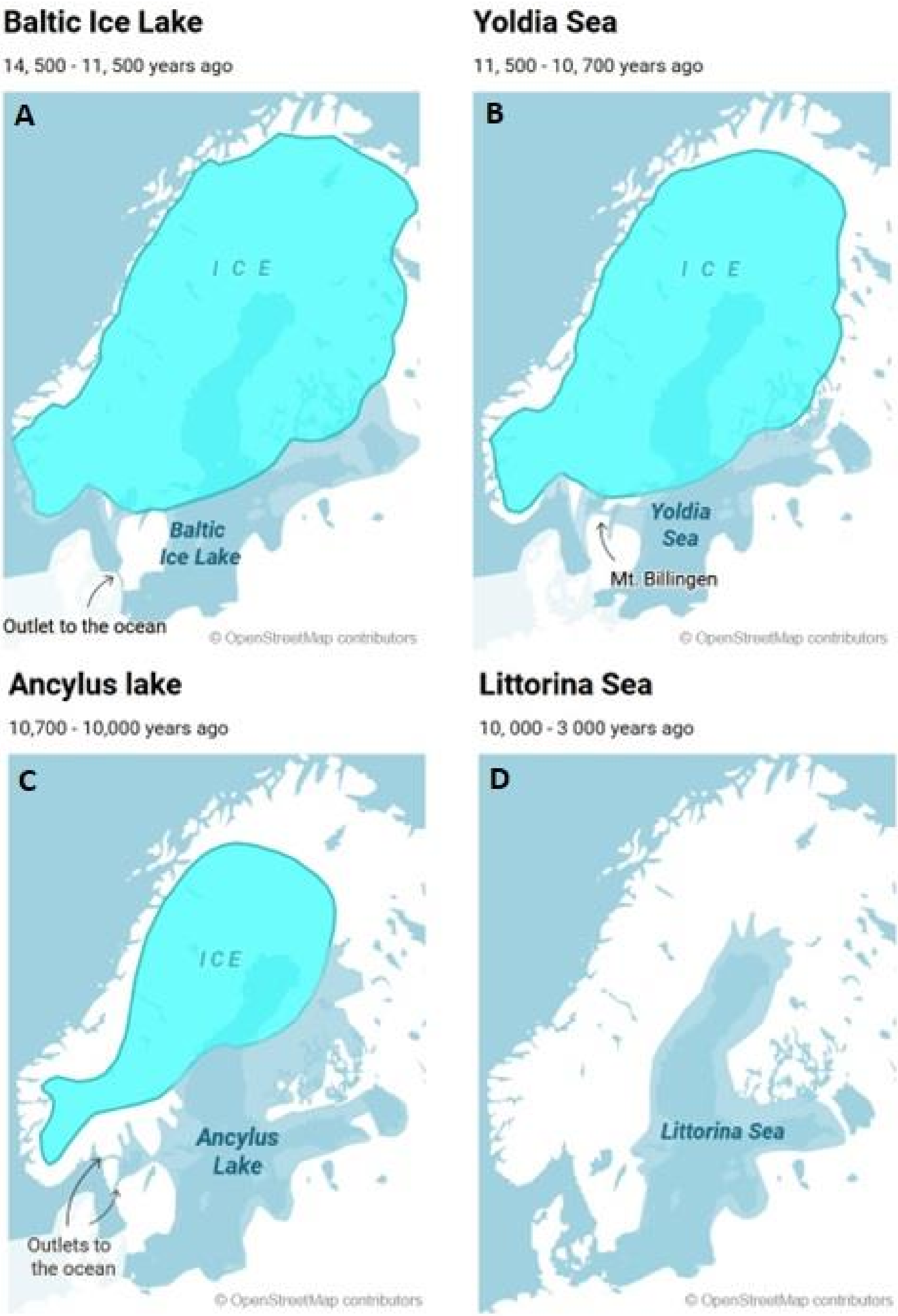


Figure 8. The development history of Baltic Sea (Thieme, 2019).

The Fennoscandian Ice Sheet retreated from Turku region circa 10 700 years ago, leaving the area under water with 130 m higher sea level than nowadays (Ojala et al., 2013; Stroeven et al., 2016). The traces of the oldest phase of the development of Baltic Sea Basin, also known as Yoldia sea phase, cannot be seen in the Turku region because of the submersion. With fast post-glacial rebound, the highest peaks in the Southwestern Finland began to rise from the sea during the transformation from Yoldia sea to Ancylus lake. The Anculys lake phase ended in 9000 cal BP in Turku region, cal BP meaning calendar years before AD 1950. The highest tops in the area, currently 60-80 m above the sea level, then rose from the sea with the rest of the region following behind (Glückert, 1977). Figure 9 shows the shoreline displacement in Turku. In the figure, there can be seen two obvious slowdowns in the curve, which indicate for transgression. During transgression, the sea level rose nearly as fast as the Earth's crust, which meant that the water level remained at almost the same level for some time in the terrain (Glückert, 1976).

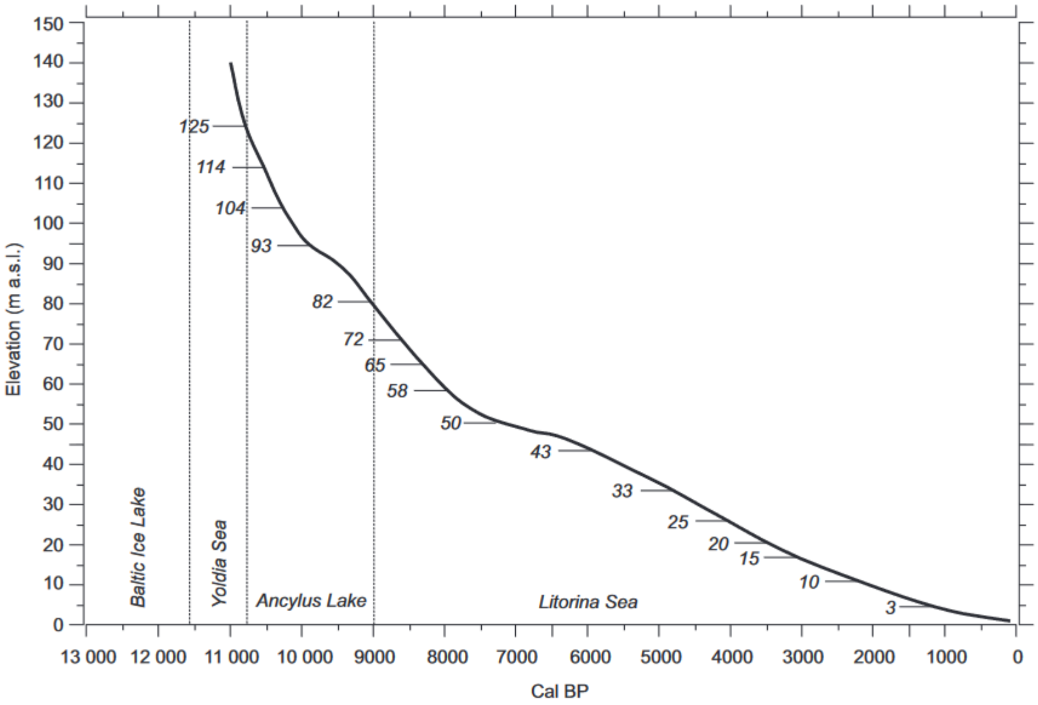


Figure 9. Shoreline displacement in Turku, based on Glückert (1976) and modified according to Eronen et al. (2001) and Ojala et al. (2013).

Post-glacial shore-level displacement have been studied for instance by Glückert in past decades (1976, 1977) and later results have been collected to reconstruction papers made by e.g., Ojala et al. (2013) and Rosentau et al. (2021). By exploiting these studies, it was possible to create additional paleotopographic elevation models in the Turku region. Models were made in the ArcGIS environment (®ESRI) after isobase TIN-surfaces from the study by Ojala et al (2013), and shoreline displacement curves. The paleotopographic elevation models were produced to simulate the terrain surface level and environmental conditions in different phases, in other words, to reconstruct ancient shorelines. Figure 10 shows the submersion of Turku region after the ice sheet retreated in 10 700 cal BP. Figure 11 displays terrain after the end of the Anculys lake in 9 000 cal BP, when the highest peaks in the area started to rise from the sea due to post-glacial rebound. Figure 12 demonstrates Turku region in 4 000 cal BP.

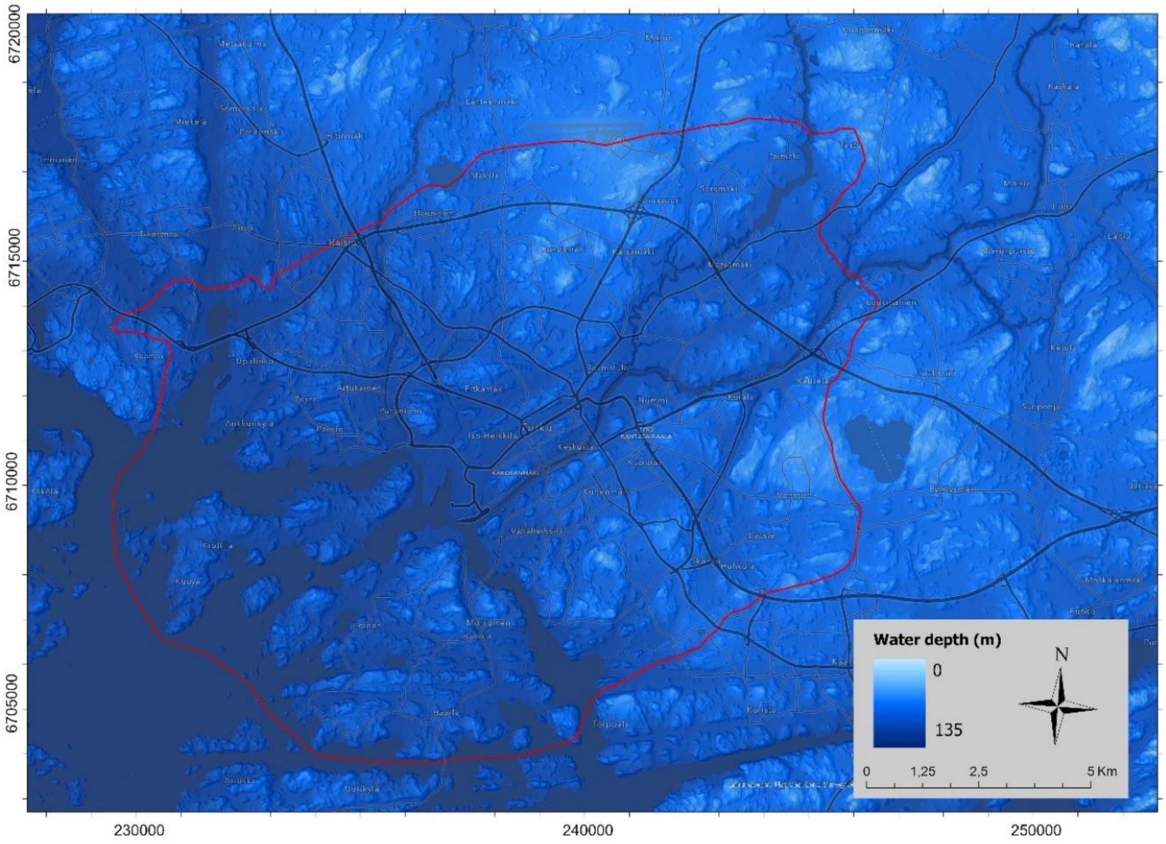


Figure 10. Water depth in Southwestern Finland 10 700 cal BP. Based on Ojala et al (2013).

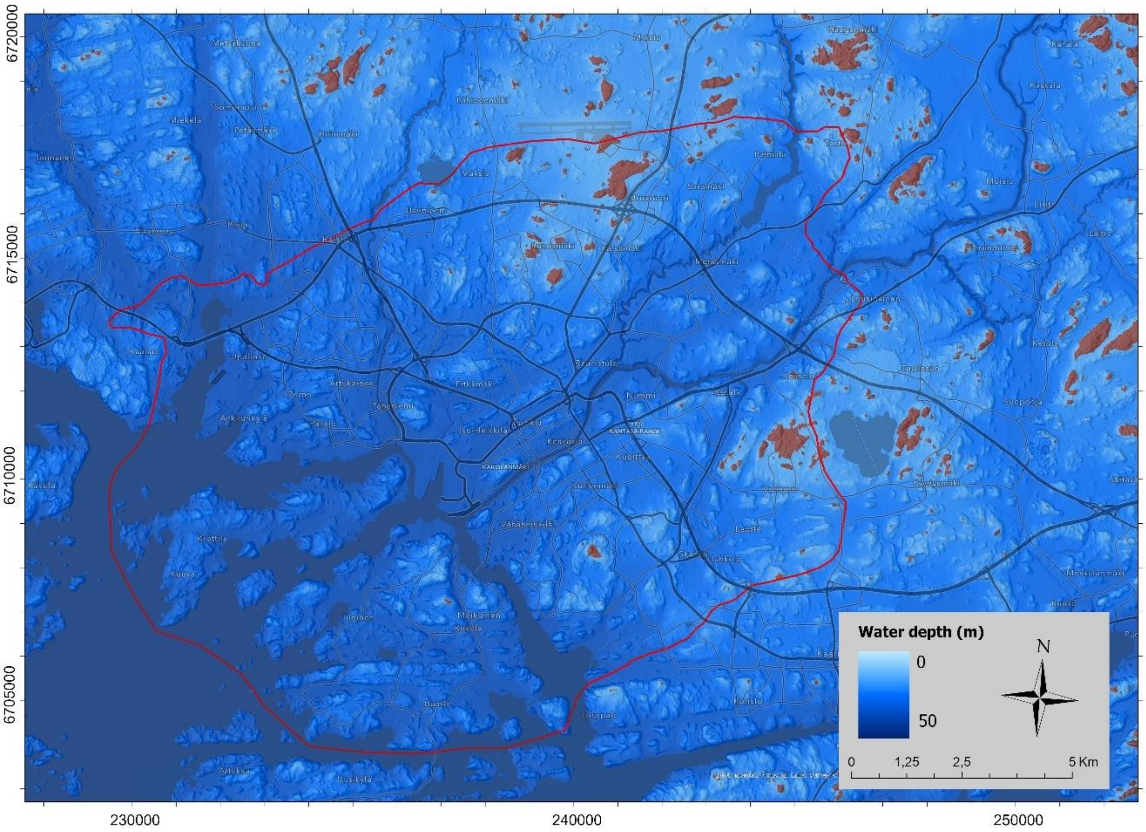


Figure 11. Water depth in Southwestern Finland 8000 cal BP. Based on Ojala et al (2013).

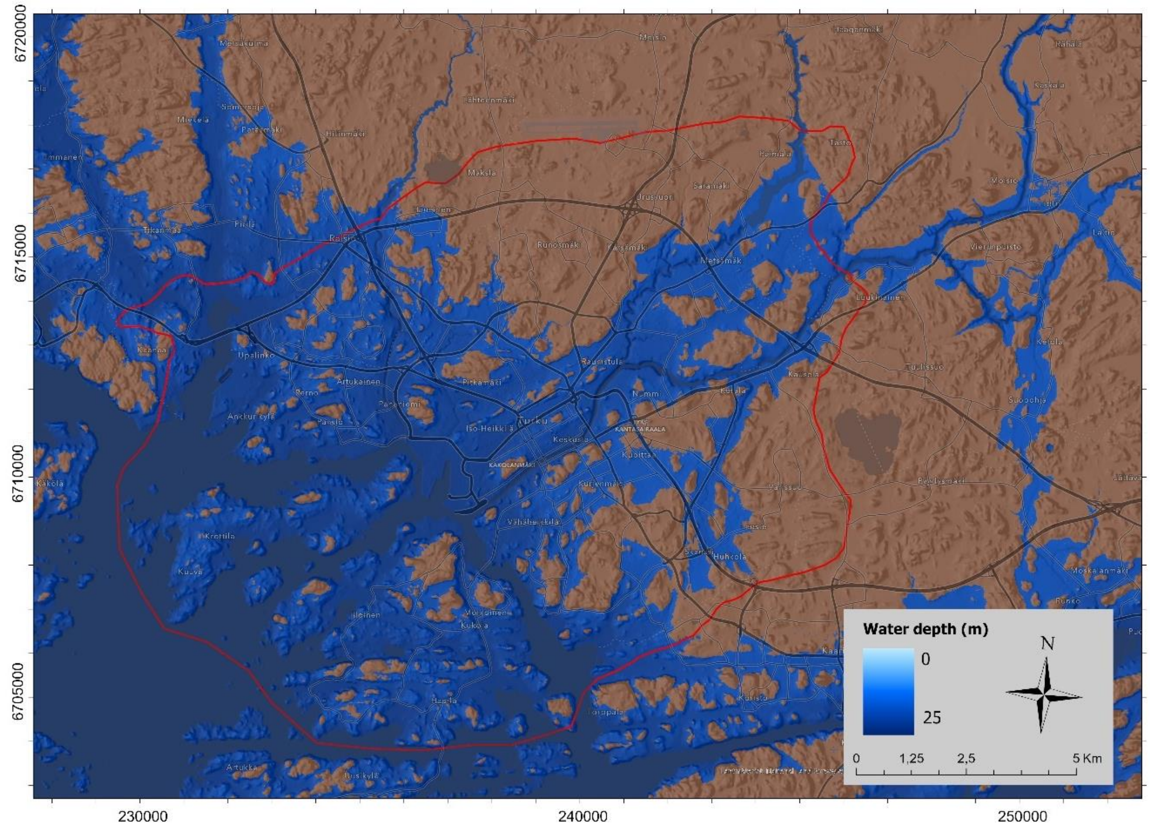


Figure 12. Sea level and water depth in Southwestern Finland 4000 cal BP. Based on Ojala et al (2013).

3. Materials

Paleotopographic model for the ancient Baltic Sea Basin in the Turku region 1) after deglaciation 2) during the Litorina transgression and classifying it into bathymetric terrain zones and structures (Saresma et al, 2021) provides a basis to build a model for the aim to identify fine-grained sediments and their thickness in the Turku region. In the present work, this framework has been supplemented with the following information and datasets.

3.1. Datasets

The datasets used in this study were combined from different kinds of sources (Table 1). Most of the geological data are from map services and online data sets of The Geological Survey of Finland (GTK), which has the main archive of geological data in Finland (HAKKU, GTK, https://hakku.gtk.fi/fi/locations/search). The GTK database provided geological maps of Quaternary superficial deposits (1:20 000/1:50 000, 1:100 000), Bedrock of Finland (1:200 000) data to this study. Data for ground level model of the land area, airborne scanning light detection and ranging (LiDAR) data, a digital elevation model (DEM) and multidirectional hillshade (MDHS) was contributed by the National Land Survey of Finland (MML). Shoreline reconstructions were created based on the research results of studies by Ojala et al. (2013) and Rosentau et al. (2021) on sea-level changes in Baltic Sea Basin.

