WP3: Baseline Study

Chapter 4: Mapping salinization intensity and risks in the North Sea Region

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Contents

4. Introduction

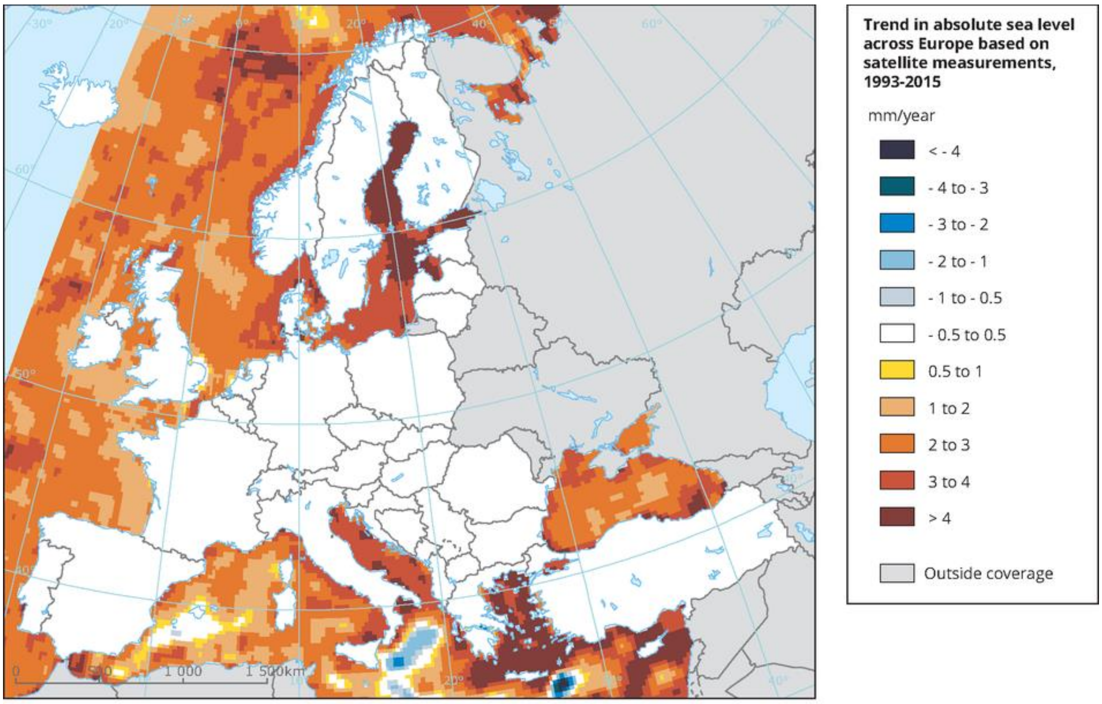
While salinization is one of the major threats to agriculture worldwide, it is unevenly spread with the biggest impacts observed in arid and semi-arid zones as well as around low-lying delta areas. Each scenario brings a particular vulnerability. Arid regions are home to precarious communities for whom any further worsening of soils could lead to starvation. Delta regions, by contrast, traditionally have highly fertile soils, large populations and abundant food which has seen them develop international economies, supported by major transport infrastructure. However, fresh ground water resources have been intensively exploited for domestic, agricultural and industrial purposes (Van Weert et al., 2009), therefore, future fresh water exploitation is expected to increase due to population and economic growth, agricultural intensification and loss of surface water resources due to contamination (Ranjan et al., 2006).

In this chapter we begin with a review of previous attempts to map salinization globally, and specifically in the European context. We then drill down to case study regions in the North Sea Region to examine more closely the of degrees of salinization and danger of degradation of farmland for coastal areas. Although the data is incomplete and not always comparable at the European level, local case studies are included to present examples of the nature of the threats across different regions facing different types of salinization threats. While this meant that certain assumption had to be made to fill in gaps, the evidence begins to present a baseline picture for policy makers, agricultural organisations and practitioners. It also underpins SalFar's call for greater coverage and consistency of efforts to measure soil and groundwater salinity to inform mitigation strategies and to support advances in saline agriculture.

4.1. Climate change forecasts for the NSR

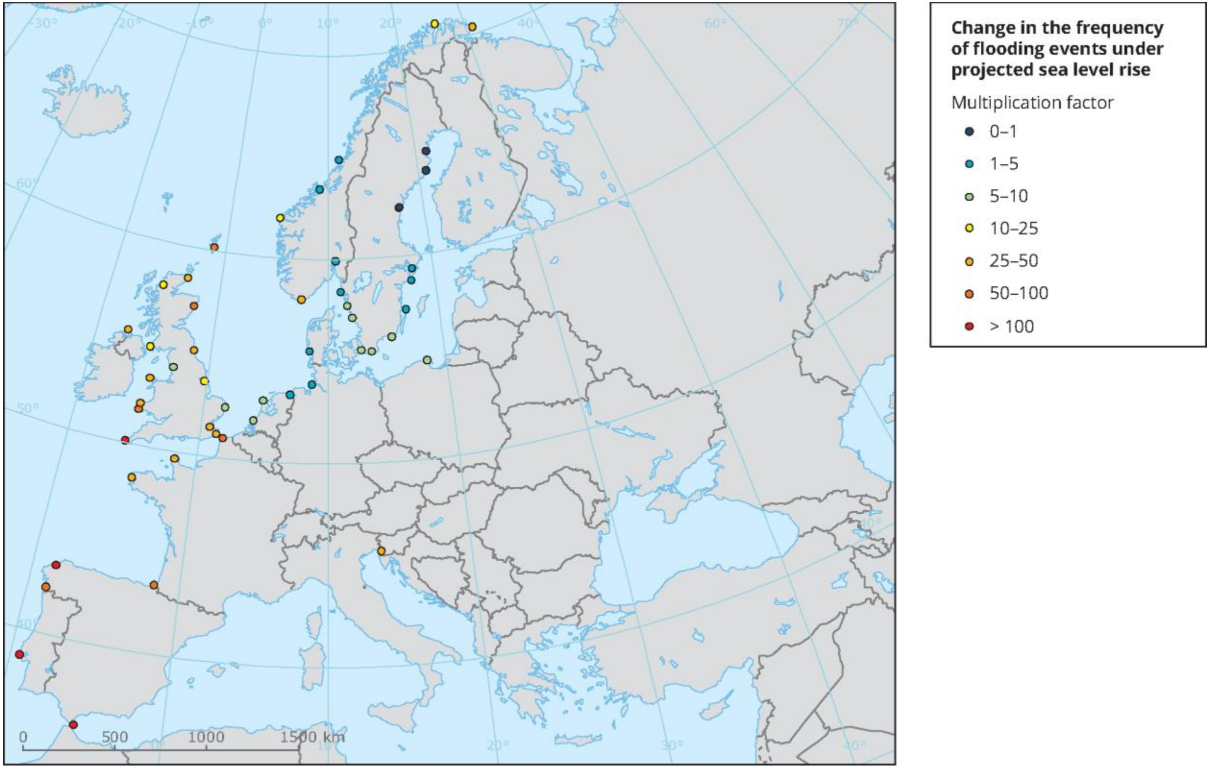
Trends in sea level rise are monitored by the European Environment Agency (EEA) who produced the map in Figure 4.1 which illustrates that this is not consistent across the continent, with the Baltic Sea experiencing the highest increases.

Figure 4.1. Trend in absolute sea level across Europe based on satellite measurements. Source: EEA (2017): https://www.eea.europa.eu/data-and-maps/indicators/sea-level-rise-5/assessment



The predictions for increases in flooding events related to sea level rise are illustrated in Figure 4.2 and show a number of vulnerable sites around the NSR. The map shows the estimated multiplication factor, by which the frequency of flooding events of a given height changes between 2010 and 2100 due to projected regional sea relative level rise under the RCP4.5 scenario[1]. Values larger than 1 indicate an increase in flooding frequency (European Environment Agency, 2017).