DATASETS
Quaternary superficial deposits / GTK / 1:20 000/1:50 000, 1:100 000
Bedrock of Finland / GTK / 1:200 000
Airborne scanning light detection and ranging (2m LiDAR DEM) / MML
Digital elevation model (10 m DEM) / MML
Multidirectional hillshade / MML
Paleotopographic models / Ojala et al 2013
Geotechnical soundings / City of Turku and GTK / 60 000 pcs

Table 1. Datasets.

The City of Turku provided an essential part of geotechnical investigations used in the present study more detailed data specifically of Turku area with the geotechnical investigation done during different construction works. This data was also used in Laura Piriläs master's thesis (2016), where the purpose of the study was to clarify the quality and the thickness of the clay deposits, and to reconcile its formation history in the Turku area. During her study, Pirilä sorted out all the geotechnical data until the year 2015 which included clay information out of tens of thousands of data points. She purposely left out the data which was marked as unbalanced or had some obscurity during the drilling process, because they do not describe the natural state of clay deposits. Also, data which did not point out the surficial deposits type was left out. This sorted dataset was utilized in this study. And to complete the target research area, more geotechnical investigations from the surrounding areas, such as Raisio and Kaarina, were attached from the Geological Survey of Finland's ground investigations database (https://gtkdata.gtk.fi/Pohjatutkimukset/index.html). In all, over 60 000 datapoints of geotechnical investigation were processed in the Turku area (Figure 13). More detailed classification and frequency of the geotechnical sounding data can be seen in Table 2 and Table 3.

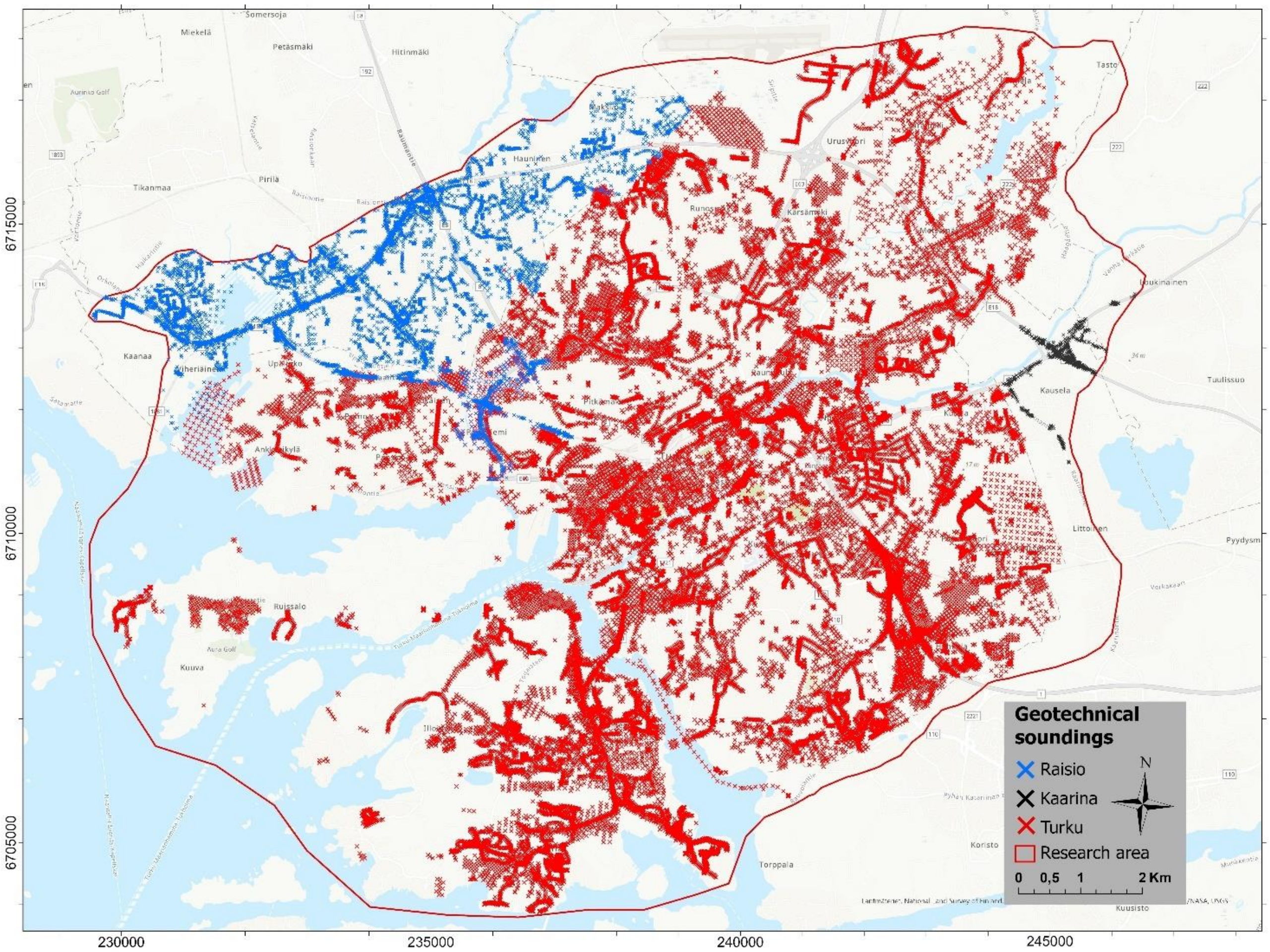


Figure 13. Geotechnical investigation points in research area, total 55 394. Different areas specified by different colors.

Frequency	Location
50 415	Turku
9994	Raisio
916	Kaarina
57 694	Research area

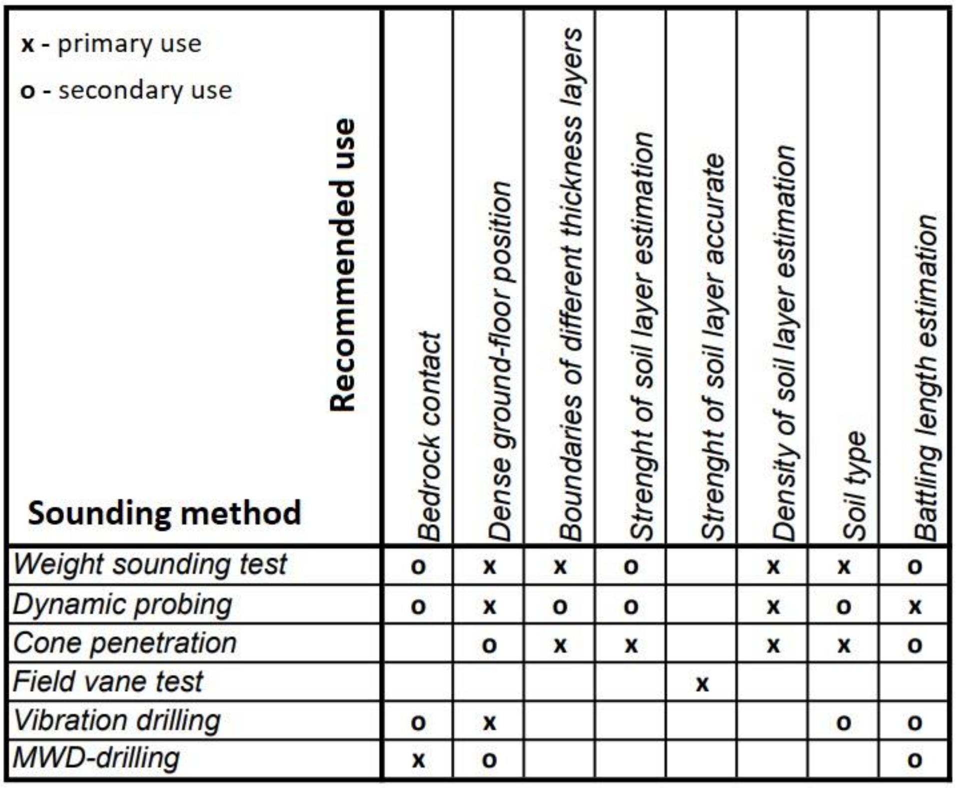
Table 2. Starting situation with the sounding data.

Location	Soundings	Frequency
Turku	Including clay	26 949
Turku	Weight sound test	18 408
Turku	Field vane test	1 421
Turku	Static dynamic penetration test	350
Raisio	Including clay	6 336
Raisio	Weight sound test	6 718
Raisio	Field vane test	362
Raisio	Static dynamic penetration test	592
Kaarina	Including clay	410
Kaarina	Weight sound test	453
Kaarina	Field vane test	85
Kaarina	Static dynamic penetration test	58

Table 3. Used geotechnical soundings classified.

3.2. Soundings

As reported by Jääskeläinen (2011), engineering-geotechnical soundings are a part of ground survey and a way to conduct geotechnical investigations. The main goal of ground survey is to determine the surficial deposits conditions at the site so that the necessary ground construction work can be reliably planned and safely operated for future construction. Before the construction planning it is necessary to define the present ground water surface and different surficial deposit layers and their quality. Also, it is needed to research the possible bedrock contact or dense ground-floor. These studies can be used to identify information such as load capacity calculation, depression calculation and ground pressure drop. And from these can be deduced volume-weight, friction angle, cutting strength, etc. of the surficial deposit (Jääskeläinen, 2011). In Table 4 can be seen different kinds of soundings and their recommended use. During soundings the observations are recorded, and results are interpreted from diagrams. Figure 17 shows how different symbols in the diagrams are read. In this study weight sound tests, field vane tests and static dynamic penetration tests are examined because they produce the most suitable data for the study's purpose.



x - primary use **o** - secondary use **Recommended use** **Sounding method**	*Bedrock contact*	*Dense ground-floor position*	*Boundaries of different thickness layers*	*Strenght of soil layer estimation*	*Strenght of soil layer accurate*	*Density of soil layer estimation*	*Soil type*	*Battling length estimation*
Weight sounding test	o	x	x	o		x	x	o
Dynamic probing	o	x	o	o		x	o	x
Cone penetration		o	x	x		x	x	o
Field vane test					x			
Vibration drilling	o	x					o	o
MWD-drilling	x	o						o

Table 4. Most popular sounding methods and their recommended use, modified from Jääskeläinen (2011).

Weight sound testing is the most used sounding method in Finland. It is a so-called general auger, because it provides basic information from all kinds of surficial deposits, from soft clays to medium compact moraine (Jääskeläinen, 2011). With weight sound testing it is possible to estimate the borderlines for different surficial deposits layers and the relative tightness of friction surficial deposits layers. This sounding is based on static load mode when the auger is pressed into the ground by loading it with different weights while rotating it (SGY, 1980). At the beginning, the aim is to keep the minimum weight at which the auger sinks by itself and add weight when needed. When the weights are at maximum and the auger has stopped sinking, it is time to start rotating the auger rod. Every 20 cm of sinking, it is needed to record the depth of the tip and the half-turns. When the auger doesn't go any deeper with maximum weight and rotating, the weights are taken off and the auger is attempted to hit deeper with a club. When the auger has stopped sinking even with hitting, the drilling is finished. In the weight sounding test-diagram (Figure 14), the middle beam indicates the surficial deposit type. From the beam to the left is shown the dip with weights and to the right is shown dip with rotation as half turns and hits (Jääskeläinen, 2011).

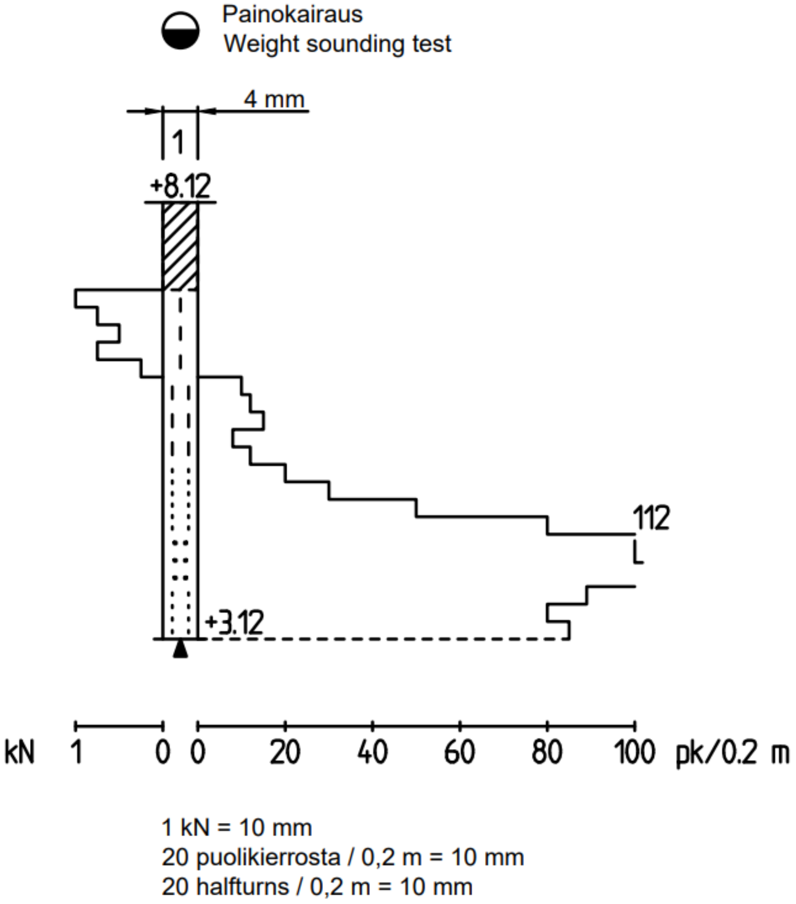


Figure 14. Weight sounding test-diagram (SGY, 2021).

Field vane testing is primarily used for fine-grained sediments to determine the shear strength. For the sake of its simplicity, it is appropriate for ground survey in soft fine-grained sediment areas, such as clay, clay-gyttja, decomposed peat and fine-grained silt. In field vane testing, a wing formed from four discs perpendicular to each other is pressed into the undisturbed ground. When the wing is rotated from the surface at constant speed, a cylindrical cutting surface is formed through the tip of the wing. The torque needed to produce the cut surface shall be measured at the top of the drill rod or immediately above the wing. The shear strength value is obtained by the torque needed to rotate the wing and by the geometry of the cutting surface (SGY, 1995). Basically, shear strength of the clay is a factor determined by the size of the wing drill blade multiplied by the torque required to move the blade (Jääskeläinen, 2011). In Figure 15, the field vane diagram shows shear strength graphs with undisturbed sediment as sharp curve on the right and with remolded sediment as dashed line on the left.

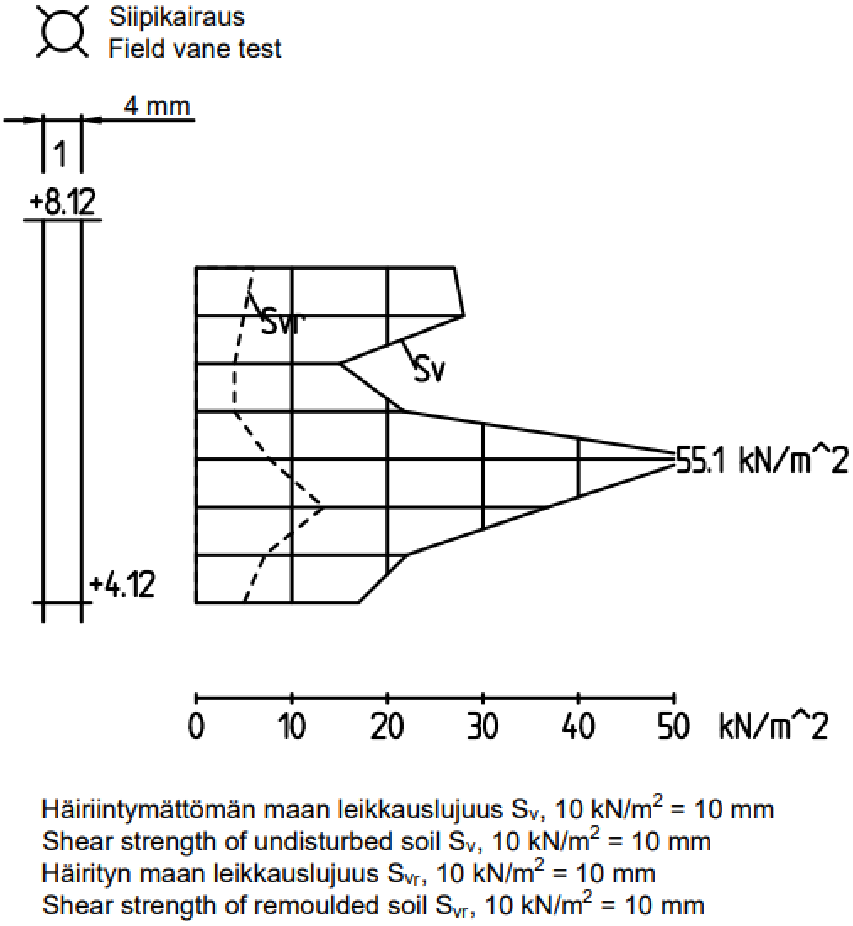


Figure 15. Field vane test-diagram. (SGY, 2021).

Static dynamic penetration test is a sounding method which combines mechanical cone penetration test and dynamic probing. With cone penetration it is possible to determine the depth of sand, till or bedrock surface and estimate the target level of battling poles and the coarse sediment layer. And by combining it with dynamic probing it is also possible to obtain more detailed information about soft surficial deposit layers, the characteristic of dense layers and their layer limits. The test starts with cone penetration test where the auger rods are pressed and rotated at the same time. When the maximum extrusion force (approximately 30 kN) is reached, switch to dynamic probing. While the auger rods still rotate at constant speed, the probe is dropped at constant frequency until the total batting number is 5 or under within over 0,4 meters. After this it is time to switch back to cone penetration test and repeat from the start. The following variables are monitored during the test; compression force, torque, number of battings, drilling depth and rotation speed (SGY, 2001). Figure 16 presents the static dynamic penetration test diagram, where the middle beam indicates surficial sediment type, and the left-side curve shows torque, and the right-side curve shows compression pressure.