Figure 4.2. Change in the frequency of flooding events under projected sea level rise
Source: https://www.eea.europa.eu/data-and-maps/figures/increase-in-the-frequency-of-1



The areas at greater risk of flooding have also been identified by Paprotny et al. (2017) who produced the map in Figure 4.3 illustrating the higher risks in Belgium, Northern Germany, Eastern England and parts of Western France.

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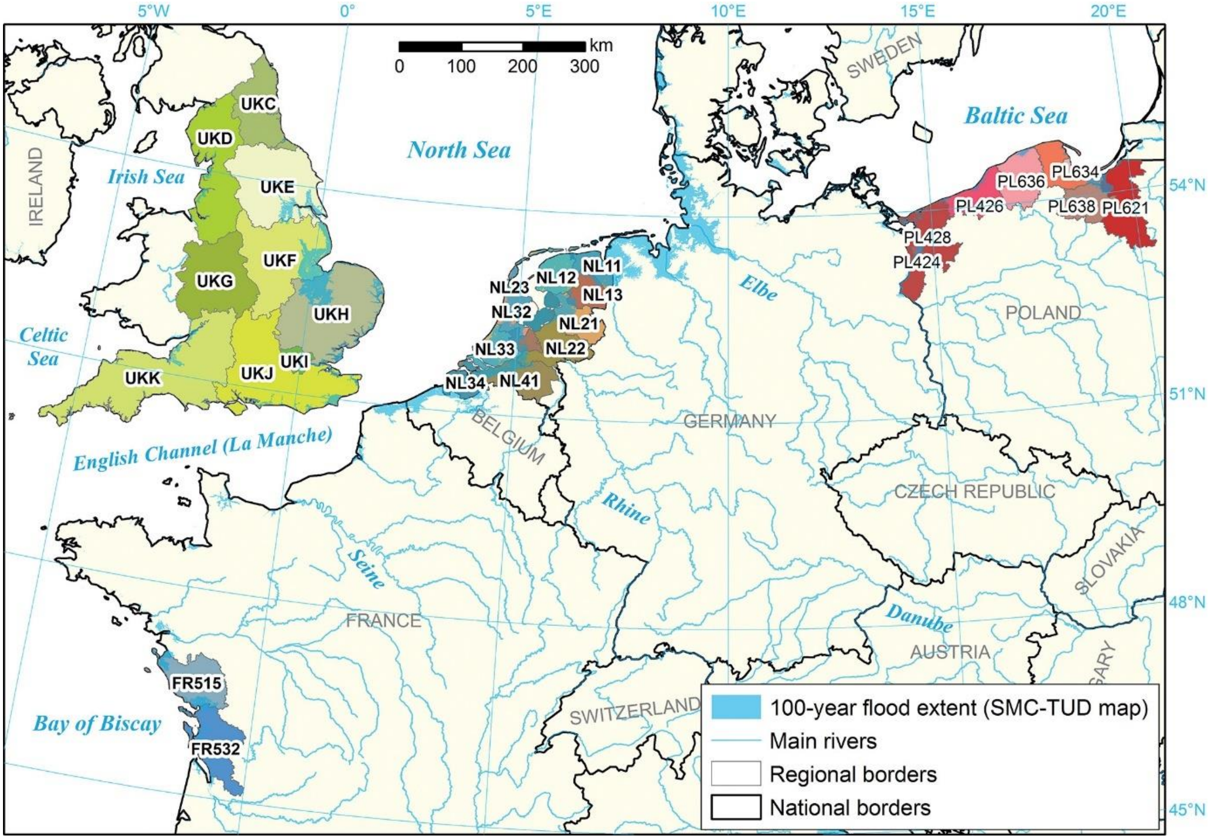
[1] RCP 4.5 is a stabilization scenario and assumes that climate policies, in this instance the introduction of a set of global greenhouse gas emissions prices, are invoked to achieve the goal of limiting emissions, concentrations and radiative forcing (Thomson et al., 2011)

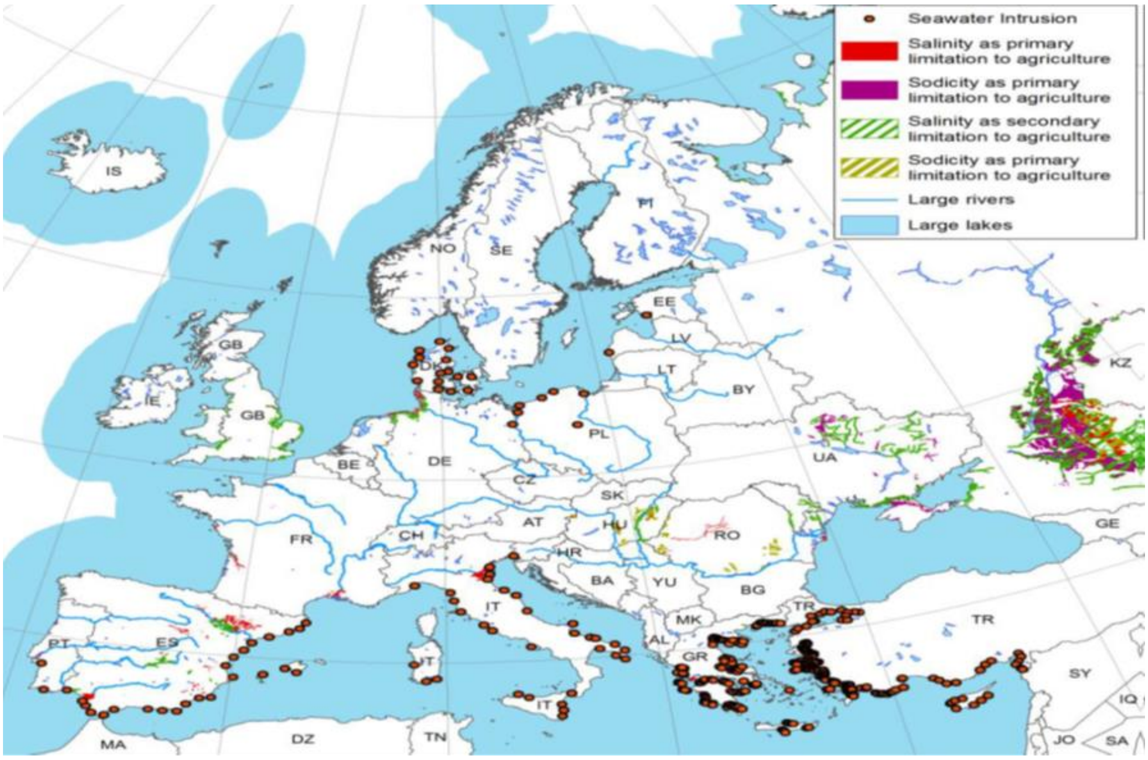
Figure 4.3. Forecast 100-year flood extent. *Source: Paprotny et al. (2017)* [*https://onlinelibrary.wiley.com/doi/10.1111/jfr3.12459*](https://onlinelibrary.wiley.com/doi/10.1111/jfr3.12459)



4.2. A Review of Previous Salinization Maps

The most recent comprehensive estimation of the extent of soil salinity levels in the EU has be provided by the European Soil Data Centre (ESDAC) (2018). The map in Figure 4.4 shows the area distribution of saline, sodic and potentially salt affected areas within the European Union. The accuracy of input data only allows the designation of salt affected areas with a limited level of reliability (e.g. < 50 or > 50% of the area); therefore the results represented in the map should only be used for orientating purposes. This map was based on a lot of similar data to the map generated by Toth et al (2008) shown subsequently in Figure 4.5.

Figure 4.4. Saline and sodic soils as agricultural constraint and as primary and secondary limitations to agricultural use, and areas of seawater intrusion in Europe. Source: Daliakopoulos et al. (2016)



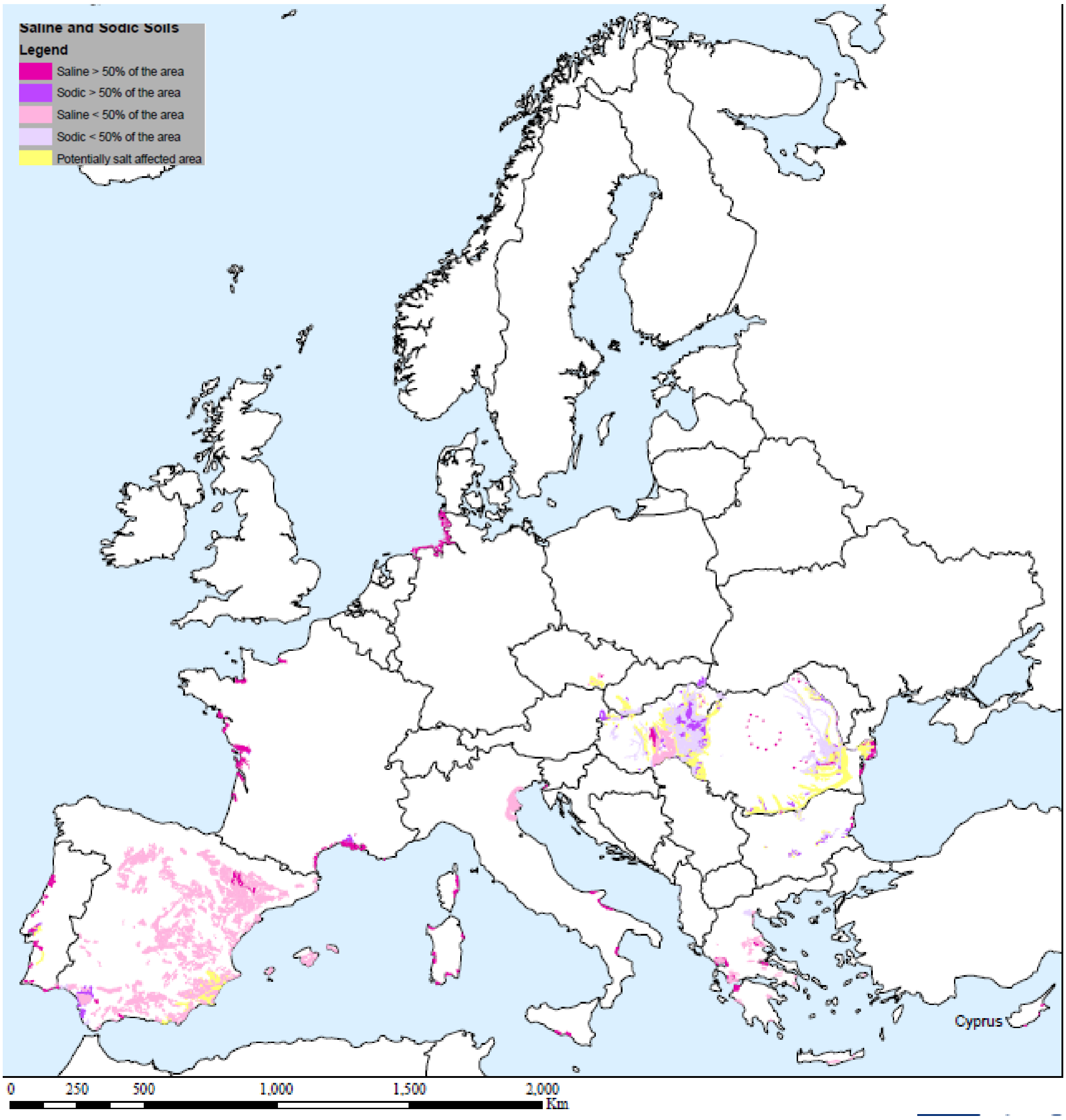
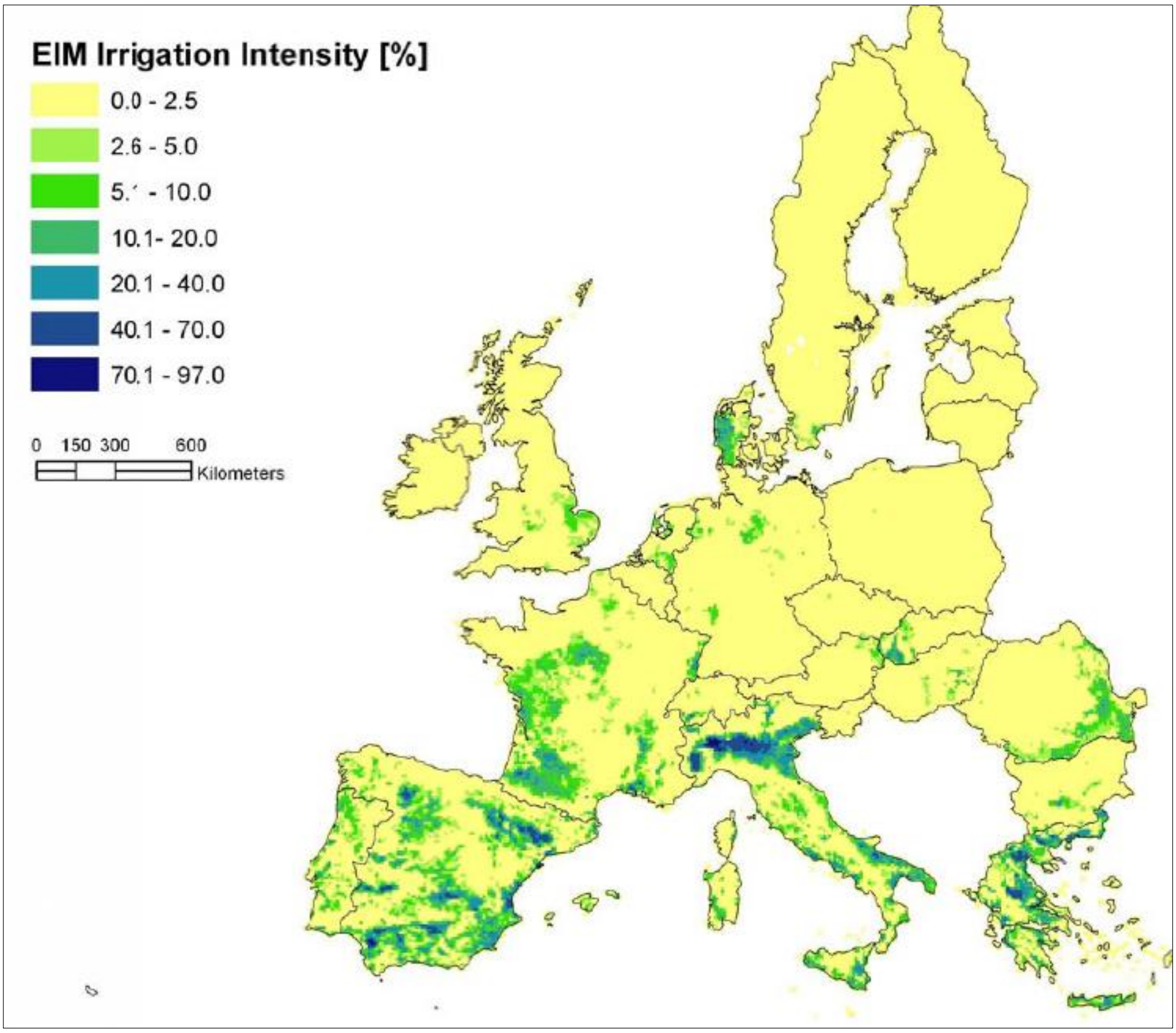


Figure 4.5. Saline and Sodic Soils in European Union. Source: *European Soil Data Centre (ESDAC) (2018)*

4.3 The Extent of Irrigation

The European Irrigation Map (EIM) is created as a binary data set (1 = irrigated, 0 = not irrigated) of 1ha resolution, complementing the land use map. The overlay of both maps provides a map of irrigated crop areas (and non-irrigated crop areas). Figure 4.6 provides an overview on irrigation intensity in the EU, summarizing irrigated areas for raster cells of 10x10km. The Map displays very well the focal areas of irrigation in Southern Europe, while in Central and Northern Europe a belt of irrigated areas extends from France to the Benelux-Countries and Denmark (Wriedt et al., 2008).