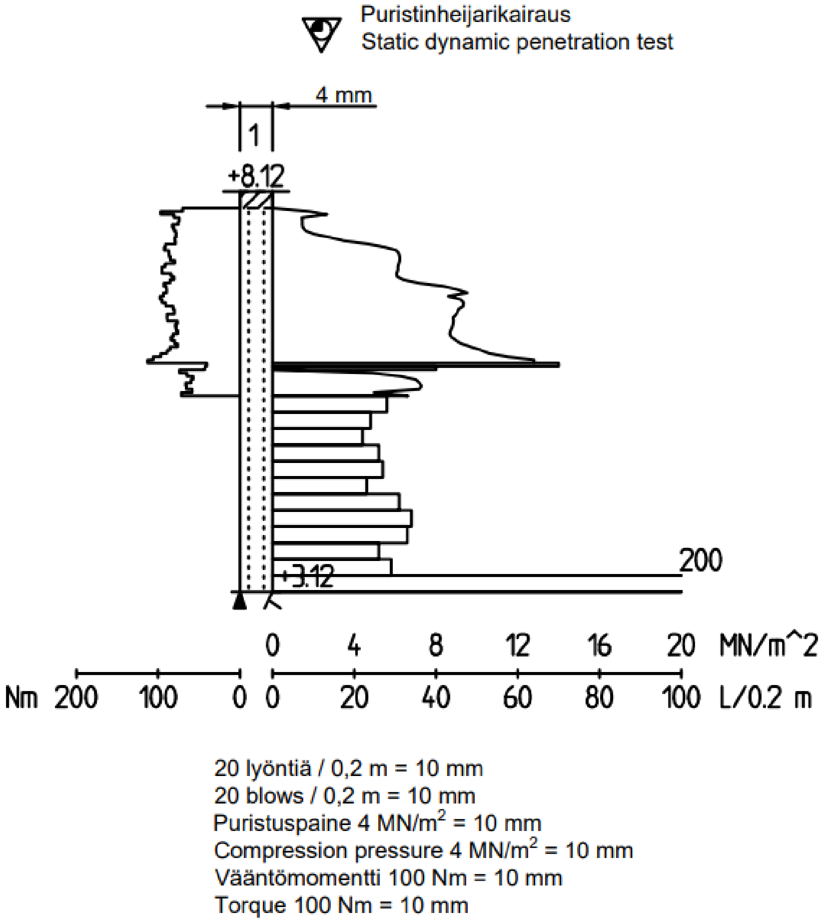


Figure 16. Static dynamic penetration test-diagram (SGY, 2021).

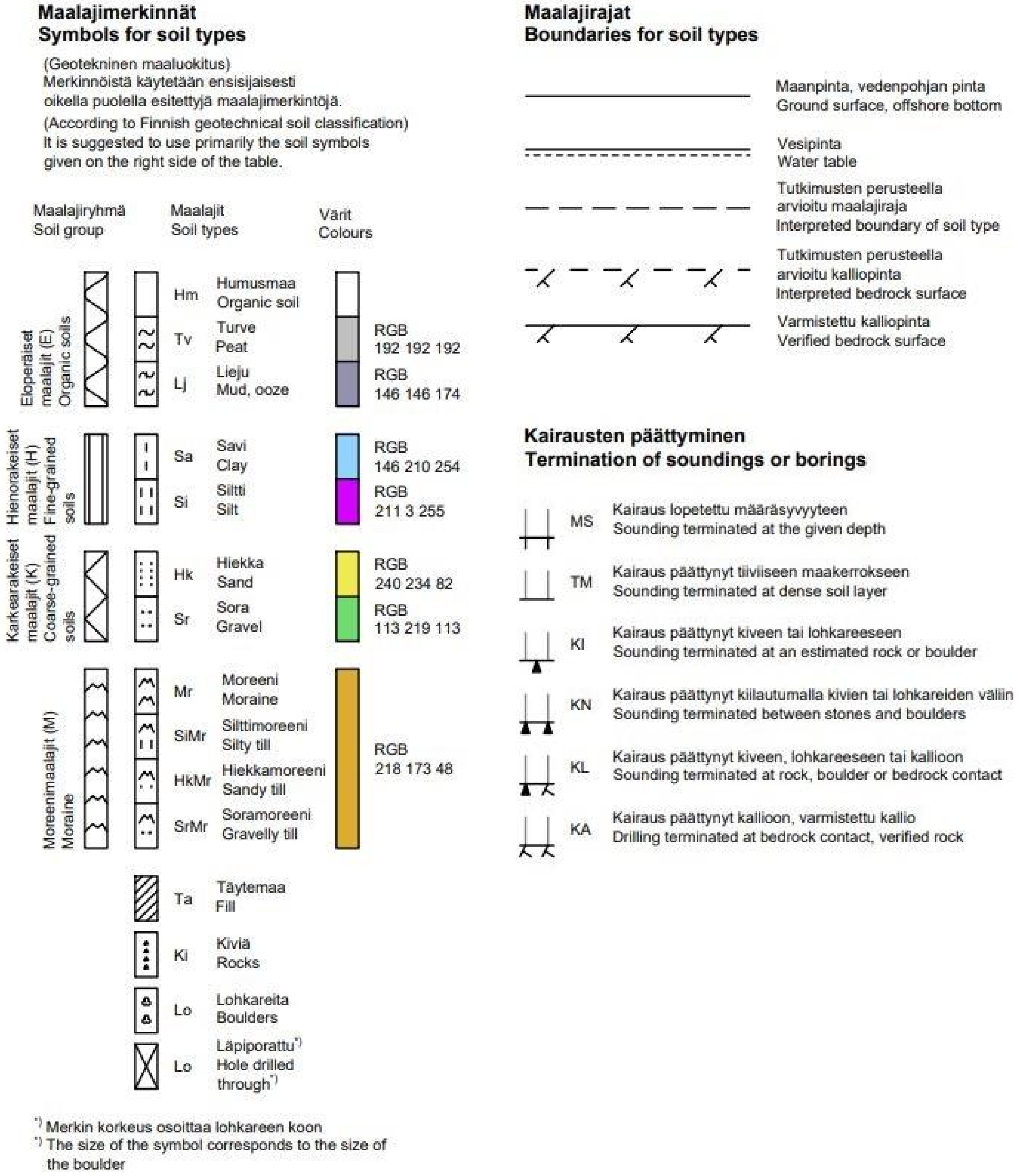


Figure 17. How to interpret a sounding symbols (SGY, 2021).

4. Methods

Datasets and how they were used during this study can be seen in Figure 18. More detailed information of the methods are presented in the subheadings 4.1-4.4..

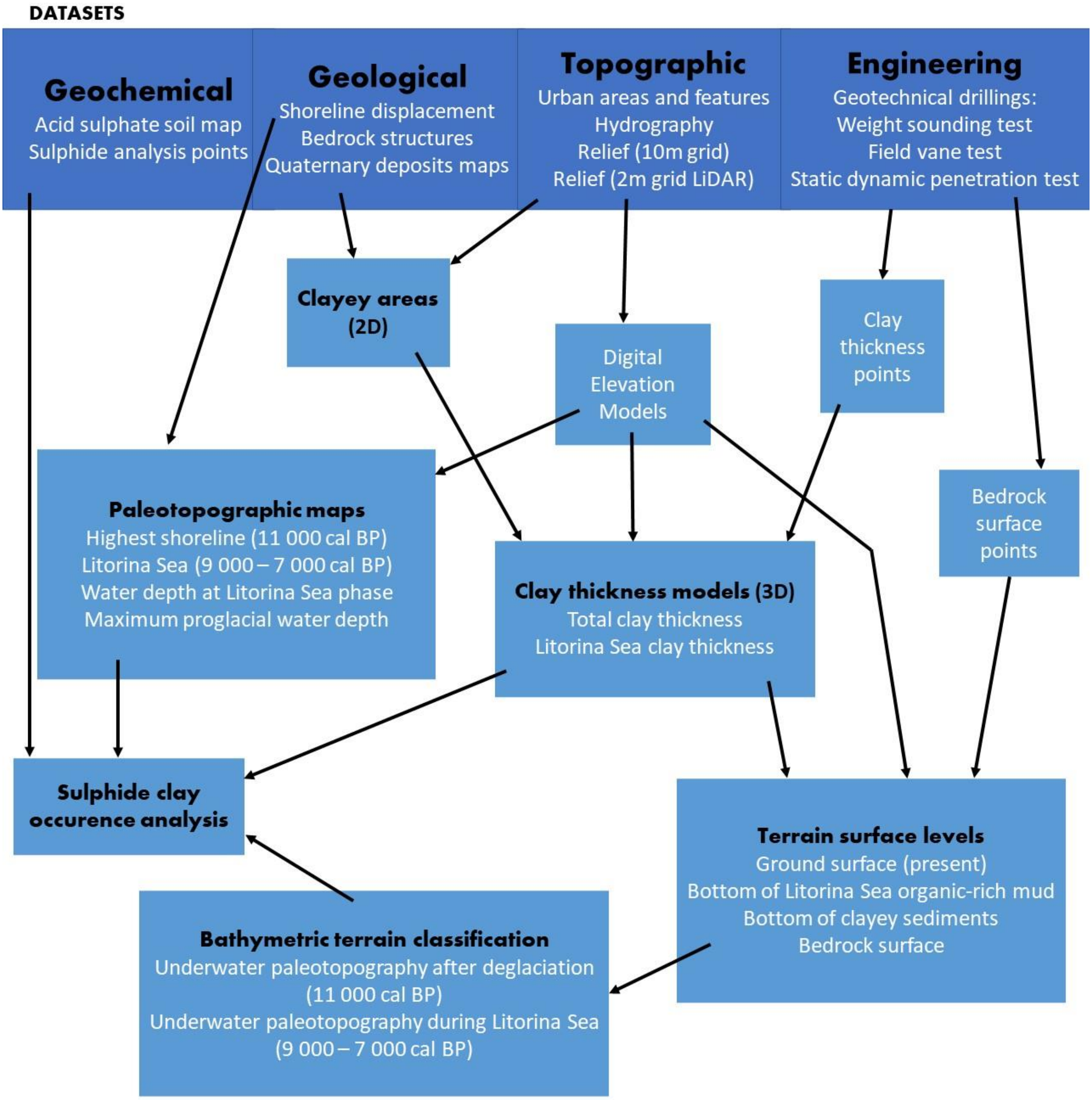


Figure 18. Flowchart of the process.

4.1. 3D-Win – sorting of soundings data

Sorting of the soundings data was made with 3D-Win. 3D-Win is a Finnish software developed to product and process measurement and design information determined for the geotechnical engineering properties of overburden and its stratigraphy. It is suitable to manage spatial data due to its diverse audit, editing and calculation characteristics. Typical users include for example surveyors, meter managers, spatial data engineers and designers, and bidder counters. 3D-Win is also one of the basic tools of design and production data model coordinators working on model-based infrastructure construction. The software can process several overlapping vector and raster image elements simultaneously and in addition to the software's own file format, files can be read and written in several formats. For example, vector files, raster data, terrain models, road geometry and drilling files. Editing of data is done graphically and can be directed either to individual points and lines, whole file elements or to active objects selected with different search methods. The software also includes versatile functions for transferring data between different coordinates and height systems, for example EUREF-FIN coordinates (Novatron Oy, 2022).

At first, most of the geotechnical data used in this study was in different coordinate systems, such as KKJ1, GK21, GK22 and TM35FIN. With 3D-Win, it was possible to convert all the data into the same coordinate system (ETRS-1989-GK23FIN). All the data combined; it contained a total of 61 325 data points. By limiting the datapoints inside the research area, the total was 57 694 points (Figure 13). After that, the geotechnical data were classified by surficial deposit type, including clay, sand, till, rocks/boulders, and bedrock. By collecting all the different surficial deposit types, it was achievable to construct a specific range for each type and make the data more manageable. With this classification, the data count decreased, total of 33 529 data points that contained fine-grained sediments (Figure 19).

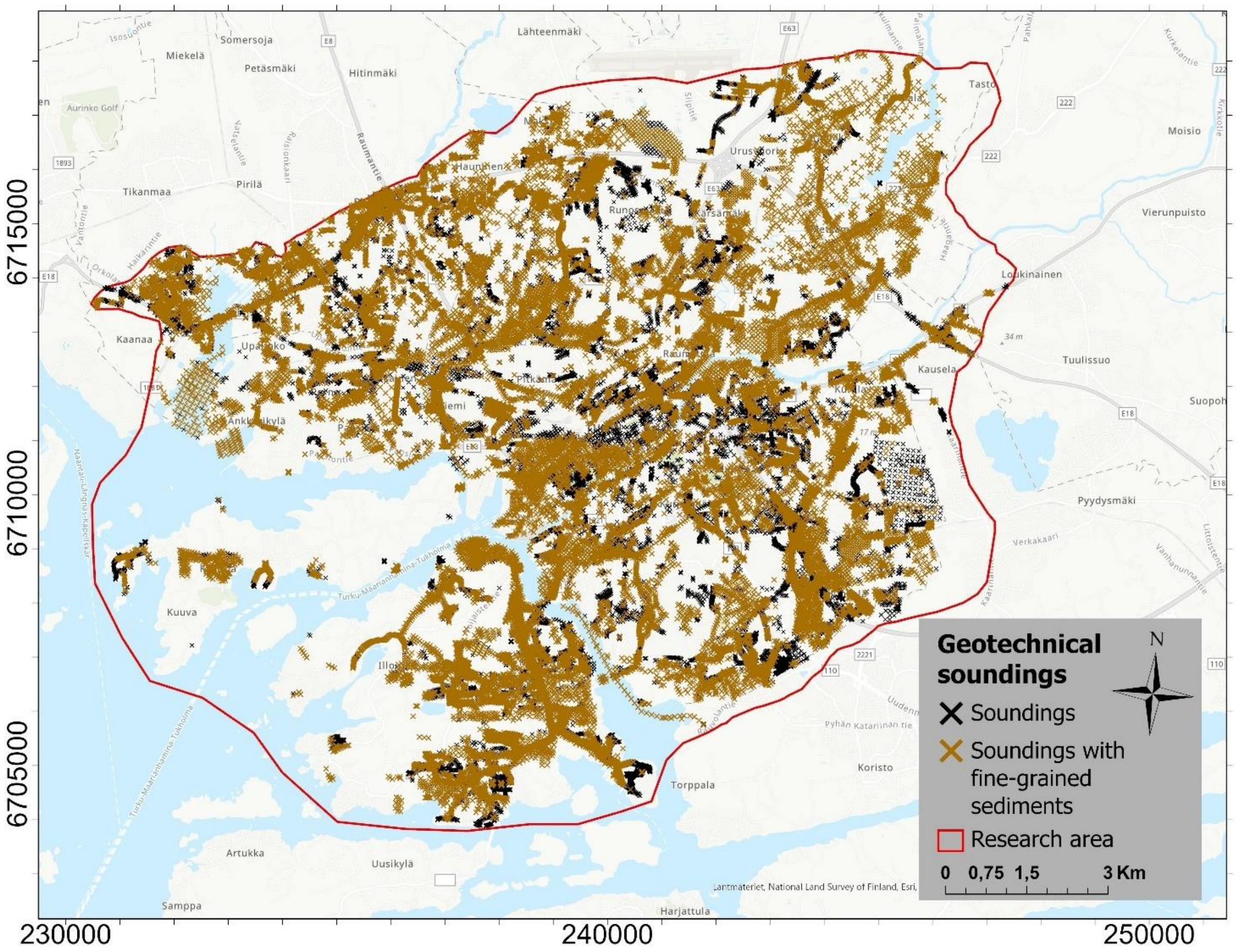


Figure 19. Comparison of all data points including and excluding fine-grained sediments.

Next, the varying sounding styles were categorized and weight sounding tests, field vane tests and static dynamic penetration test were selected for closer examination. These sounding styles were selected because of their reliability and suitability for the study. This led to a reduction in the number of data points to be considered with a total of 29 804 (Figure 20).

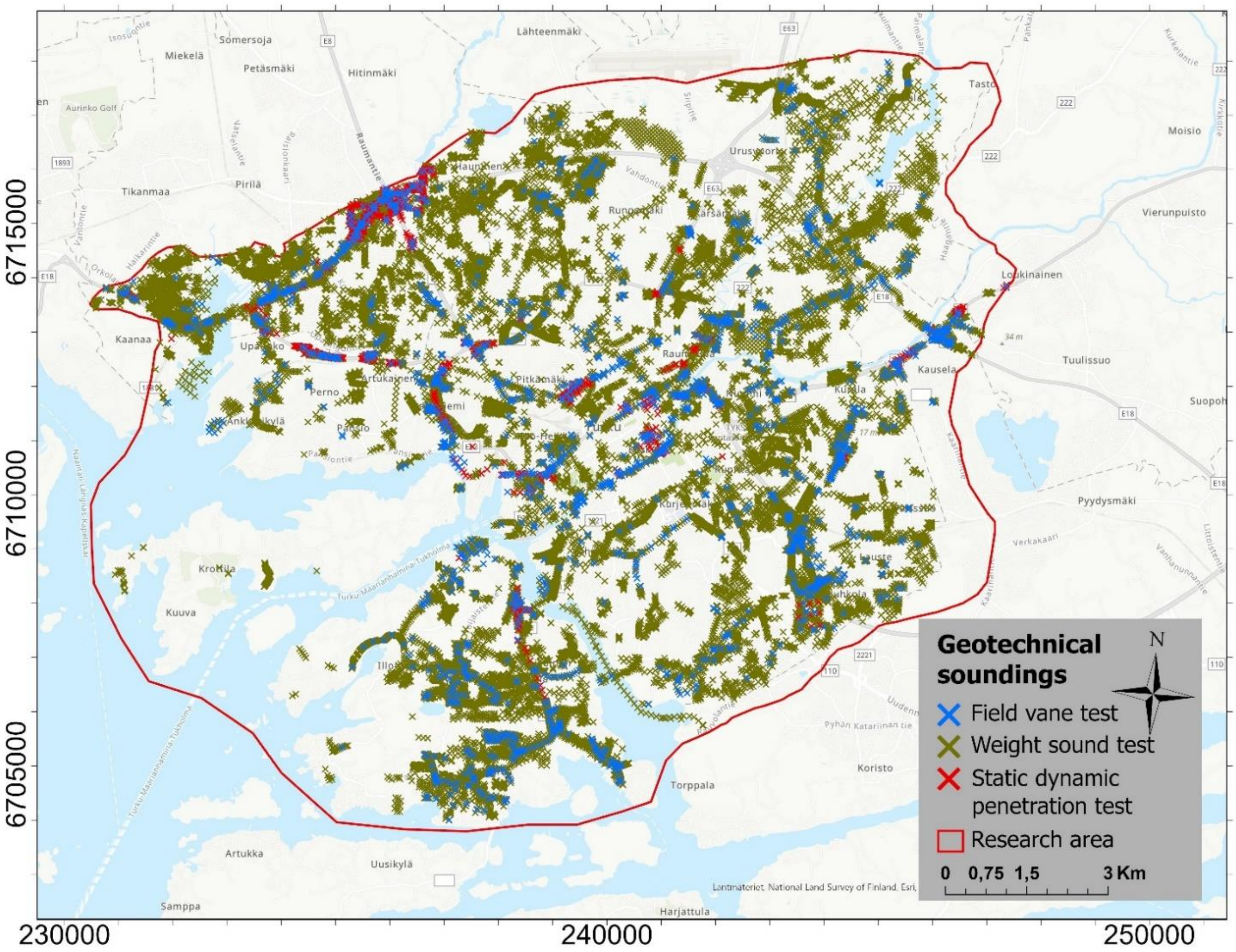


Figure 20. Comparison of the data points assorted by used soundings method.