Figure 4.6 European Irrigation Map (EIM) - Irrigation intensity in the EU as irrigated area in % of total area calculated over a 10x10km raster. NB: the regions shown are at the NUTS 2 level. *Source: Wriedt et al. (2008)*



4.4. Salinization in the North Sea Region - Case studies

The anticipated sea level rise and changes in recharge and evapotranspiration patterns will put more pressure on the coastal groundwater system (Oude Essink et al., 2010). Therefore, it is expected that coastal aquifers will become more saline due to salt water intrusion resulting in a loss in fresh groundwater (Oude Essink et al., 2010). Salinization is the increase of salt concentration in groundwater or surface water systems. Saltwater intrusion, explained below, can be considered as a type of salinization (Pauw et al., 2012).

4.4.1. Netherlands

The main causes of salinity in the coastal groundwater in the Netherlands are closely linked to the paleo-geographic evolution of the coastal zone and anthropogenic activities: the coastal development since the last ice age (the Holocene) and the process of reclamation (drainage, land reclamation and drying) since the Middle Ages (Staveren and Velstra, 2012).

The North Sea covered most of the Netherlands during the Early Pliocene (Zagwijn, 1989) but there was a shift of the coastline and the depocenters toward the north-west at that time, which continued into the Early Pleistocene. Those influences have disappeared from the present coastal area by 1.6 Ma BP (Post et al., 2003). However, in the Holsteinian interglacial the sea entered the western part of the Netherlands again. Marine sediments from this period are found in deep valleys that were created during the Elsterian glacial stage (~300 kA PB).

During the Saalian glacial period (180 kA – 130 kA BP.), half of the Netherlands (Zagwijn, 1974) was covered by ice, which created subglacial basins up to 100 meters deep (De Gans et al., 1987). The sea level rise which occurred during the Eemian (130 kA – 110 kA BP.), infiltrated the former glacial basins resulting in widespread marine conditions. The increase in groundwater levels in combination with poor drainage of the flat area led to the formation of peat (Basal peat) (Post et al., 2003). During Calais transgression, 8-3.8 kA BP., sea level continued to rise flooding large parts of the peat areas. Around 2 kA BP. (Beets et al., 1992) sea level rise had decreased to 0.05m/century and from about 1 kA BP.

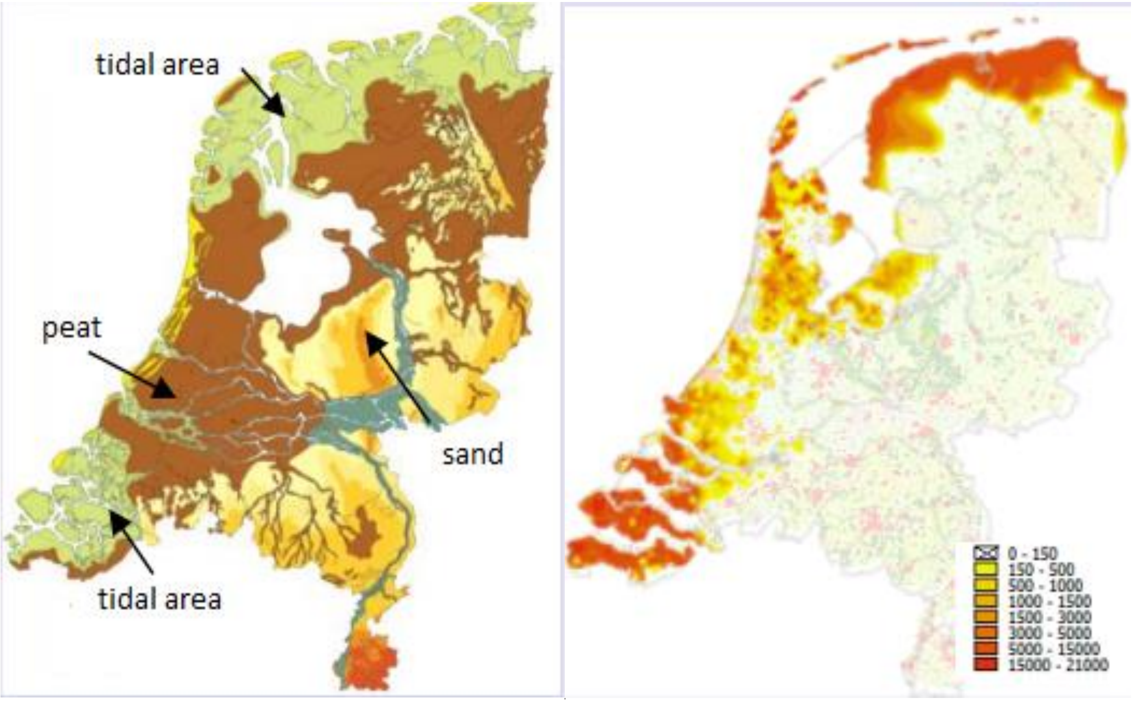
Since Roman times humans have started draining the peat areas resulting in land subsidence due to compaction and decomposition of peat. Land was reclaimed on tidal flat areas in the south-western and northern part of the coastal area building dikes. Dikes were also built to protect their properties from rivers flooding. Compaction, decomposition, erosion and sea level rise have created the characteristic polder landscape as known today (Post et al., 2003). Therefore, polders are low-lying and artificially drained areas that are surrounded by dikes which are connected through hydraulic structures such as weirs and sluices. They are frequently found in The Netherlands, Belgium and parts of Denmark and Germany.

Water levels in polders and surrounding storage canals are maintained at certain point, in order to control the groundwater levels in the polders (Aydin et al., 2017). Therefore, water from excess rain and seepage are pumped into the canals and rivers that drain into the North Sea (Post et al., 2003). Keeping groundwater levels close to a target level contributes to avoid dike failures in storage canals and prevent the acceleration of land subsidence (Lobbrecht et al., 1999). Differences in surface water level between polders, lakes, canals and ricers predominately control groundwater, flow patterns which end up in a complex system of local to regional groundwater systems (Post et al., 2003).

In the Netherlands, salinization of the polders occurs by lateral intrusion of seawater, mainly because their elevation is below mean sea level. This process is accelerated by sea-level rise, while an older study showed that modern sea water has already intruded about 2 to 6 km from the coastline (Stuyfzand, 1993). Apart from sea level rise and soil subsidence, the increase in temperature (climate change) also plays a role in groundwater salinization: as plants evaporate more moisture, more water is extracted from the soil. In dry conditions, the freshwater lens decrease in size. This allows the salt water to reach the root zone. The current way of draining in the agricultural land is also responsible for an increase in salinization. However, this can be done by means of adapted drainage methods, so that fresh water in the subsoil can be better preserved and managed.

Figure 4.7 shows how the fresh-salt water distribution are explained through the different geological phases. In particular, the areas with a high Cl concentration (>10,000 mg/l) correspond to the areas, which were still tidal at the final stage of the coast formation (800 AD): Zeeland, Friesland, Groningen and the head of North Holland. The salt in these areas is located at a small depth. The other areas with salt groundwater correspond to the areas that have been reclaimed since 1300. These are the areas where the salt has risen as a result of the reclamation. The location of Groningen shows that groundwater salinization has been occurred because large areas used to be tidal and due to land reclamation.

Figure 4.7. Left: The Netherlands 1150 years ago (RACM & TNO), right the creation of polders since 1300 (Atlas of the Netherlands) and bottom left the salinity to approx. 20m depth (TNO). Source: *Staveren and Velstra (2012)*



The soil 1150 years ago (800 AD) **Salinity in the groundwater in 2000**

Figure 4.8 projects the risk of groundwater salinization in the Netherlands for 2050. The groundwater salinity risk map in 2050 is developed based on rigorous hydrological models taking into account the geophysical aspects as well as using field salinity measurements of the last ten years. Although the intrusion of saline water occurs very quickly, the process of groundwater to go back to the state it was before the intrusion, takes up to 5 years (expert knowledge; Jouke Verlstra, Acacia), which points to the complexity of the impacts of salt water intrusion. The map in Figure indicates in purple the areas at high risk of groundwater salinization and they are mainly extended along the coast of Northern Ireland and the eastern part of island Texel. Large areas in the province of Groningen are at medium risk and fewer at high risk. Most of the areas in Texel island, however, appear be at high or medium risk. Information on the extent of the land at risk of groundwater salinization was not available by AcaciaWater.

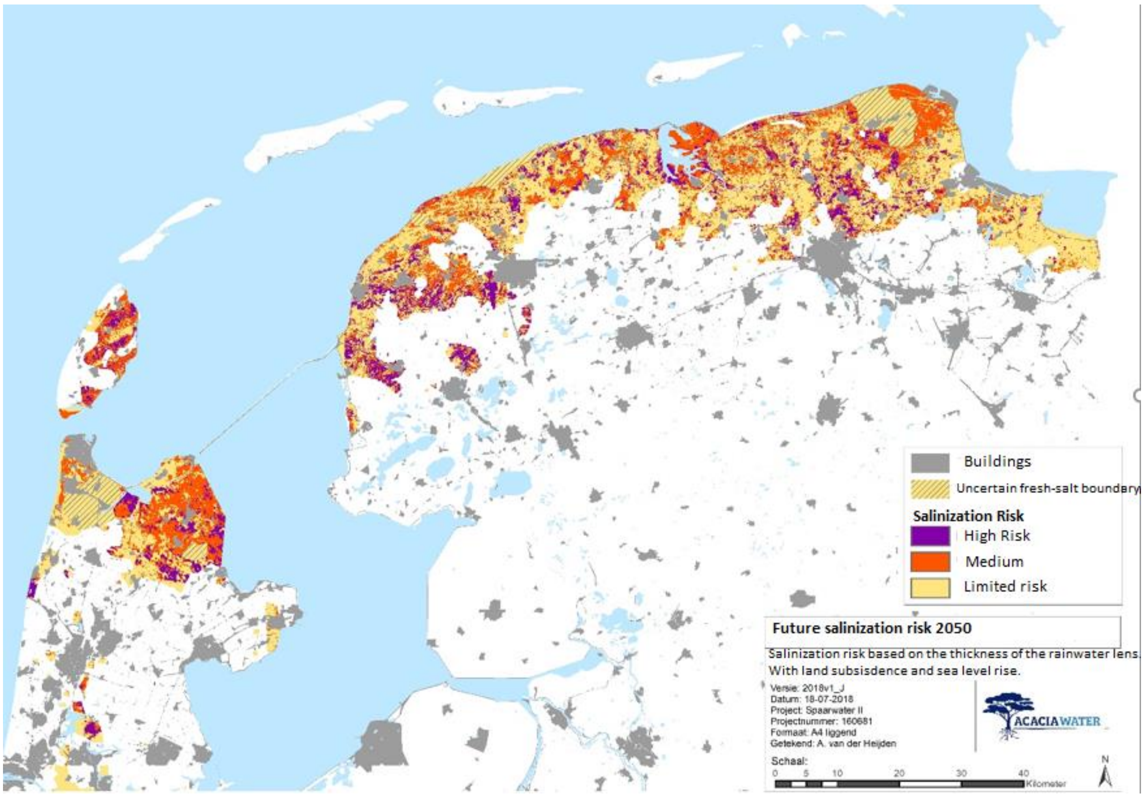


Figure 4.8 Future risk of groundwater salinity for 2050. Source: *AcaciaWater (2017)*

As the sea level rise will continue to incur, seawater intrusion processes are likely to continue in the Netherlands, and the future water availability from both fresh groundwater and surface water systems will be jeopardised (Oude Essink et al., 2010). A relative sea level rise of 0.75 m per century will exacerbate the problem leading to further increase in salt load in the polders

Groningen, Friesland, Northern Holland, Southern Holland, Flevoland and Zeeland are the areas recognised as areas at risk of salinity. In this report the two areas in the Netherlands comprise the case study, the province of Groningen and the Island of Texel.

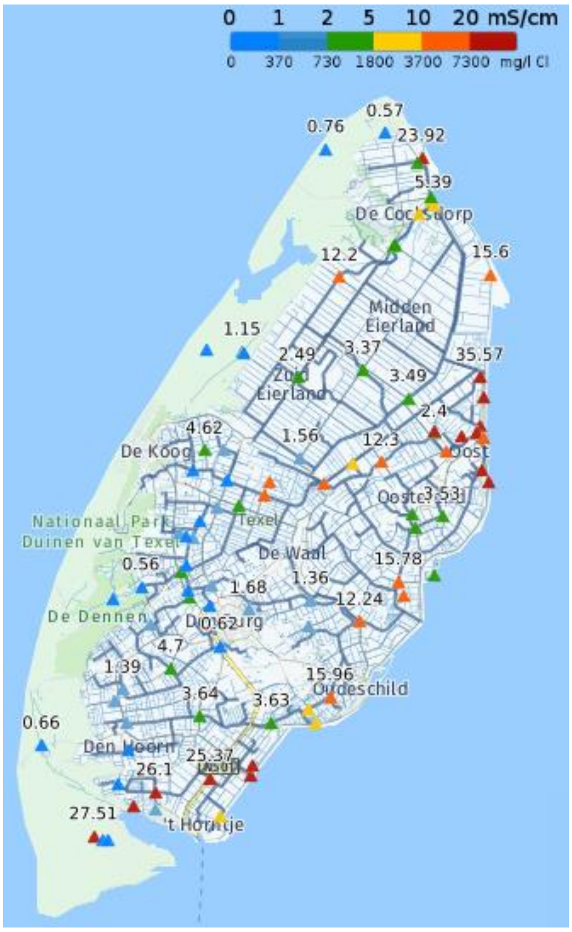
4.4.1.1. Texel

The island of Texel is the largest Wadden Island (~ 170 km2) characterised by an elongated dune area bordering the North Sea (Pauw et al., 2012). The population of the island is 13,000, while during the summer months the number of people can be as high as 60,000 (Oude Essink, 2000). This coastal dune area exists on the western side of the island, with phreatic water levels ((in the saturated zone beneath the water table) up to four meters above mean sea level (MSL). In the northern side of the island a tidal inlet is located, The Slufter, and in the eastern side four low-lying areas with controlled water levels (polders) are located. It is found that the Prins Hendrik polder has the lowest phreatic levels (-2.0 m MSL), while in the Dijkmashuizen polder area the phreatic water reaches +4.75 m MSL, mainly due to the existence of a small ice pushed hill (Pauw et al., 2012).

Texel has a gently sloping and mostly flat landscape with height varying between 15.30 m and -70 cm above sea level. The climate of Texel is moderate and humid without dry season. The mean annual precipitation is approximately 733 mm and average annual temperature varies between 2.6 and 17.8˚C (Abdulghani, 1965). Recent data suggests that this is now estimated at 765.3mm average rainfall and average summer monthly high temperatures reach 22˚C (Weather-and-climate.com).In Texel island sea water intrusion is the major factor responsible for increase of salts in groundwater and soils. The detailed soil information of the area is given in Kloosterhuis et al. (1986). According to Oude Essink (2000) brackish water already occurs close to the surface of low-lying polder areas at the eastern part of the island and the salinity in the top layer will increase substantially during the next centuries.

Figure 4.9. 4.9 reports the most recent geographically selecting measurement data of the quality of surface waters across Texel. The map shows that higher salinity surface water is observed east of the island. Closer to the sea the Cl concentrations of the surface water are very high (Cl > 7,300 mg/l), while inland Cl concentrations fluctuate between 730 mg/l and less than 7,300 mg/l.