Since the classification via 3D-win is based on the interpretations of the driller, it was decided to spin some of the geotechnical sounding data through GTK's specialists. These specialists have a tool, that "can interpret", for example, the drilling resistance of the bottom surface of the fine-grained sediment in weight sound test diagrams. With this tool, it was possible to define the bottom surface of the fine-grained sediments at the point where the drilling resistance changes for instance to 20 half-turns in such drillings where the soil type information is missing. This tool was only used on the sounding data from Raisio and Kaarina, since the data from Turku was mostly processed already by Pirilä in her thesis in 2015 and the total amount of the sounding data was too large and time consuming to process in GTK's tool. The decided determination of 20 half-turns was chosen based on Pirilä's interpretations for the soil type diagrams.

By studying the categorized, selected datapoints with the detailed information and diagrams they contain, it was possible to figure out the lower and upper surface levels for the fine-grained sediment. By utilizing this information, it was possible to create a model of the thickness of fine-grained sediments and to calculate the bottom level of fine-grained sediments in the area. In Figure 21 can be seen how the used datapoints are located and how thick the fine-grained sediment level datapoints are in the research area.

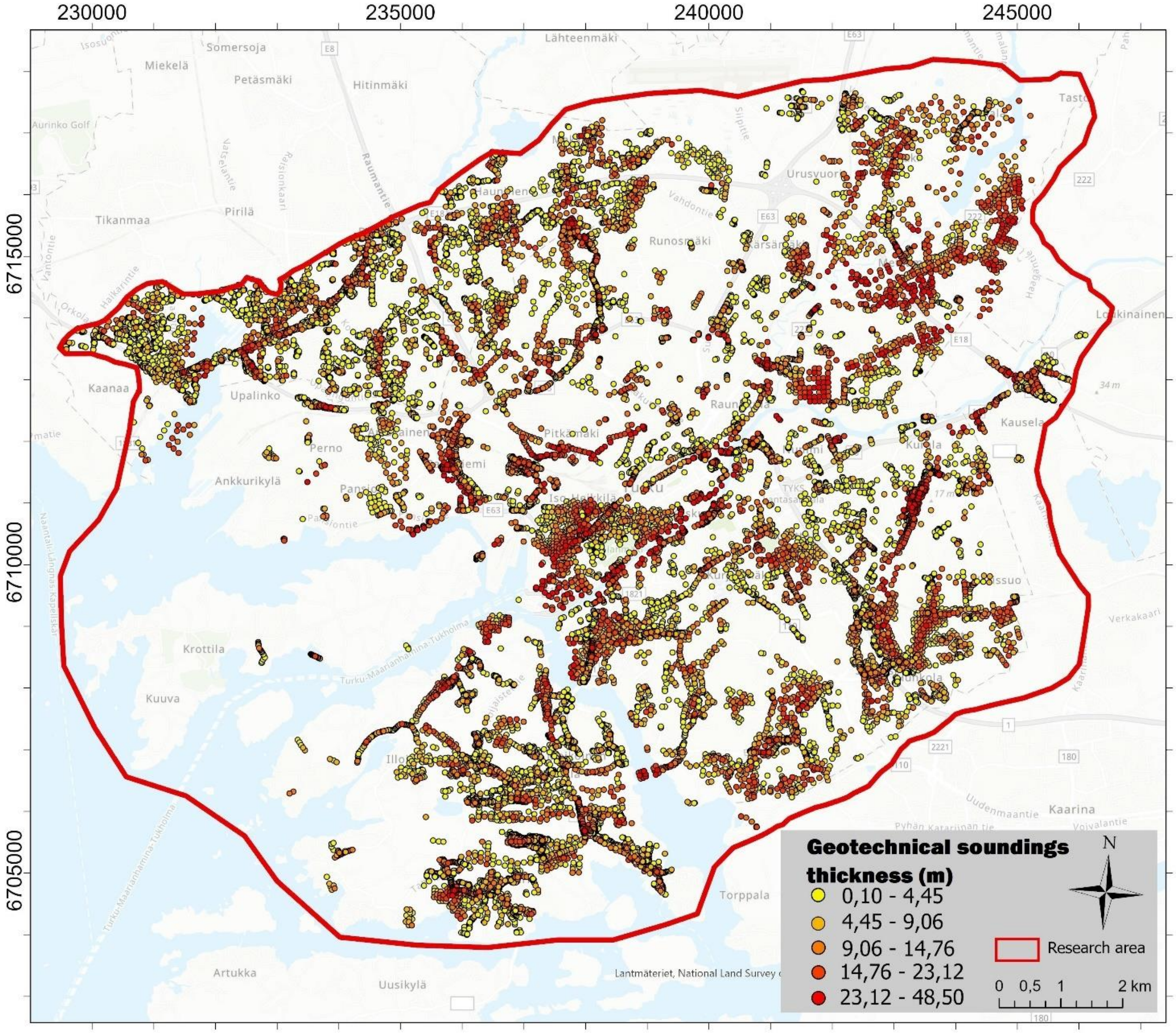


Figure 21. Location and thickness of the geotechnical datapoints in ArcGIS.

4.2. Delineation of areas with fine-grained sediments

By using LiDAR digital elevation models and soundings data sorting in 3D-Win the areas with fine-grained sediments (so called ‘level zero of clay deposits’) were first delineated in ArcGIS Pro environment. The intention of ‘level zero’ is to define the level where the fine-grained sediments begin. This was done by comparing the GTKs map of Quaternary deposits with geotechnical drilling data, topographic maps, aerial photographs, and LiDAR DEM characteristics in order to form borders for the fine-grained sediments. In the GTKs map of Quaternary deposits, the sediment is shown as a construction engineering determined type at a depth of 1 m. Therefore, reviewing and comparing the geotechnical drilling data helped to modify the surficial deposit map more accurately.

After creating the level zero of fine-grained sediment deposits, the outlines of the level were changed every 2 m into points for which the current height level was determined after MML topographic models. Then spatial and height information of these curves was used to count the thickness of fine-grained sediments and to determine the bottom level of the different depth levels of fine-grained sediments.

4.3. Interpolation of clay lower boundary surface and clay thickness

Interpolation of the clay thickness was created in ArcGIS based on the delineation of level zero of clay deposits and information from the geotechnical sounding datapoints. The lower boundary surface of clay was created by defining heights for the level zero of clay deposits and using the information from geotechnical sounding data for the bottom surface point of clay layers. To end up with the final result, the interpolated lower boundary surface of clay and clay thickness were cut with the borders of the research area, and it was masked with waterbodies and areas above the level zero of clay deposits.

4.4 Benthic Terrain Modeler (BTM)

With Benthic Terrain Modeler (BTM) it was possible to characterize and classify the underwater paleotopography of the Baltic Sea Basin i) after deglaciation in 11 000 cal BP and ii) during Litorina transgression in 7 000 - 9 000 cal BP in Turku region.

The following description of the Benthic Terrain Modeler is based on the Introduction and exercise-manual by NOAA Coastal Services Center (2013). Benthic Terrain Modeler (BTM) is a toolbox for ArcGIS 10.1, developed by the NOAA Coastal Services Center to process data of marine and coastal benthic environment. With this collection of ESRI® ArcGIS®-based tools marine and coastal resource managers may study and classify benthic environment combined with bathymetric data sets. BTM was created for the needs of coral ecosystem assessment in American Samoa. The toolbar allows to create grids of slope, bathymetric position index (BPI) and rugosity from an input data set with self-defined classifications and the relationships that characterize them. Along that, the tool offers a wizard-like functionality that leads the user step by step through the process of characterization of benthic terrains and provides access to information on key concepts along the way. In Figure 22 can be seen the flowchart of the Benthic Terrain Modeler process steps.

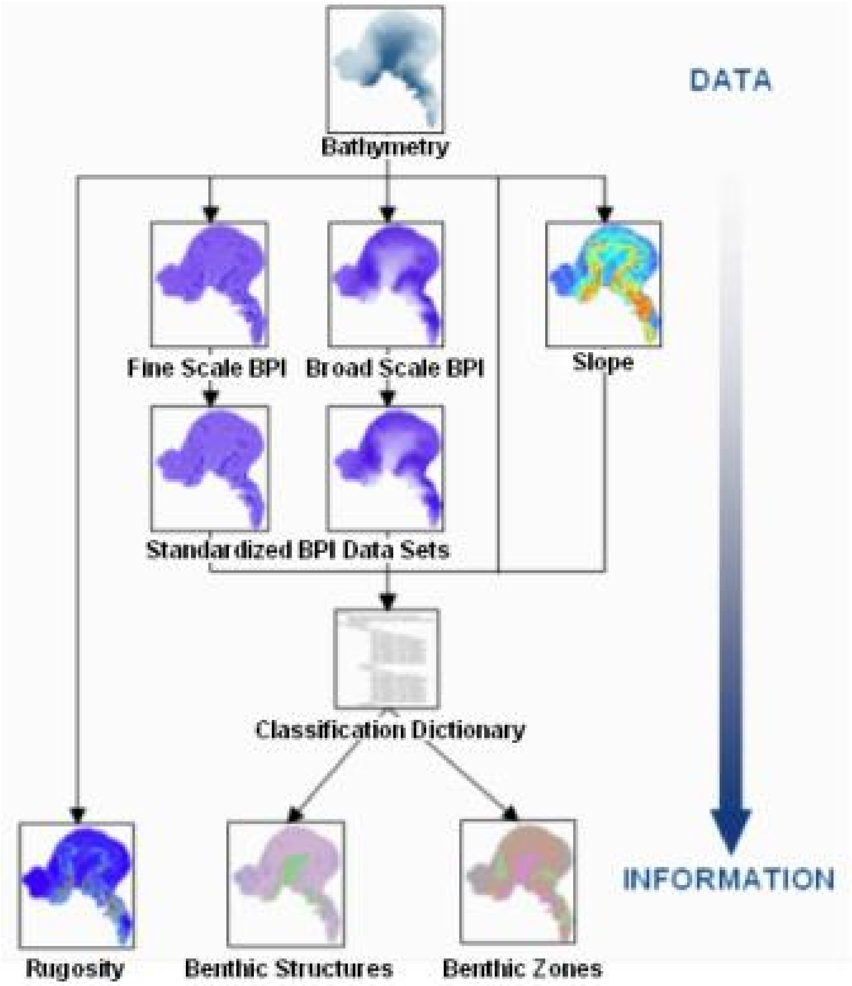


Figure 22. Flowchart of BTM process steps (NOAA, 2013).

Bathymetric position index (BPI) is a measure of how a certain defined elevation georeferenced location is related to surrounding landscape in general. BPI is a modification of the input bathymetric data set combined with topographic position index (TPI) algorithm, which is used in the terrestrial environment. TPI was developed to classify terrain by Andrew Weiss during his studies of terrestrial watersheds in Central Oregon. BPI data sets constructions are based on a neighborhood analysis function, where an input bathymetric dataset takes advantage of an algorithm which uses neighborhood function. These functions produce an output raster in which the output cell value at each location is a function of the input cell value and the values of the cells in a specified "neighborhood" surrounding that location. Demonstration of neighborhood analysis function can be seen in Figure 23.

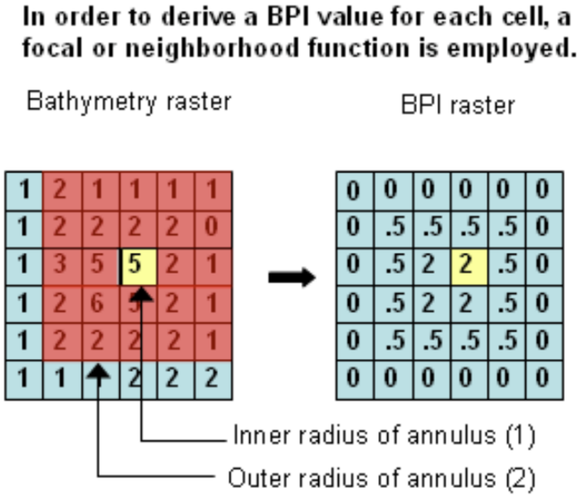


Figure 23. An example of a neighborhood analysis function using an annulus shape (NOAA, 2013).

Therefore, in BPI dataset construction, the positive cells stand for higher features and regions than the surrounding area, and negative cells stand for lower regions and features. So, areas of positive values designate for ridges and other associated features whilst areas with negative values designate for valleys and other features alike. In Figure 24 is shown a demonstration of positive and negative BPI value derivation for ridges and valleys.

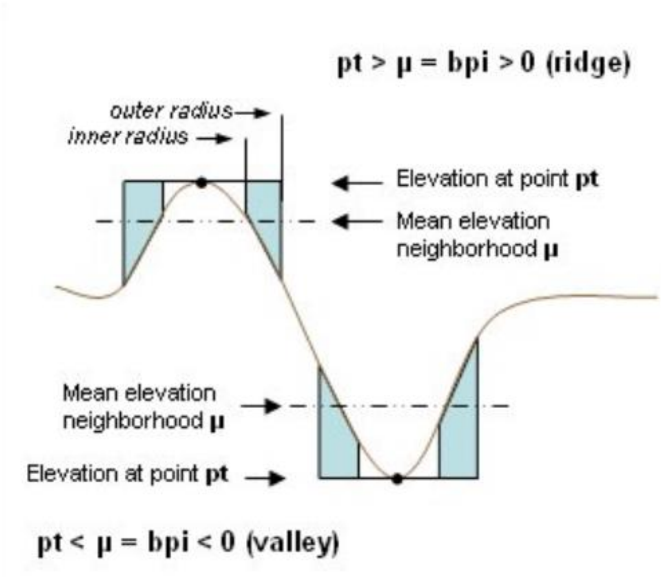


Figure 24. Demonstration of BPI value derivation (NOAA, 2013).

Values near zero or equal to zero in BPI are calculated as flat areas, when the slope is near zero, or areas of constant slope, when the slope of the point is significantly greater than zero. Demonstration can be seen in Figure 25.

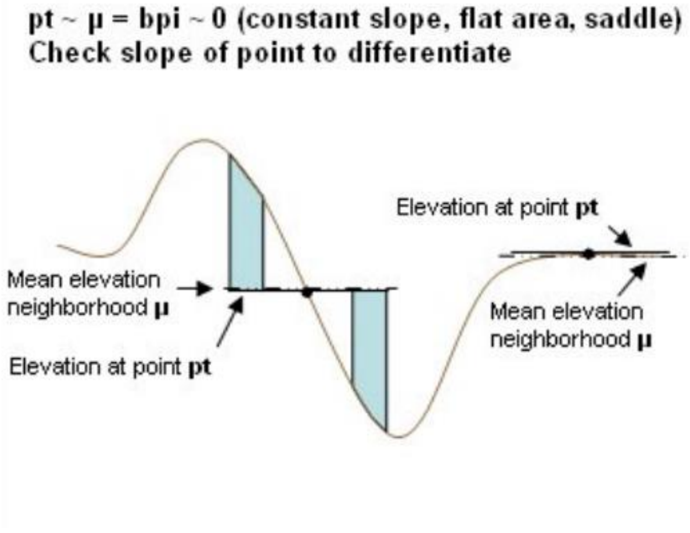


Figure 25. Demonstration of near zero values in BPI (NOAA, 2013).

During the process of benthic terrain classification, two distinct BPI datasets are generated, each featuring unique scale factors. Fine scale BPI datasets have smaller analysis neighborhoods, and so they have a smaller scale factor, and they are useful for smaller benthic terrain feature identification. Board scale BPI datasets have a larger analysis neighborhood, and they are useful for identifying larger benthic terrain regions or areas because their larger scale factor. After creating the fine and the board scale BPI datasets, next in the benthic terrain classification is to standardize the values of these raster dataset. Since the BPI data tends to be spatially autocorrelated, meaning that the closer locations are more related to each other than locations farther apart, the range of BPI values increases with scale. As an illustration, broad scale BPI datasets would have smaller BPI values since a larger analysis neighborhood is in commission and fine scale BPI datasets would have larger BPI values since a smaller neighborhood analysis in use. When combining board scale and fine scale BPI data sets into one composite grid, it forms a cross-scalar spatial heterogeneity of terrain features with coarse features and fine features considered. Figure 26 shows the flowchart of BTM operation used in this study. The classification included four different zones and ten structures.

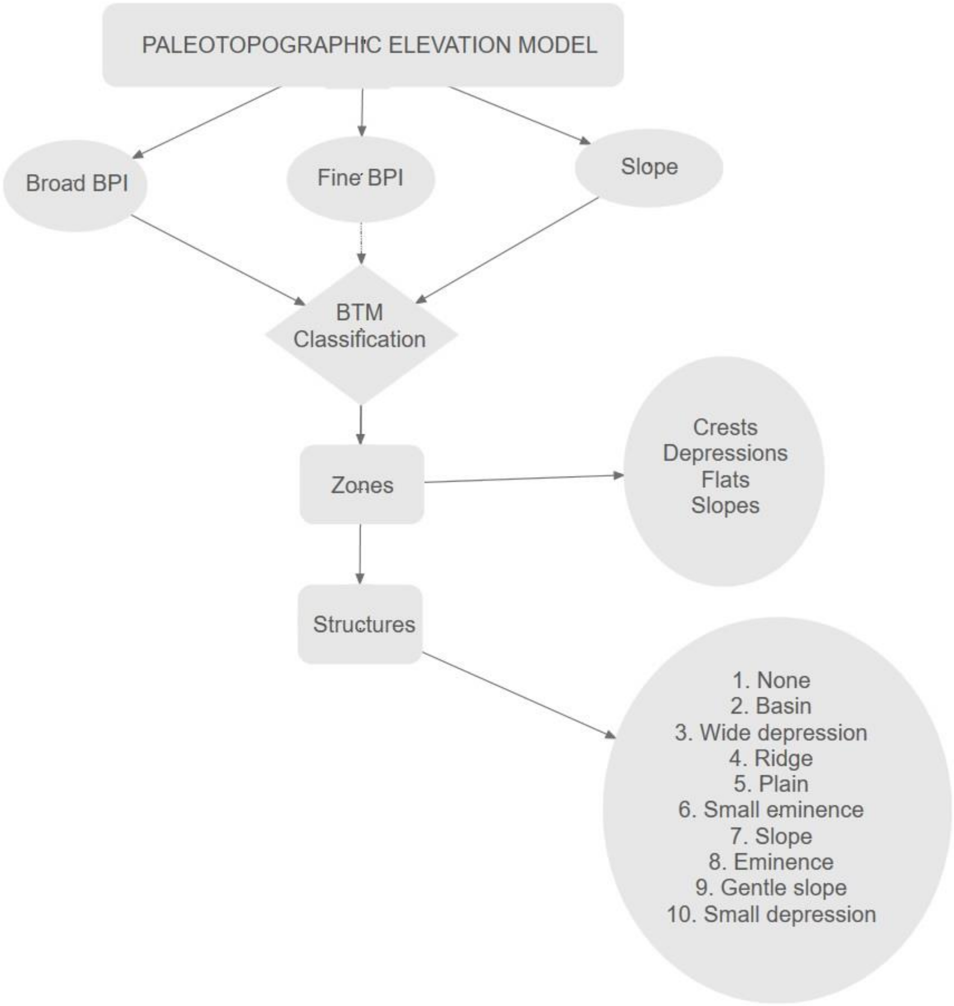


Figure 26. Flowchart of Benthic Terrain Modeler operation steps.

5. Results

As a result of this study, a map of fine-grained sediments in the Turku region was created. The thickness of the fine-grained sediments varies between 0-47 meters in the study area. In the Figure 27, the grey area shows the areas above fine-grained sediments, and the blue bordered area shows the water areas in the research area. The clay areas are presented as brown, where thin layers are light brown and the color changes darker gradually as the clay layer gets thicker. The scale starts from 0-3 m with light brown, continues to 3-7 m, 7-15 m and ends to 15-47 m with the darkest brown.

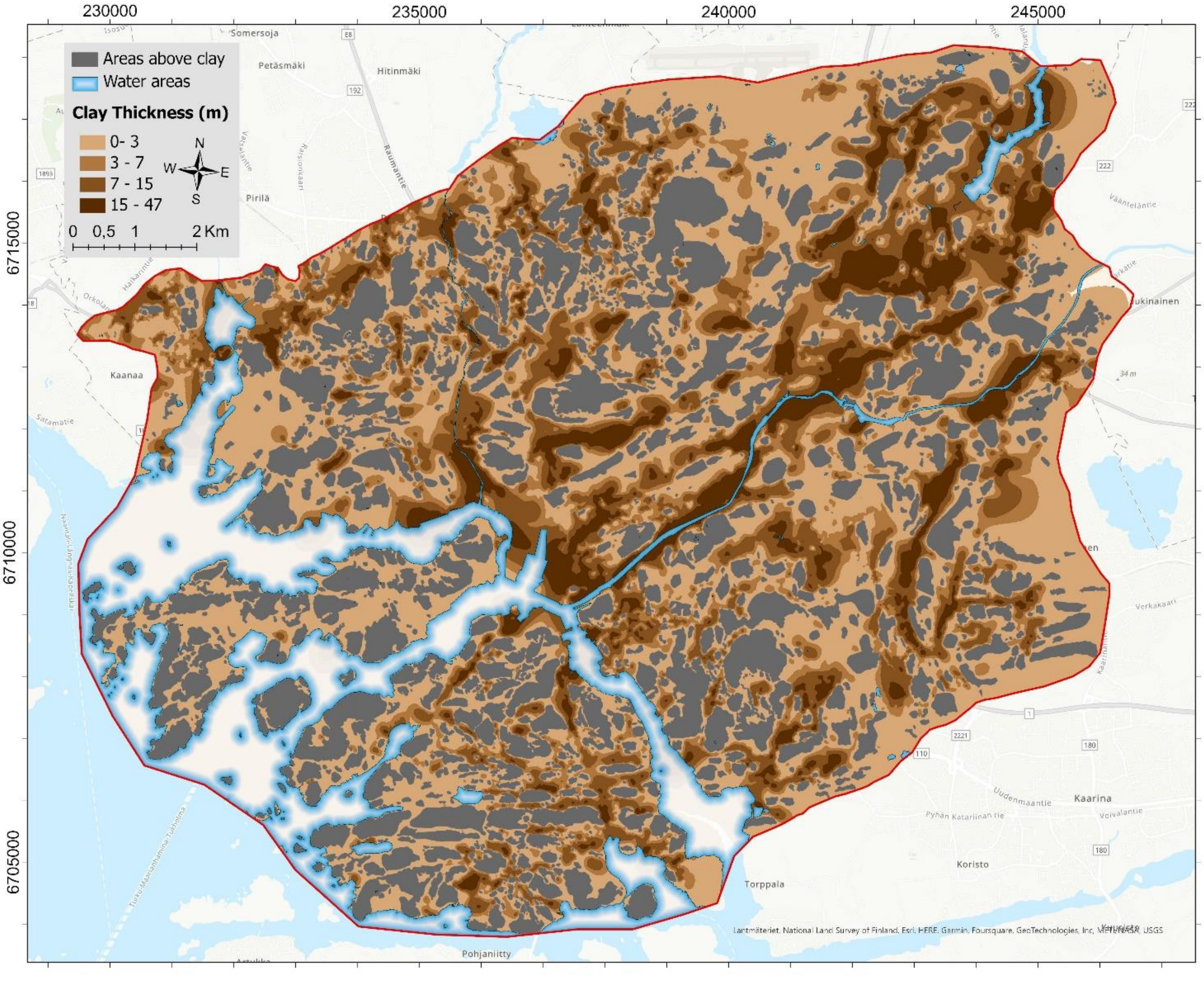


Figure 27. Clay thickness in the study area.

The thickest layers of fine-grained sediments are located along the Aurajoki river, in the harbor area and in the bedrock depression valleys. These places, such as Pahaniemi, Kurala, Raunistula and Metsämäki, have from 15 m to 47 m thick clay deposits. These deposits have formed when the depressions of bedrock weakness zones and fractures have filled with fine-grained sediments during the development of Baltic Sea Basin. The same depressions dominated the landscape after deglaciation during the Litorina transgression as seen in the paleotopographic elevation models created by the post-glacial shore-level displacement data.

The research areas surface being a total of 178 km^2 in size, it contains 104 km^2 of fine-grained sediments. Rest of the research area is covered by waterbodies or are areas above clay. Areas above clay cover approximately 44 km^2. In the Figure 28, can be seen the distribution of fine-grained sediment thickness and Figure 29 shows the percentage distribution. 51% of the fine-grained areas are covered with the thickness of 0-3 m, which means it covers 53 km^2. The second thickest layer, 3-7 m, covers a 19 km^2 area, which means 18% of the fine-grained area. The layer thickness of 7-15 m is the second most common (20,5%) in the area with total of 21 km^2 and the thickest sediments, around 15-47 m, covers the total of 11 km^2, which is 10,5% of the area.

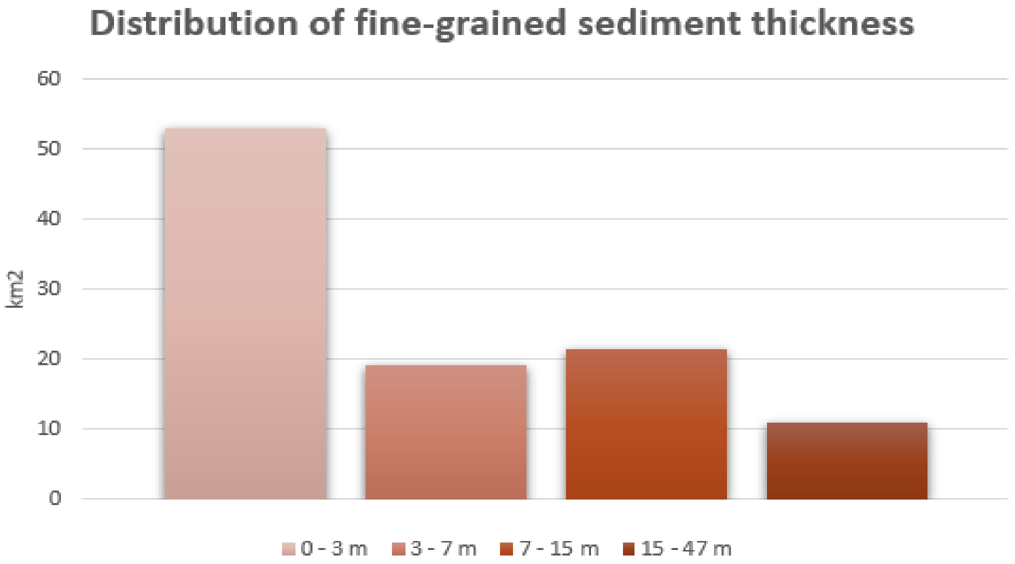


Figure 28. Distribution of fine-grained sediment by thickness.

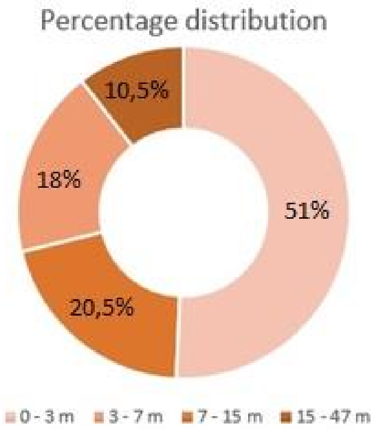


Figure 29. Percentage distribution of the fine-grained sediments thickness.

5.1. Paleotopographic models

With detailed geotechnical sounding data, it was possible to create elevation models of the different layers of fine-grained sediments, such as the bottom and the upper levels of the fine-grained sediments. Based on the calculations, is also possible to create a bottom level of the fine-grained sediments during the Litorina Sea phase. In Figure 30, is presented the bottom level of the fine-grained sediments. Figure 31 presents the bottom level of fine-grained sediments during Litorina Sea phase and Figure 32 presents the upper level of fine-grained sediments. The paleotopographic elevation level in the area varies between -51 – 65 m above sea level.

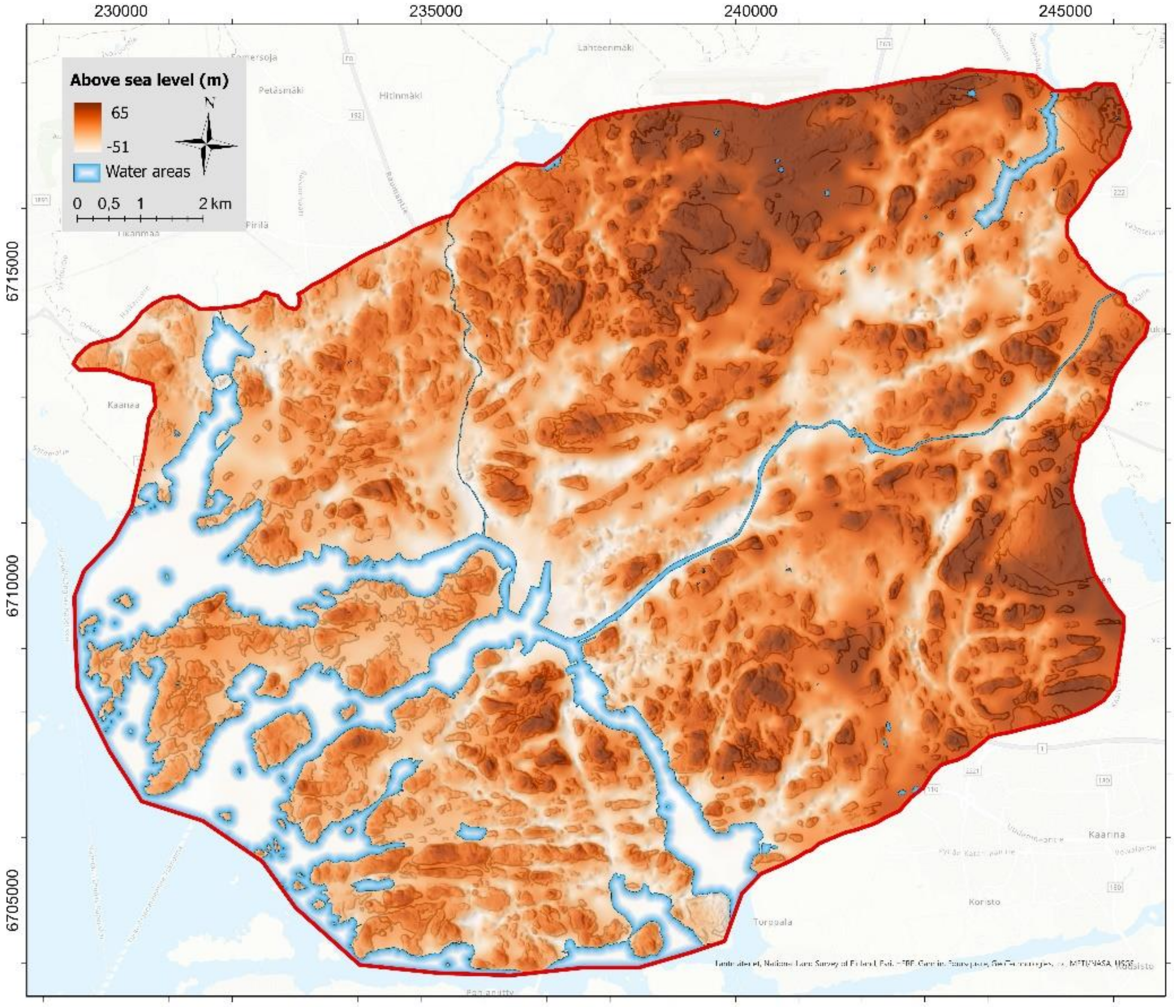


Figure 30. The bottom level of the fine-grained sediments.

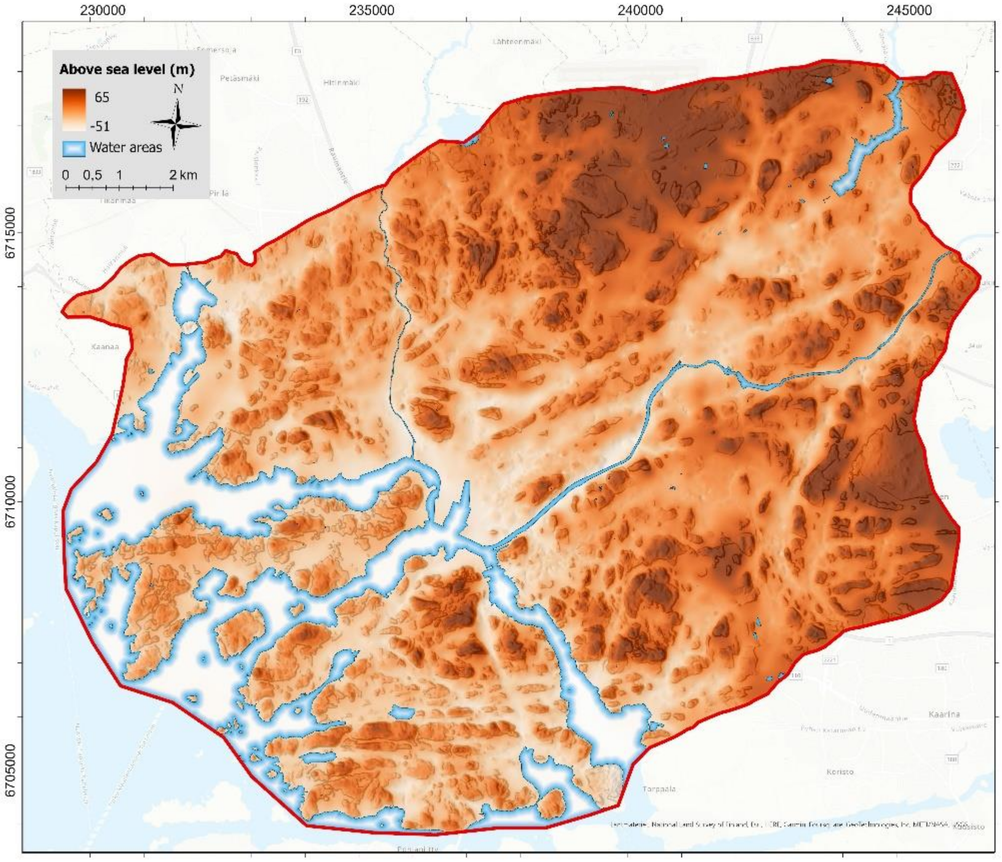


Figure 31. The bottom level of fine-grained sediments during Litorina Sea.

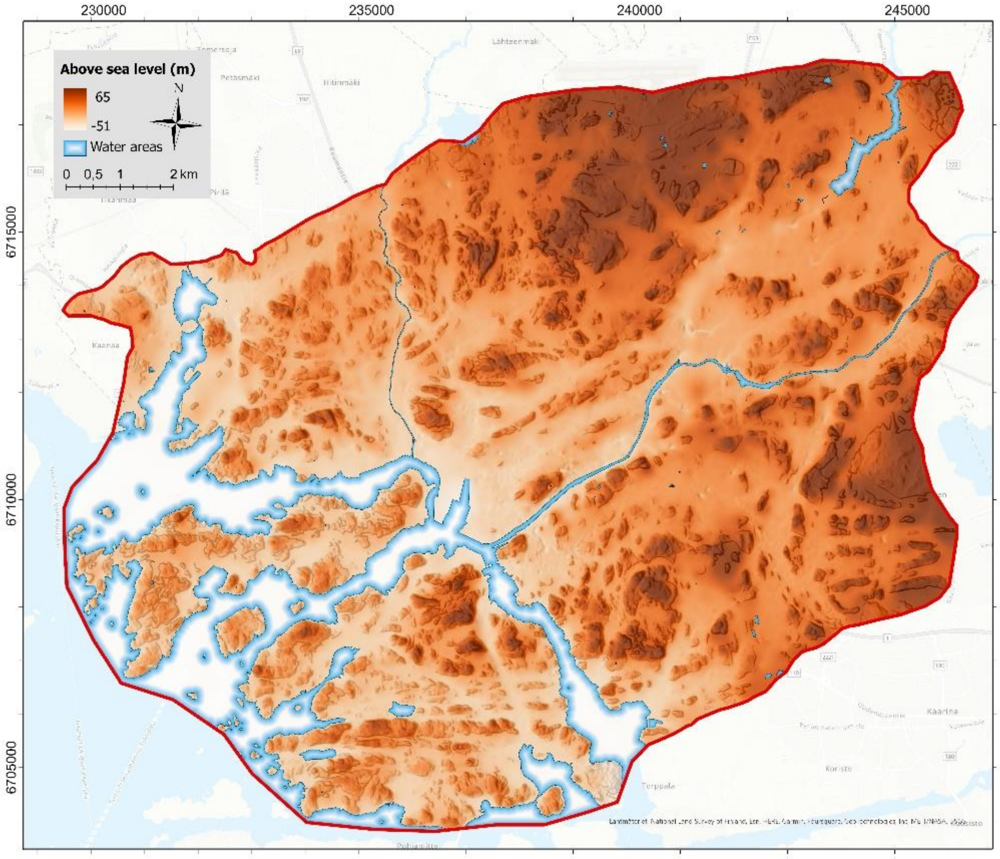


Figure 32. The upper level of fine-grained sediments.

5.2. Benthic Terrain Modeler (BTM)

With Benthic Terrain Modeler it was possible to create an ancient underwater landscape of the research area after deglaciation (Figure 33) and during Litorina transgression (Figure 34).