Figure 4.9. Cl measurements of surface water in Texel end September end November, 2018. Source: *(texelmeet, 2018)*



4.4.1.2. Groningen

In the province of Groningen there is available time series data in Cl groundwater concentrations from 1973 until 2018 measured in 187 boreholes along the province (

FigureFigure 4.10). In this section we present the results of groundwater Cl measured in 2018. In order to get a better understanding of the concentration of Cl in the ground water of the whole province, we used interpolation in ArcGIS. Figure 4.11(a) shows the level of Cl in depth under the ground of 1-10 m. The map shows that higher Cl levels exist in the northern part of the province and closer to the coast. Similar results we observe in Figure 4.6 and Figure 4.7 where Cl are measure at depth 10-50m and 50-172.41m respectively. Comparing the three maps it sees that the ground water at 10-50m seems to have higher levels of Cl than the other two.

Figure 4.10. Cl groundwater measurement points in Groningen, 1973-2018

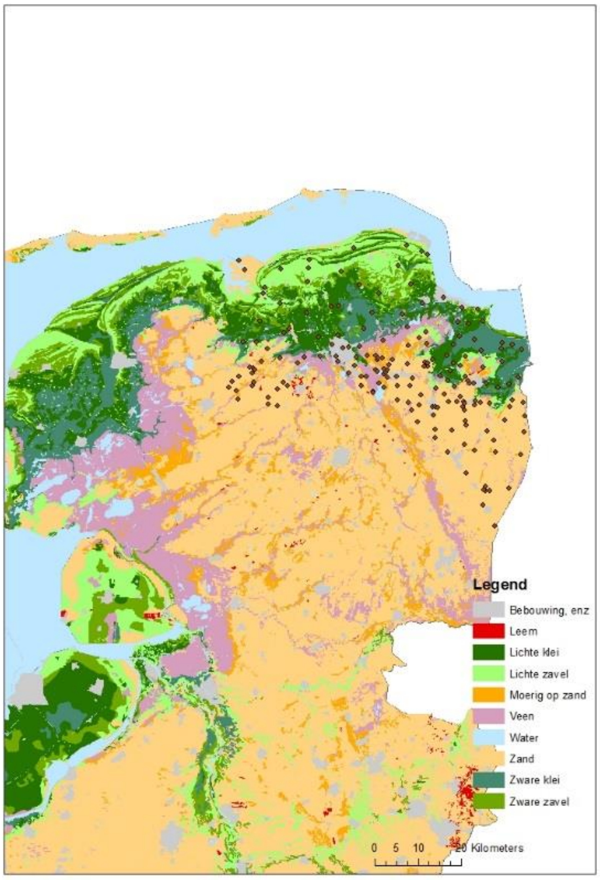


Figure 4.11(a). Cl (mg/l) in 2018 at depth 1-10m

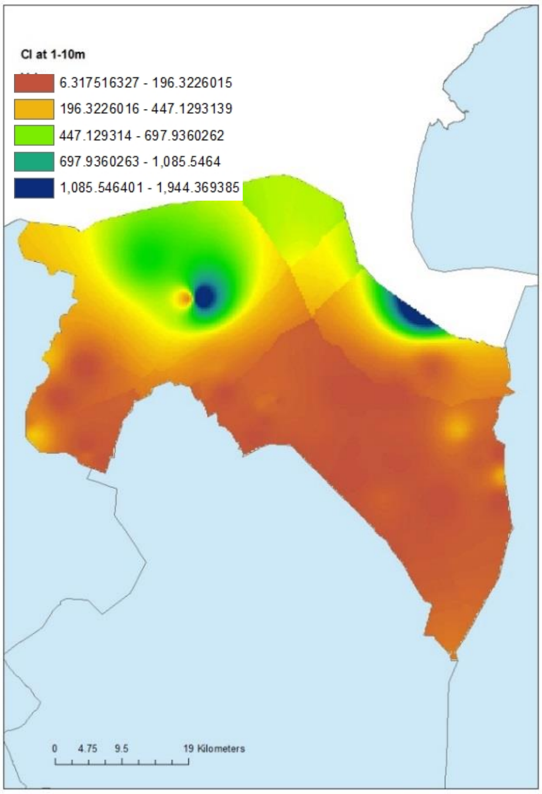


Figure 4.11(b). Cl (mg/l) in 2018 at depth 10-50m

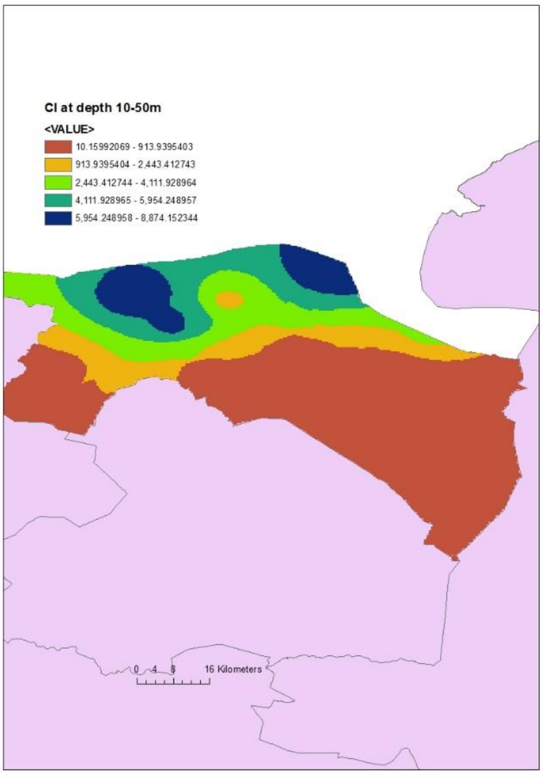
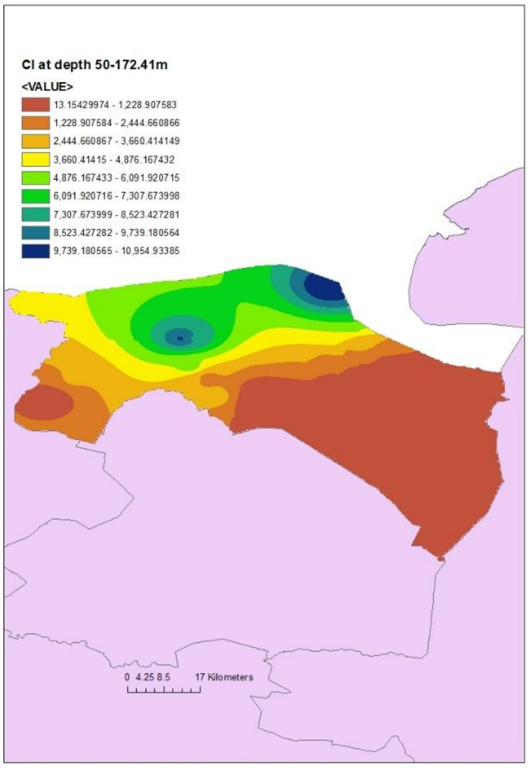


Figure 4.11(c) Cl (mg/l) in 2018 at depth 50-172.41m



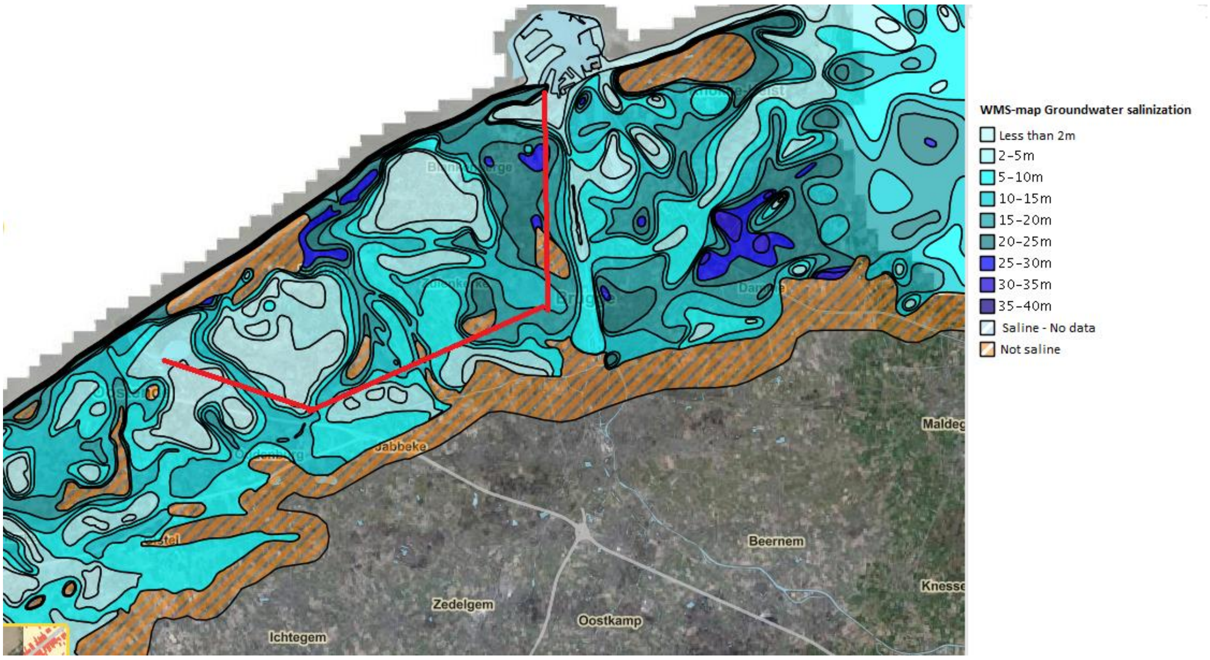
4.4.2. Belgium

The Coastal Hydrographic Service (part of the Waterways and Maritime Affairs Administration) in Belgium, attempted to interpret the measurements from three tide gauges along the Belgian coast (Oostende, Zeebrugge and Nieuwpoort). Results suggested an increase of 2 mm/year in High Water at Oostende, which is located in the western part of the Oudlandpolder, and an increase in low water of 1 mm/year for the period 1820-2000. Therefore, the Belgian coast is considered geologically stable, so regional land subsidence is assumed to be negligible (Lebbe et al., 2008). According to the climate scenarios of Konnen (2001), Flemish management authorities are currently taking into account a 60 cm increase in 100 years when calculating design standards for coastal flood defence structures (Marchand, 2006).

The last two decades in Belgium were marked by very high annual average temperatures and the warming trend is well established. In relation to precipitation in Belgium, recent studies mention an increase in winter precipitation by 3-13% in 2100 (Beersma, 2004). An increase of 10-40% in number and intensity of rain showers is estimated as well as an increase in the number and intensity of storms (wind speed and wave height). Summer seasons will be drier, that is increase in evaporation will be higher than the increase in summer precipitation (Können, 2001).

The Belgian dunes are relatively small therefore, the amount of freshwater captured by these dunes depends on the dune dimensions. The present fresh-salt water distribution in the 'Belgische Middenkust' is shown in Figure 4.12. Freshwater lenses are found in the dune area and under old tidal channel ridges. However, sea level rise is expected to affect the distribution of this fresh-salt water. For instance, intrusion of salt water through watercourses can lead to a loss of fresh groundwater resources, while saltwater seepage will lead to more saline groundwater and surface water systems.

Figure 4.12 Depth to the 1500 mg/L isosurface in the central Belgian coastal plain. Source: Geopunt (2015)



Measuring the electric conductivity of watercourses in the Oudlandpolder have shown EC higher than 50 dS/m especially during dry summers (Figure 4.13). While outliers up to more than 70 dS/m are not uncommon. In areas where water is used for livestock, irrigation or for drinking, high EC levels might be a problem for the quality of this water. The problem arises when in a long lasting drought there is high demand in water for irrigating crops and watering animals, causing transferable watercourses enter into the polder water system. However, surface water high in salinity is not suitable for irrigation or livestock. Dierengezondheidszorg Vlaanderen[2] allow a maximum EC of 21 dS/m in their drinking water. EC of 15 dS/m is considered less suitable for irrigation although not all crops are equally sensitive to salinity levels. For instance, most arable crops have higher than fruits.

Monitoring of salinity levels is provided by the Flemish Environment Agency, Vlaamse Milieumaatschappij, VMM measurement network with about 100 measurement points located in coastal polders. Measuring points in the Zwin and discharge points to the sea (e.g. mouth harbour channels) which have a standard high conductivity were not considered. As salinity indicator is used the EC of surface water in the Oudlanspolder polders supplemented by field measurements of the polders where the fresh/salt water interface is less than 2 meters below ground level.

The results of these measurements are reported in Figure for the January-August of 2018, showing that an increasing electrical conductivity occurs in the polder watercourses of the coastal polders.

Figure 4.13 Maximum EC for the period January-August 2018

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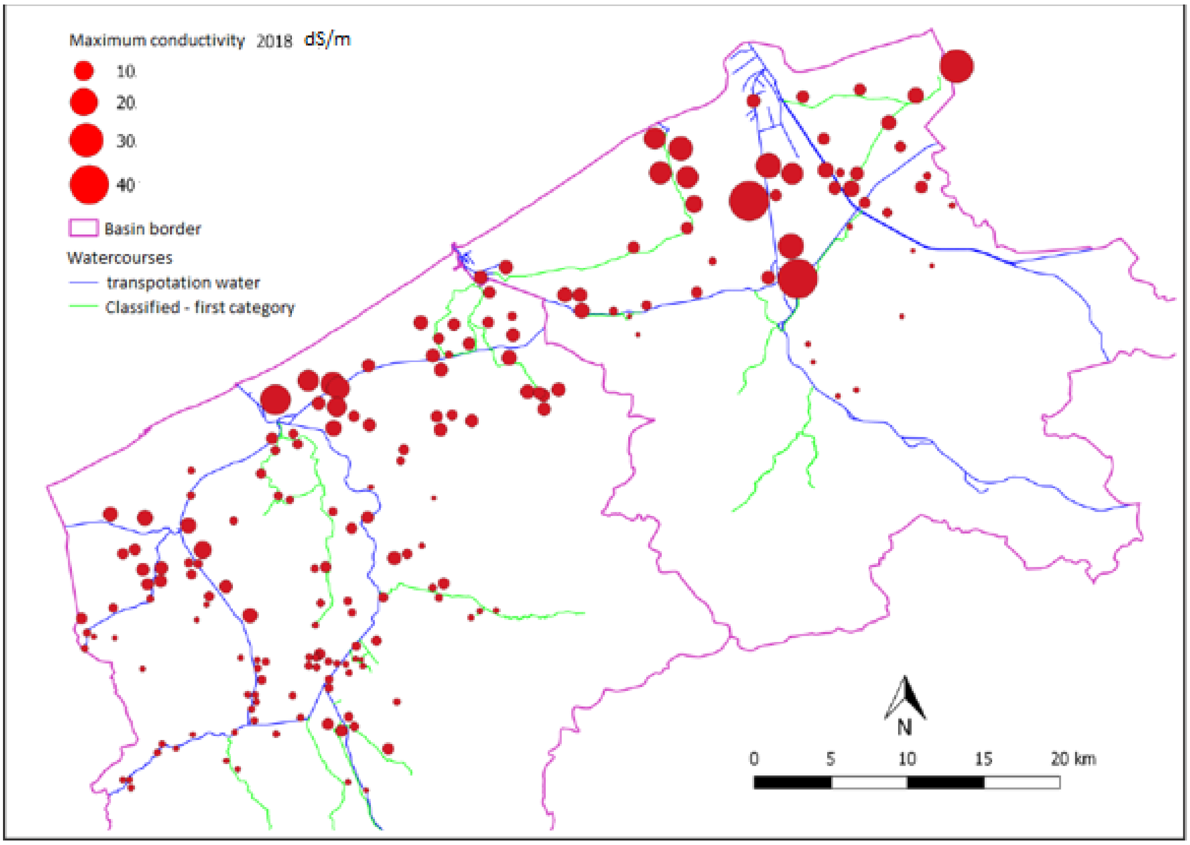
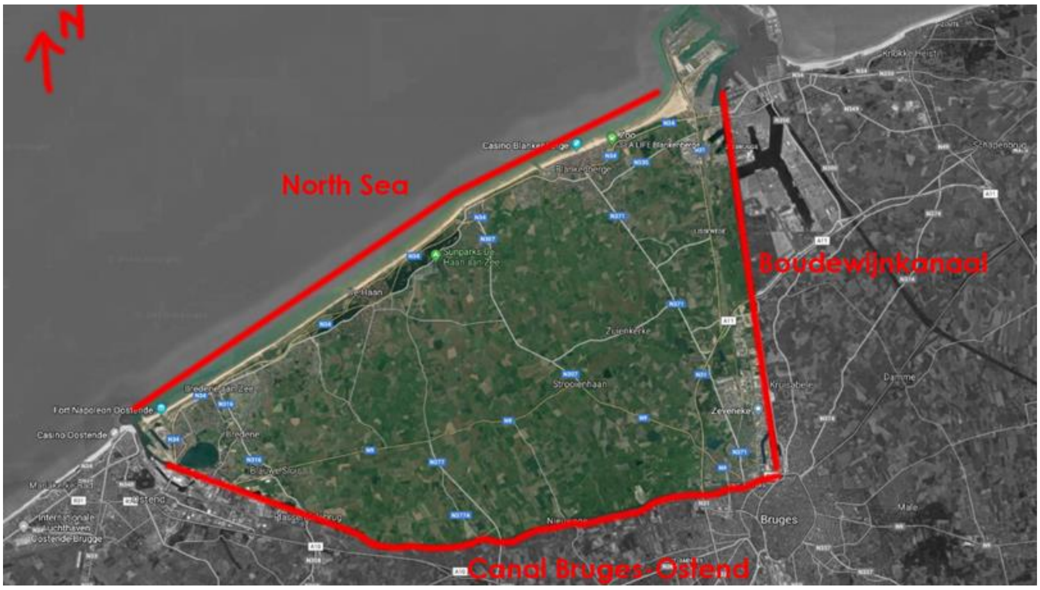
[2] Animal healthcare Flanders; is a non-profit organization from and for livestock farmers.