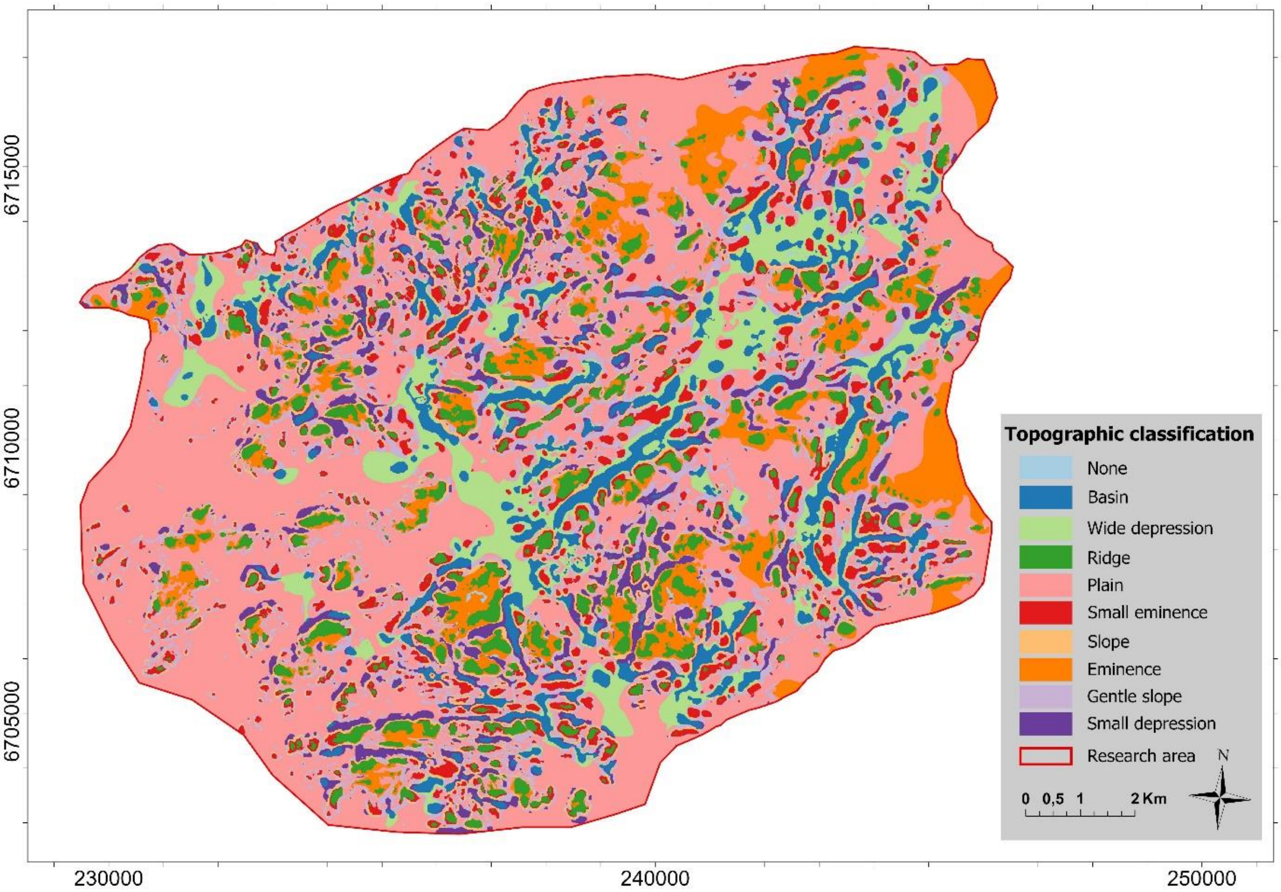


Figure 33. Topographic classification after deglaciation.

After deglaciation most of the research area classified as plain. Wide depressions in the areas are in joint valleys, where the fine-grained sediment started to deposit later. The wide depressions are adjacent by areas of basin. Except for the biggest joint valleys, the topography in the area has very small features with lots of smaller depressions, eminence, and slopes.

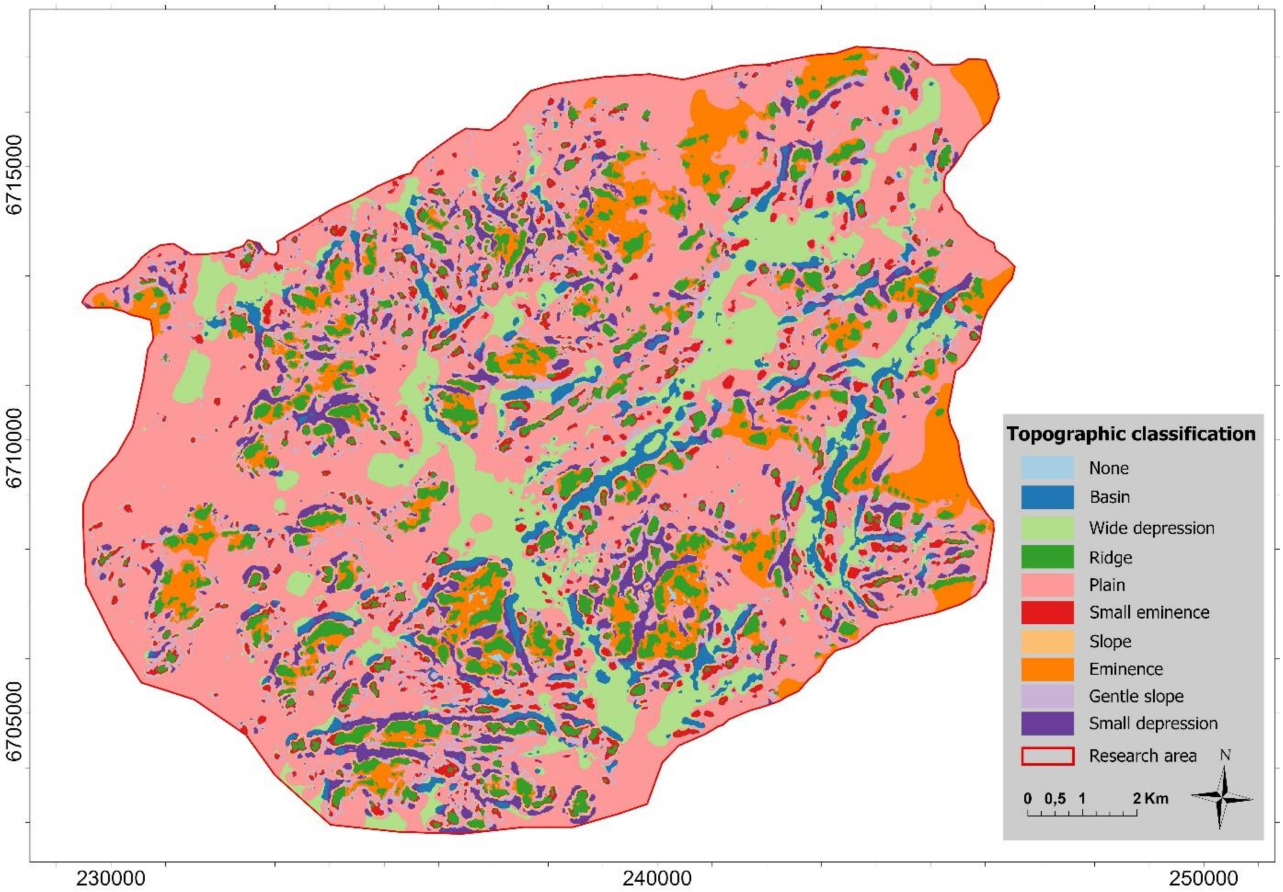


Figure 34. Topographic classification during the Litorina transgression.

During the Litorina transgression, the area began to flatter. The deepest elevation changes started to smooth by depositing the fine-grained material and the topography in the area started to even out. The biggest wide depressions are still dominant in the landscape and the area maintained its small features with many little areas of depressions, eminences, and ridges.

6. Discussion

The paleotopographic model of the Turku area after deglaciation and its classification with Benthic Terrain Modeler revealed some large lines of deeper depressions and lots of small features in the area. The large depressions locate to the bedrock weakness zones and fractures, which have been layered by fine-grained sediments during the Baltic Sea stages. The paleotopography during the Litorina transgression stage shows the same large depressions dominating the landscape, but small features in the area have smoothed the elevation.

When producing 3D-models, the coverage of the data is in a key position. For example, areas with lots of geotechnical sounding data provides more detailed information, which represents the corresponding information in the model as well. In this study, the extent of research points limits to the sea, since there are no sounding data provided in the sea areas. Also, in some areas, only a few geotechnical surveys have been done, and is therefore lacking data. This kind of regions are located near Airport, Littoistenjärvi, and Ruissalo, as well the shipyard near Raisionlahti. On the other hand, when cropping the clayey areas and defining the 'level zero of clay deposits', it gives superior premises to define spatial occurrence of clayey areas and areas with just thin layers of clay. This is because these kinds of datapoints are comprehensively included in the calculation as well.

While reviewing the basins in the area and their nature, the most characteristic feature is elongation which follows the structures of the bedrock. This type of elongated basins are located for example along the Aurajoki river, from Lauste to Kurala, and from the harbor to Pahaniemi. In the north-east part of the research area, around Saramäki, Metsämäki and Kärsämäki, can be found a larger and wider area of thicker layers of clay. The area of thicker clay sediments follows the riverbed of Maarian allas, which once flowed much larger and was united with Aurajoki river. When comparing to the similar study made in Espoo by Saresma et al (2021), the Turku area contains much thicker deposits of fine-grained sediments. Nearly 50% of the fine-grained sediments in Turku are thicker than 3m, 47m at its thickest, while in Espoo the sediment thickness reaches 35m at its pinnacle.

The produced topographic models of bottom levels of fine-grained sediments after deglaciation and after Litorina transgression, and BTM-analysis set side by side, shows how the topographic classifications done with BTM brought out features also seen in the paleotopographical models. Peculiarly the areas with strong features came out more strongly. As difference, the BTM-analysis showed the smaller features in more detail than the paleotopographical models. Likewise, in the BTM-analysis, the features were explicitly classified, which show how the thickest fine-grained sediment deposits were in the elongated basins. As a conclusion, the Benthic Terrain Modeler is an exceptional tool for this type of basin analysis, where it is needed to distinguish different depositional environments. This conclusion is supported by

Saresma et al with their study of characterization of the sedimentary depositional environments in Espoo made in 2021.

In terms of urban planning and construction, the bedrock topographic steepness and sharp features in places bring challenges to land use, especially when these features are covered with thick clay sediment layers. Another difficult characteristic regarding to construction are the large changes in clay thickness on small distances. And when considering the occurrence of acid sulphate containing fine-grained sediment deposits, the areas of deep depressions have been favorable places for Litorina clays to deposit. Therefore, while comparing the studied occurrence of ASS and the created characteristics of clay deposits in Turku region with BTM-analysis, is it probable to assume that the occurrence of ASS could be predicted via BTM-analysis. Just as Saresma et al did in Espoo in 2021, as they mapped the locations of possible acid sulphate soils in connection with the study of characterizing the sedimentary depositional environments.

6.1. Editing the ´level zero´

An example of this procedure is shown in the following figures. Editing of the ‘level zero’ involved going through the datapoints individually in 3D-Win, examine the sounding diagrams to surficial deposit map and editing the polygons in ArcGIS (Figure 35). By doing this, it was possible to discover potential errors such as presented in the figures 35-40.

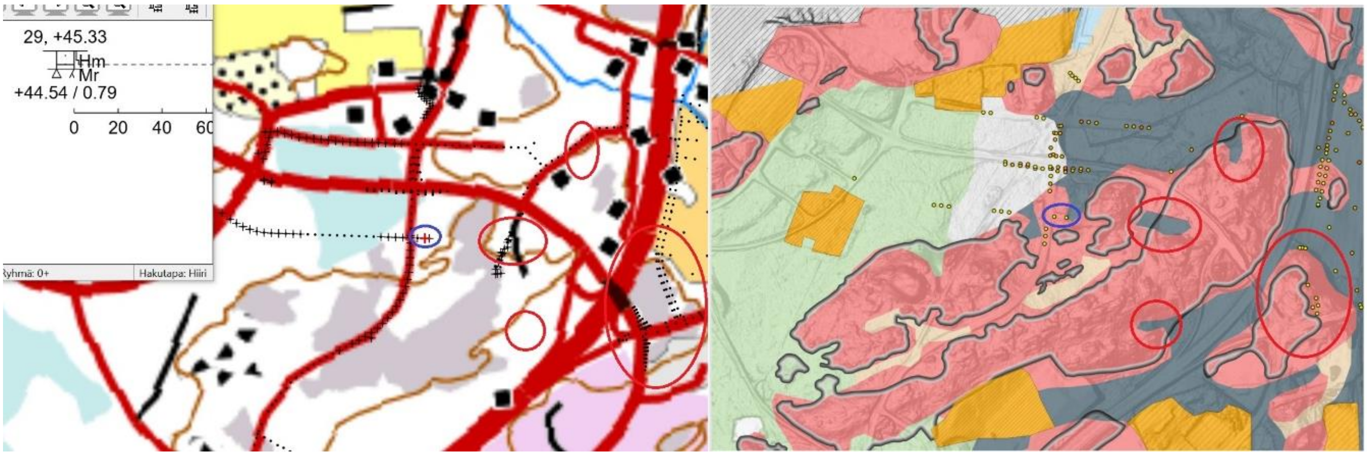


Figure 35. Comparing the data in 3D-Win and ArcGIS.

Right side of the Figure 35 is a screenshot from ArcGIS, where the grey area represents clay soils, and the red area represents bedrock areas as in GTKs soil map. The thick grey line represents bedrock ‘level zero’ created by surveying LiDAR-data and geotechnical sounding data and comparing it to GTK’s map of Quaternary deposits. Bedrocks ‘level zero’ as if the level, where bedrock rises above the ground. Yellow and red dots represent geotechnical sounding data containing clays. As seen in the areas highlighted with red circles, the GTK superficial deposit map definition of clay overlaps the bedrock ‘level zero’. As well as in the large red circle on the right, in the area defined as bedrock there are few geotechnical data points which includes clay. Fine-grained sediment area boundary was reshaped with such reviews.

On the left side of the Figure 35, there is a screenshot from 3D-Win, where the little dots and crosses represent geotechnical data points. With each data point, there is a sounding diagram (seen on the top left corner) that gives more specific details of the observations made during sounding. In this particular diagram, a data point is shown highlighted with blue circle. It seems to be between two other data points including clay but does not include clay in itself. Therefore, it is necessary to contemplate where to draw the line in challenging situations such as this.

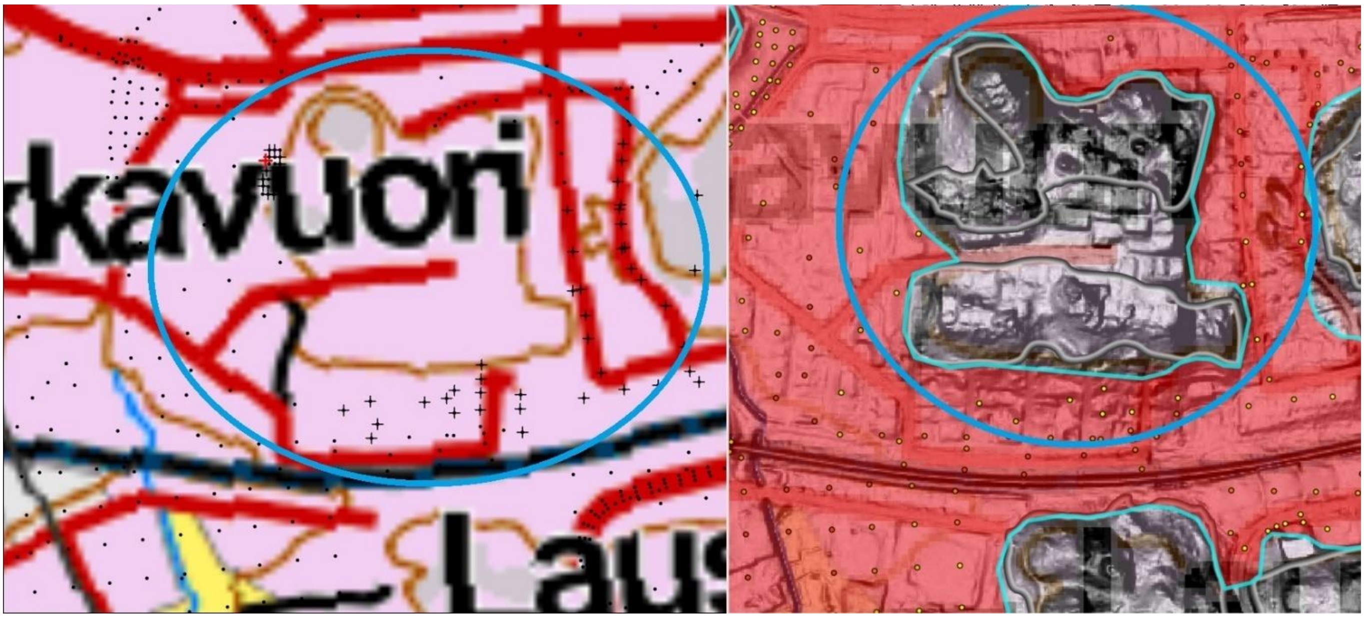


Figure 36. Challenging interpretation while editing ‘level zero’.

On the right side of Figure 36 is a screenshot from ArcGIS, where the red indicates clay. The turquoise line points out the border of bedrock according to GTK’s Quaternary deposit map and the thick grey line shows our study’s definition of bedrock ´level zero´. As seen in the picture, the thick grey line forms two separate areas, while the turquoise line includes them both. When no surveys of geotechnical soundings have been conducted in the area, as seen in the left side of the figure taken from 3D-Win, it was decided to surround just the whole area. When doing so, the software calculates the circled area as sand/gravel/moraine in the model.

Similar problematic areas were also found in Saramäki (Figure 37), where the geotechnical sounding datapoints were located only in a certain limited area and left a large part of the whole area unclear. As in this case also, leaving the obscure area as sand/gravel/moraine, was the most sensible decision.

In Figure 38, red area indicates clay, the thick grey line indicates the bedrock, and the dots are geotechnical sounding datapoints. As seen in the picture, a sounding datapoint with clay thickness of roughly 15 m located in the middle of bedrock, which must be a fault. This type of data had to be removed.

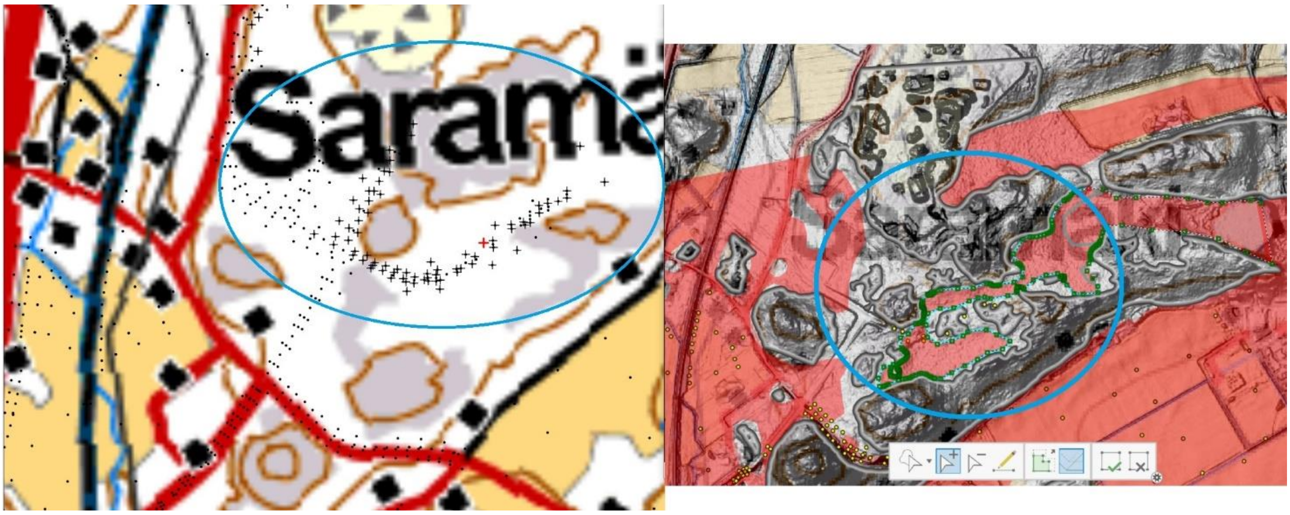


Figure 37. The problematic area of Saramäki.

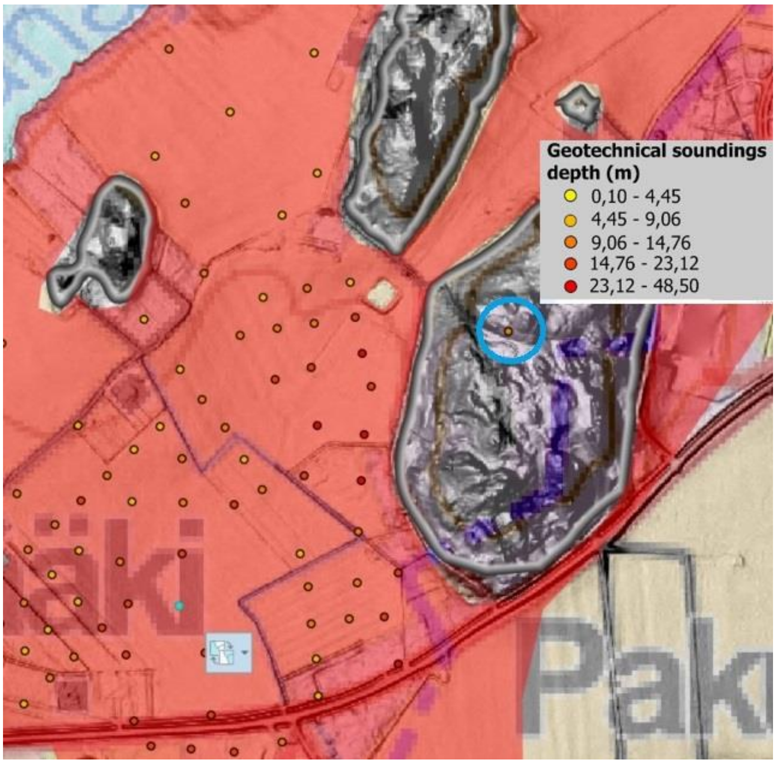


Figure 38. Error of geotechnical sounding datapoint.

Figure 39, a screenshot taken from ArcGIS, shows the same description as previously narrated. This figure shows a problematic area in Ylioppilaskylä, Nummi, where the geotechnical sounding datapoints are located inside and outside of the clay area. Also, between deep sounding datapoints of clay were found a random lower datapoint of sand and till. And some of the area is defined as ´uncharted´ or ´fill-up deposit´. When it is known that the building history of the area stretches back to the 60's and 70's, the dense construction work has modified the surficial deposits, which makes the geotechnical data in the area unreliable. And considering the location by the Aurajoki river, it is possible that the area has had a thick layer of clay at some point. Therefore, it is safe to determine all Ylioppilaskylä area as clay.

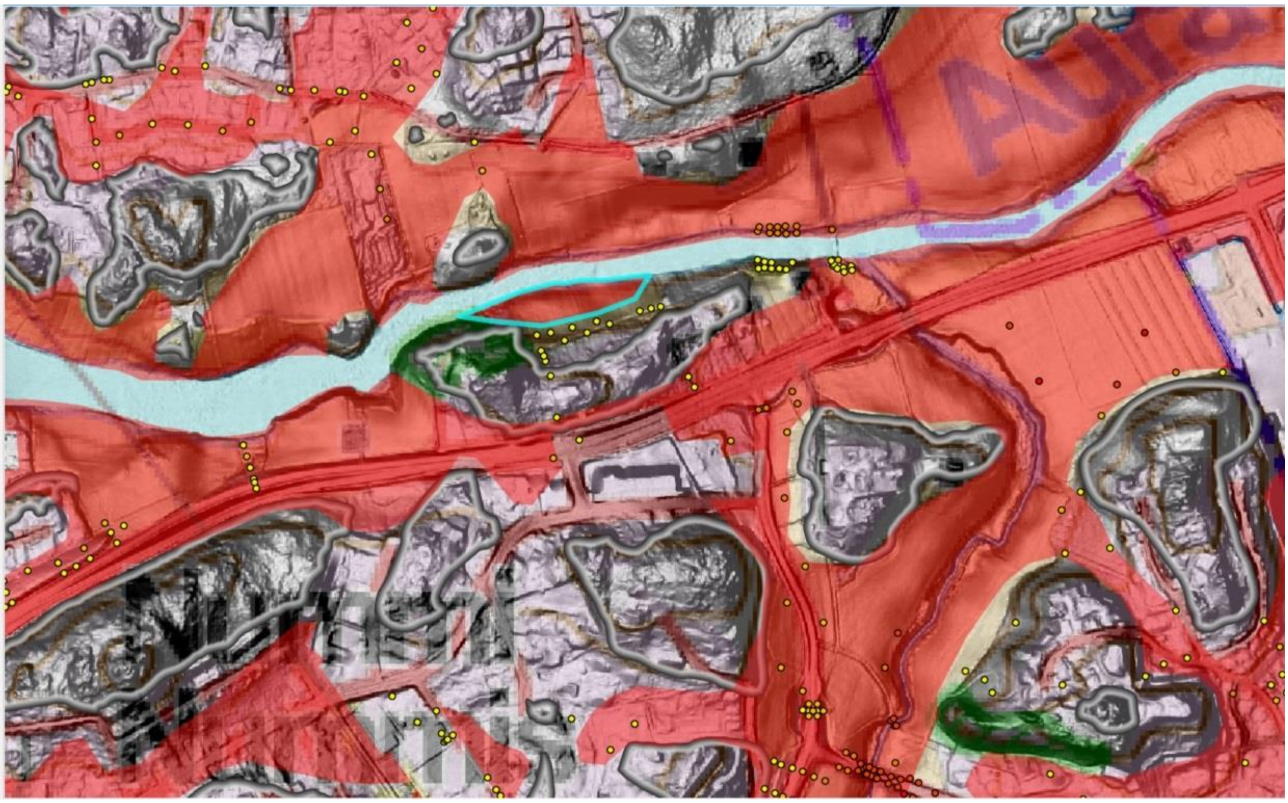


Figure 39. The problematic area of Ylioppilaskylä, Nummi.

6.2. Acid Sulphate Soils

Acid sulphate soils (later ASS) are sulfur-rich sediments with a capacity to release acidity into the soil and water bodies harmful amounts. Also, moraine and organic materials, such as peat and gyttja, with high sulfate content can be classified as ASS (Autiola et al, 2022). The release of acidity is a result of the oxidation of sulphides. Since sulfidic compounds in ASS are formed in anaerobic conditions, when in aerobic conditions, they oxidize to sulfuric acid and causes soil acidification. In Finland, ASS was peculiarly formed during the Litorina Sea phase, when SO_4^{2}- concentration and temperature in sea water were higher than nowadays. Therefore approximately 10 000 km^2 of Finland is covered with ASS, mostly on the western coast (Yli-Halla, 2022).

Acid runoff formed by released acidity causes noxious consequences not only in water bodies and in soil but also in organisms. When planning on construction activities in ASS areas, it is necessary to take into consideration the possible precautions, otherwise there might happen soil acidification and formation of acidic metal-rich runoff. This may cause corrosion of structures (Autiola et al, 2022).

The Figure 40 describes the probability of occurrence of acid sulphate soils in Turku area (GTK’s Acid Sulfate Soils map service). The background material is made of GTK’s superficial deposit maps (1:20 000 and 1:200 000), GTK’s peat investigations and airborne surveys featured with the terrain database and elevation data of the National Land Surveys of Finland. Data for the map was collected via field surveys, results of laboratory analyses and interpretation of soil maps and aerophysical material. The map basis is classified into four different color categories: major (red), moderate (orange), low (light blue) and very low (blue). The observation points present the incidence of acid sulphate soils and the depth of occurrence of the sulfide layer from ground level. The mapping of observation points was made to the depth of three meters. During the field surveys, also data of superficial deposit type, layer order, pH values, sulfide presence and depth of occurrence was collected.

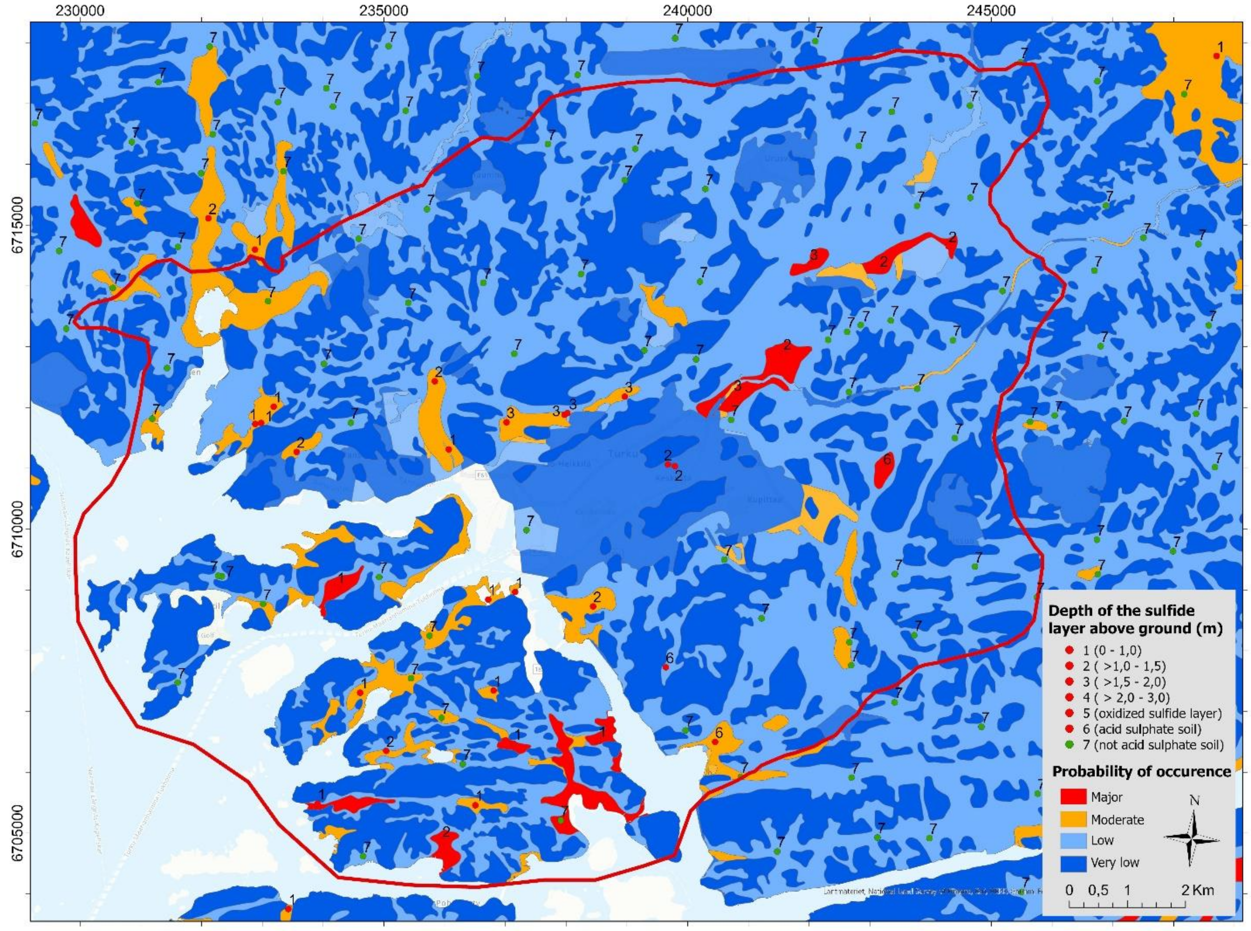


Figure 40. Map of acid sulphate soils.

Although the observation points were confirmed with various methods or combinations, such as laboratory analysis of samples, organoleptic assay, measured pH, and pH-incubation in the field, must be kept in mind that the map of occurrence is based on generalizations and interpretations of the terrain. For instance, organoleptic assay is subjective and, in some cases, used as an only method to identify acid sulphate soils, so it must be considered as a source of error. Therefore, the general map of occurrence cannot be used for detailed spatial examination (GTK's Acid Sulphate Soils map service).

According to Ojala et al (2016) classifying the late- and postglacial fine-grained sediment sections helps to recognize the boundaries between sediments formed at different phases during development of the Baltic Sea Basin. Between the brackish water mud formed during Litorina Sea and the underlying postglacial freshwater silty clay formed during Anculys Lake can be found an unconformable boundary which can be recognize geotechnically. The sediments deposited in Litorina Sea are stated as naturally containing sulfide bearing minerals, organic-rich and softer than the underlying postglacial lacustrine clayey sediments deposited in Anculys Lake phase. Acknowledge of the spatial unconformity provides a proper basis for engineering-geological modelling of fine-grained deposits in coastal areas of Baltic Sea.

Åbo Akademi and GTK have been studying the Turku region by doing characterizations of the area's lithology to recognize possible acid sulphate soils in the area. By reviewing the characterization studies' nearby geotechnical sounding datapoints and their diagrams, can be often found a thin and compact layer of more coarse material in fine-grained sediments. As seen in Figure 41. This layer occurs mainly in the depth of 1-5 m and presumably refers to the unconformity boundary between the Litorina Sea and Anculys Lake sediments. By studying the engineering-geological properties of fine-grained sediments, it is possible to predict and model potential areas that contain acid sulphate soils to prevent possible problems for urban planning and construction.

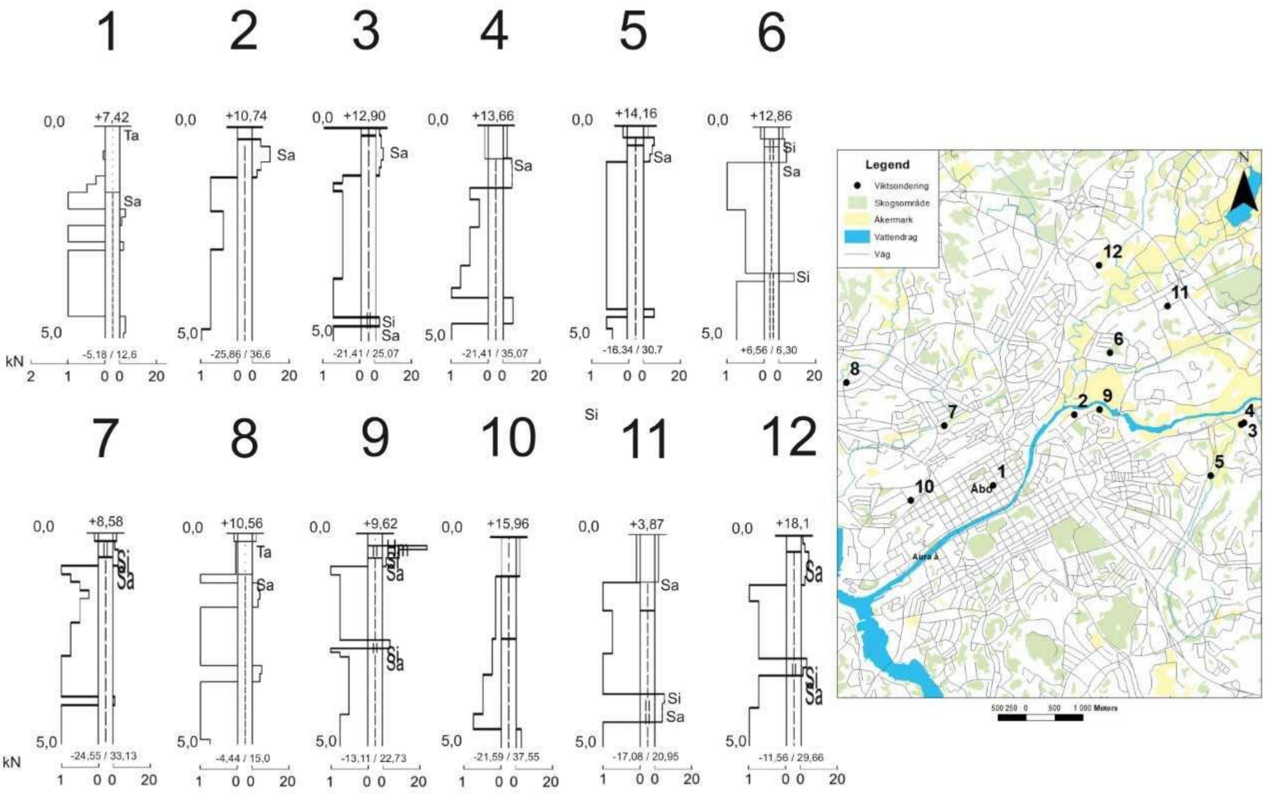


Figure 41. Examining the geotechnical sounding data in confirmed ASS-drilling locations, figure by Walter Strandell (2023).

6.3. Uncertainty and possible error factors

When placing the geotechnical sounding datapoints on top of the depth model, like in Figure 42, can be seen how the variability of the soundings data takes place in the research area.

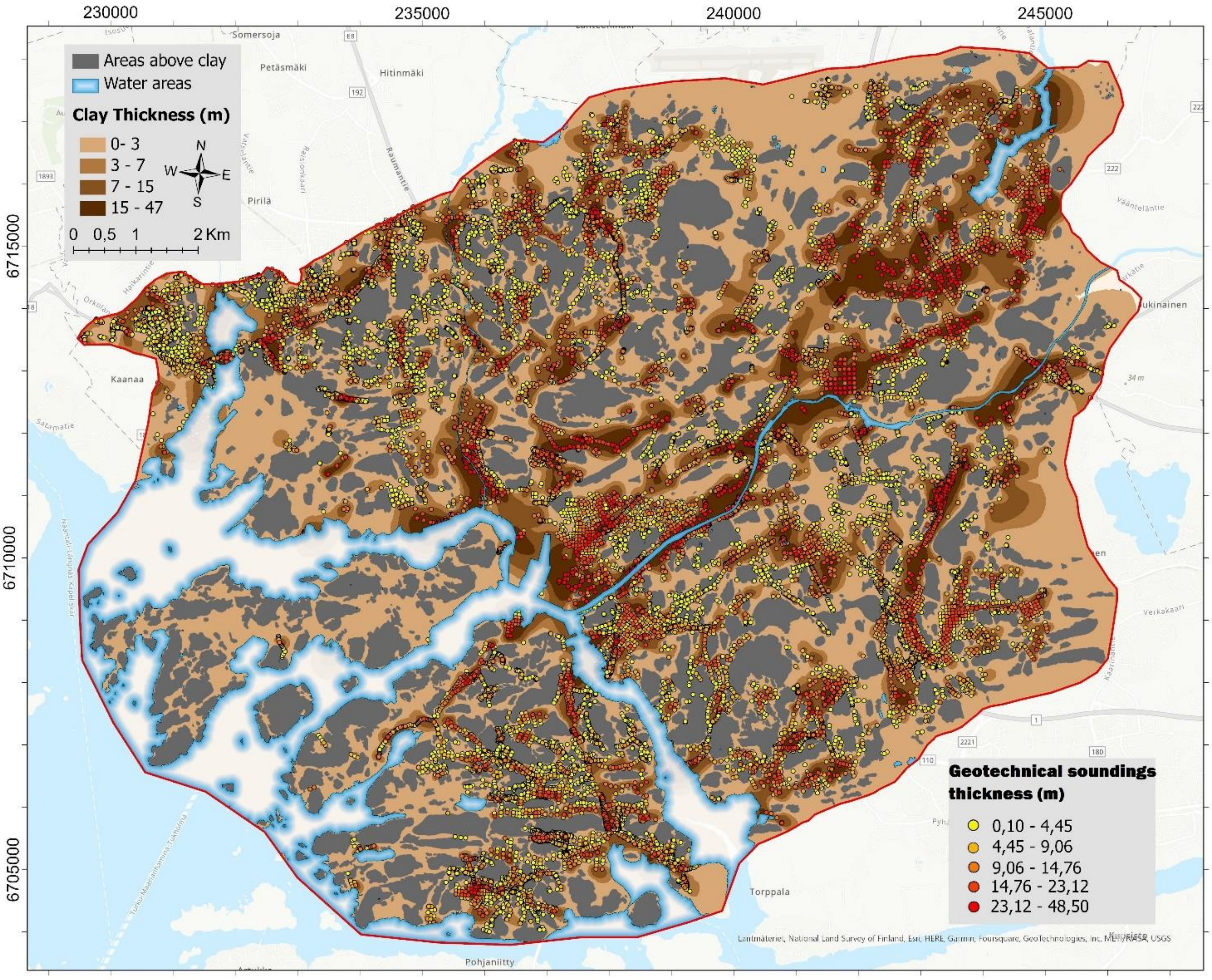
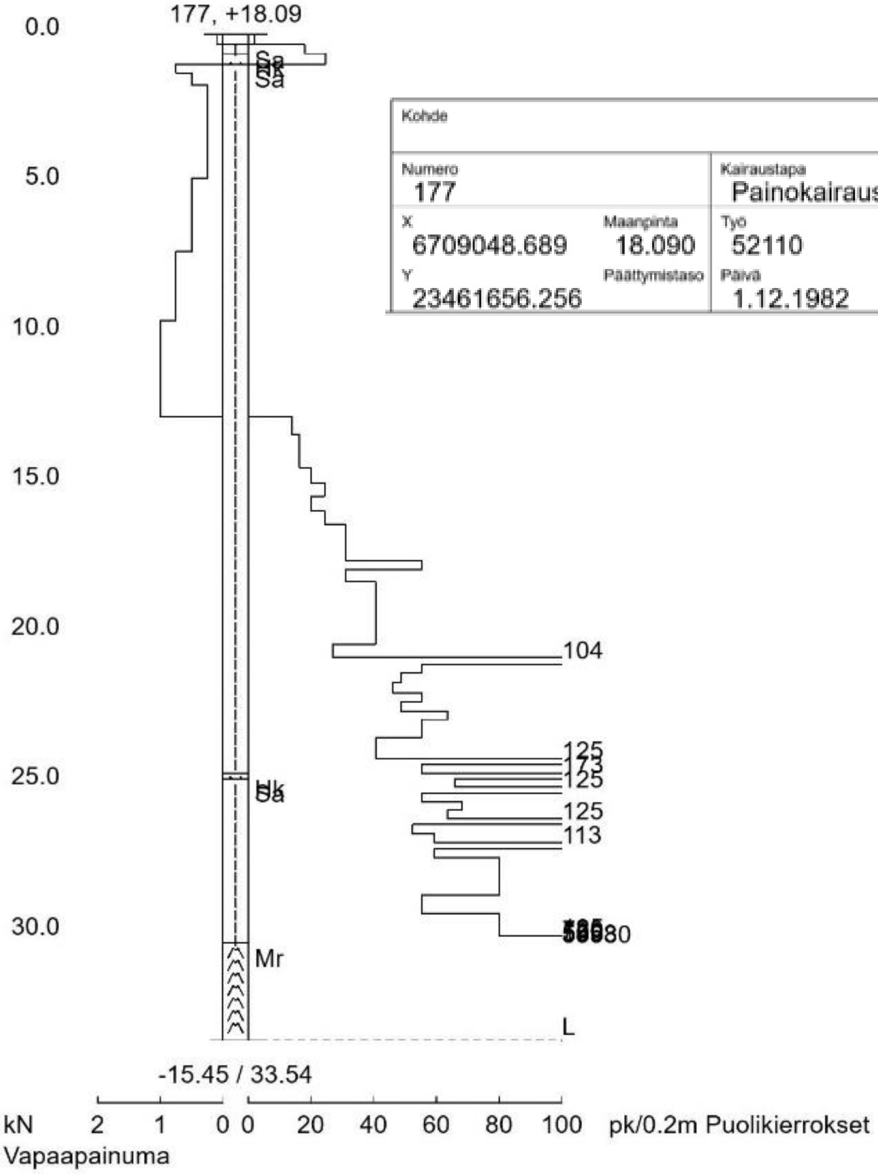


Figure 42. Geotechnical sounding datapoints on top of the clay thickness model.

The location of the geotechnical sounding datapoints confirm the calculations of the thickness of fine-grained sediments in the area. The deepest soundings, depth of 23 m to 48 m, are positioned in the bedrock depressions.

The reliability of this study decreases by the possible error factors and by the fact that the source information is not impermeable. The geotechnical sounding data does not cover the entire area evenly, but rather concentrates on areas with modern community structures. For instance, land areas in the city center covered by old structures built like 50 years ago, the underlying surficial deposit is not verifiable. Also, the areas in the islands off the coast offers weak data because data of the seafloor clay thickness is not available.

By viewing all the data used to create the 3D-model, the margin of error is increased with all the geotechnical data which are only determined into a certain depth level and not certified until to the bedrock. Also, after reviewing the data more closely for making the 'level zero of fine-grained sediments', it was noticed that the written observation compared to the drilling diagram had some inequalities between them. To exemplify this error, a sounding diagram dated back 1982 shown in Figure 43.



Kohde			
Numero 177		Kairaustapa Painokairaus	
X 6709048.689	Maanpinta 18.090	Työ 52110	Mittakaava 1:209
Y 23461656.256	Päättymistaso	Päivä 1.12.1982	

Figure 43. Weight sounding test-diagram dated 1982.

The sounding diagram in Figure 43 displays the recorded inaccuracy, where middle beam indicates surficial deposit type and drawing line its coarseness. So, a higher number on the scale and the drawing line further on the right indicates for coarser sediments. By observing the numerical value around the depth of 20 m, the diagram shows 104 which indicates for a coarse sediment, but the written observation refers to fine-grained sediments. Therefore, the reliability of these types of soundings can be speculated. By further examined, most of the inconsistent soundings like this were dated in the 1970's or in the 1980's, which may explain a lot. This finding sets the original dataset from Piriläs thesis (2016) doubtful, since she used only the written observations while forming the excel sheet of the sounding data used as a base on this study as well.

7. Conclusions

The areas of post-glacial fine-grained sediment, like Finland and other Nordic countries, face numerous challenges in land use and construction because of the characteristics of their surficial deposits. This study gives an illustration how to identify areas with such features. The Turku area, being an ancient seabed, contains evidently lots of fine-grained sediments. By classifying the area into structures and zones according to the paleotopography after deglaciation and during the Litorina transgression, and combining with selected environmental variables, the deposition environments of fine-grained sediments was revealed. The produced three-dimensional geological models display the most challenging areas for urban planning and construction with thick deposits of fine-grained sediments. The thickest deposits are mainly located in depressions along the Aurajoki river and in other deep bedrock formations in the area. Topographic analysis and classification can be contemplated as appropriate method to do more detailed research of the fine-grained sediment deposition environments on a regional scale. The methodology presented in this study can be utilized in similar coastal areas to study fine-grained sediments.

8. Acknowledgements

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References

Andrén, T. 2004: Littorinahavet – en salt historia. Havsutsikt 1, 2004, 8–9.

Andrén, T., Björck, S., Andrén, E., Conley, D., Zillen, L. ja Anjar, J. 2011. The development of the Baltic Sea basin during the last 130 ka. The Baltic Sea Basin, Central and Eastern European Development Studies (CEEDES). Springer, 75–97 p.

Autiola, M., Suonperä, E., Suvanto, S., Napari, M., Nylund, M., Kupiainen, V., Vienonen, S., Forsman, J., Suikkanen, T., Auri, J., Boman, A. & Mattbäck, S. (2022). National guide on acid sulphate soils for construction projects. A guide to taking account of acid sulphate soils and managing their impacts (in Finnish with an English abstract). Publications of the Ministry of the Environment 2022, 3. https://julkaisut.valtioneuvosto.fi/handle/10024/163782.

Eklund, O. Soesoo, A. ja Linna, A. 2007: Etelä-Suomen ja Viron prekambrinen kallioperä. Tallinnan Teknillisen Yliopiston Geologian Instituutti ja Turun Yliopiston Geologian Laitos. MTÜ GEOGuide Baltoscandia. 36 p.

Eronen, M., Glückert, G., Hatakka, L., van de Plassche, O., van der Plicht, J. & Rantala, P., 2001. Rates of Holocene isostatic uplift and relative sea-level lowering of the Baltic in SW Finland based on studies of isolation contacts. Boreas 30, 17–30.

Gardemeister, R., 1975. On engineering-geological properties of fine-grained sediments in Finland. Technical Research Centre of Finland, Building Technology and Community Development, Helsinki, Publications 9, 91 p.

Glückert, G. 1967. Post-glacial shore-level displacement of the Baltic in SW Finland. Annaled Academiae Scientiarum Fennicae. Series A. III. Geologica-Geographica. Suomalainen Tiedeakatemia, Helsinki.

Glückert, G. 1977. Itämeren rannansiirtymisestä Turussa ja sen lähiympäristössä. Publications of the department of quaternary geology, University of Turku.

GTK’s Acid Sulfate Soils map service https://gtkdata.gtk.fi/hasu/index.html

HAKKU-service, GTK. https://hakku.gtk.fi/fi/locations/search

Haavisto-Hyvärinen, M. & Kutvonen, H. 2007: Maaperäkartan käyttöopas. Geologian Tutkimuskeskus, Espoo.

Johnson, M.D., Öhrling, C., Bergström, A., Dreyer Isaksson, O. and Pizarro Rajala, E. (2022), Geomorphology and sedimentology of features formed at the outlet during the final drainage of the Baltic Ice Lake. Boreas, 51: 20-40. https://doi.org/10.1111/bor.12547

Jääskeläinen, R. 2011. Geotekniikan perusteet. Tammertekniikka/Amk-kustannus Oy, Jyväskylä. 387 p.

Kakkuri, J. 2012: Fennoscandian Land Uplift: Past, Present and Future. Lecture Notes in Earth System Sciences. From the Earth's Core to the Outer Space. Springer. 10 p

Karhima, A., Raukas, A. ja Linna, A. 2007: Jäätikön jäljillä Etelä-Suomessa ja Virossa. Tallinnan Teknillisen Yliopiston Geologian Instituutti ja Turun Yliopiston Geologian Laitos. MTÜ GEOGuide Baltoscandia. 36 p.

Kivikoski, E. & Gardberg, C.J. 1971: Turun kaupungin historia – Kivikaudesta vuoteen 1366. Oy Lounasrannikko, Turku.

Kohonen, J. & Tarvainen, T. (eds) 2021. Developments in map data management and geological unit nomenclature in Finland. Geological Survey of Finland, Bulletin 412, 169 p.

Kuntaliitto: https://www.kuntaliitto.fi/tietotuotteet-ja-palvelut/kaupunkien-ja-kuntien-lukumaarat-ja-vaestotiedot (visited 07/2022)

Lappalainen, J. 1999. Turun sataman historia. Gummerus Kirjapaino Oy, Jyväksylä. 448p

Lehtonen, K. 1997. Aurajokilaakson maisema-alueen kulttuurihistorialliset arvot

Lounas-Suomen Seutukaavaliitto, 1966. Turun seudun geologisen maaperäkartoituksen selitys vuodelta 1966. Geologian tutkimuskeskus, maaperäosasto. 15p.

Lumiaho, K. 1983. Kotimaisten savien käyttömahdollisuudesta täyttömateriaalina ydinjätteiden loppusijoituksessa. Geologinen tutkimuslaitos, Espoo.

Miller, G.K. et al 2020. Cenozoic sea-level and cryospheric evolution from deep-sea geochemical and continental margin records.Sci. Adv.6, eaaz1346 DOI:10.1126/sciadv.aaz1346

Niini, H., Uusinoka, R., Niinimäki R. 2007. Geologia ympäristötoiminnassa. Rakennusgeologinen yhdistys – Byggnadsgeologiska föreningen r.y. Helsinki. 353 p.

NOAA Coastal Services Center, 2013. Benthic Terrain Modeler for ArcGIS 10.1, Exercise https://dusk.geo.orst.edu/djl/samoa/BTM_Exercise.pdf

Novatron Oy, 2022. 3D-Win perusohje. Versio 6.7. Novatron Oy, Espoo. 52 p. https://3d-system.fi/download/155/

Ojala, A.E.K., Palmu, J.-P, Åberg, A., Åberg, S. & Virkki, H., 2013. Development of an ancient shoreline database to reconstruct the Litorina Sea maximum extension and the highest shoreline of the Baltic Sea basin in Finland. Bulletin of the Geological Society of Finland 85, 127–144. http://www.geologinenseura.fi/bulletin/Volume85/Bulletin_vol85_2_2013_Ojala.pdf

Ojala, A.E.K., Saresma, M., Virtasalo, J.J. et al. (2018). An allostratigraphic approach to subdivide fine-grained sediments for urban planning. Bull Eng Geol Environ 77, 879–892 https://doi.org/10.1007/s10064-016-0981-4

Pirilä, L. 2016: Savikerrostumien syntyhistoria, niiden paksuus- ja ominaisuusvaihtelut sekä vaikutukset yhdyskuntatekniikkaan Turun alueella. Turun yliopisto, Maantieteen ja geologian laitos.

Rosentau, A., Klemann, V., Bennike, O., Steffen, H., Wehr, J., Latinović, M., Bagge, M., Ojala, A E K, Berglund, M., Peterson Becher, G., Schoning, K., Hansson, A., Nielsen, L., Clemmensen, L.B., Hede, M.U., Kroon, A., Pejrup, M., Sander, L., Stattegger, K., Schwarzer, K., Lampe, R., Lampe, M., Uścinowicz, S., Bitinas, A., Grudzinska, I., Vassiljev, J., Nirgi, T., Kublitskiy, Y., Subetto, D.. 2021. A Holocene relative sea-level database for the Baltic Sea. Quaternary Science Reviews, Volume 266, 107071, ISSN 0277-3791, https://doi.org/10.1016/j.quascirev.2021.107071.

Salonen, V-P., Eronen, M. & Saarnisto, M. 2002. Käytännön maaperägeologia. Kirja-Aurora. Turku 237 p.

Saresma, M., Kosonen, E., Ojala, A. E. K., Kaskela, A., & Korkiala-Tanttu, L. 2021. Characterization of sedimentary depositional environments for land use and urban planning in Espoo, Finland. BULLETIN OF THE GEOLOGICAL SOCIETY OF FINLAND, 93(1), 31-51. https://doi.org/10.17741/bgsf/93.1.003

Selonen, O. & Ehlers, C. 2021. Natural stone in urban design in the City of Turku in southwestern Finland. Geotechnical report 17. Lahti 2021. 80p.

Strandell, W. 2023. Miljöeffekter i samband med masstabilisering av sulfidlera i Åbo. Pro Gradu, Fakulteten för naturvetenskaper och teknik, Åbo Akademi.

Suikkanen, T., Lindroos, N., Autiola, M., Napari, M., Taipale, T., Laine, J., Forsman, J., Auri, J. & Boman, A., 2018. Esiselvitys happamien sulfaattimaiden kartoitusmenetelmistä ja suosituksia toimenpiteiksi infrahankkeissa pääkaupunkiseudulla. Ramboll.

Suomen Geoteknillinen yhdistys, 1980. Kairausopas I: Painokairaus, tärykairaus, heijarikairaus. Rakentajain Kustannus Oy, Helsinki. 11 p.

Suomen Geoteknillinen yhdisty, 1995. Kairausopas II: Siipikairaus. Suomen geoteknillinen yhdistys ry, Nummela. 28 p.

Suomen Geoteknillinen yhdistys, 2001. Kairausopas VI: CPTU/Puristinkairaus, puristin-heijarikairaus. Suomen geoteknillinen yhdistys ry, Nummela. 91 p.

Suomen Geoteknillinen yhdistys, 2021. Pohjatutkimusmerkinnät. 8 p.

Thieme, A., 2019. The Baltic Sea during the last 15,000 years. https://blog.datawrapper.de/weekly-history-of-the-baltic-sea-locator-map/ (visited 12/2022)

Tilastokeskuksen maksuttomat tilastotietokannat: https://pxnet2.stat.fi/PXWeb/pxweb/fi/Kuntien_avainluvut/Kuntien_avainluvut__2021/kuntien_avainluvut_2021_aikasarja.px/table/tableViewLayout1/ (visited 07/2022)

Tilastokeskus: https://tilastokeskus.fi/tup/seutunet/turun_alue.html (visited 07/2022)

Turun kaupunki, 2013. Yleiskaava 2035, lähtökohdat ja tavoitteet. Turun kaupunki. p. 169 https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwj2uMm_w4r9AhXWQ_EDHetqDSEQFnoECAsQAQ&url=https%3A%2F%2Fwww.turku.fi%2Fsites%2Fdefault%2Ffiles%2Fatoms%2Ffiles%2Fturku_yleiskaava_2029_lahtokohdat_ja_tavoitteet.pdf&usg=AOvVaw1oK0_2

Yli-Halla, M. 2022. Acid sulfate soils: A challenge for environmental sustainability ', Annales Academiae Scientiarum Fennicae. Geologica-Geographica , vol. 1 , no. 1 , pp. 124-141 .
https://doi.org/10.57048/aasf.122859