The Belgian coastline consists of an open wave exposed coast alongside the more sheltered upper reaches of the Schelde estuary. Continuous dunes are extended along the wave-exposed coast (65 km long) that protect the inland. This dune barrier consists of two arcs, one stretching from Dunkerque (France) to Wenduine and a second arc from Wenduine to Breskens (The Netherlands) (Lebbe et al., 2008). However, the presence of the dune barrier has failed to protect the hinterland in the past; hence during storms, seawater has entered the inland at several breaching points and through tidal channels (Lebbe et al., 2008).

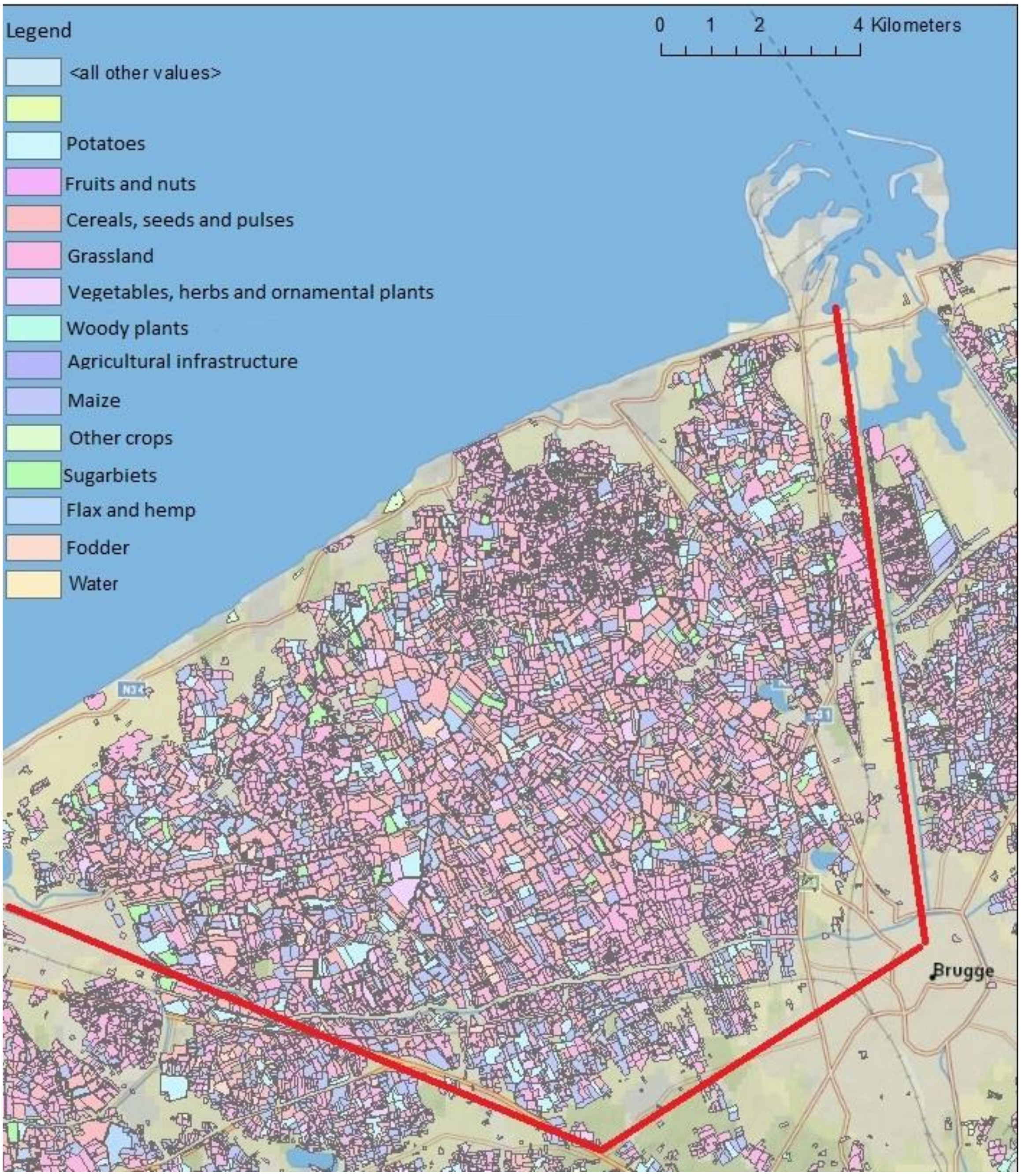
Since the 11th century, people's attempt to protect their land and houses led to the creation of dikes and polders. This process has resulted in the formation of the current coastal plain with sand-filled channels and creeks consisting of clay and peat. The plain consists now of the low-lying polder areas (the major part of the coastal plain), the dunes, and the shore. The width of the low-lying coastal plain ranges between 10 km and 18 km and can be subdivided into four characteristic regions: the Old Land, the Middle Land, the New Land, and the Deep Polders (Tavernier et al., 1970). The focus area of this project in Belgium is the Oudlandpolder, which is located in the Belgian coastline plain, and is the area in between the North Sea, the Boudewijnkanaal and the Canal Bruges-Ostend (**Fejl! Henvisningskilde ikke fundet.**). The dominating type of soils in this area is cambisol (Geopunt, 2015), which according to the FAO classification system, is characterised by the absence of appreciable quantities of illuviated, organic matter, aluminium and/or iron compounds (FAO, 2001). Arenosols are the second most common soil type, having a sandier composition, and mostly found closer to the coastline of Oudlandpolder.

Figure 4.14. The Oudlandpolder is the area in between the North Sea, the Boudewijnkanaal and the Canal Bruges-Ostend



Oudlandpolder’s agricultural land use is presented in Figure 4.15. The map of land use in Belgium is publicly and freely available on www.geopunt.be. Using ArcGIS software, the area of each agricultural group was estimated. Results showed that in Oudlandpolder, outlined in Figure 4.15, the largest part of the area consists of grassland (57,904.51 km^2), followed by the cultivation of cereals (29,237.08 km^2). Maize occupied the third largest area (19,108.11 km^2) while sugar beet and fodder are grown in 3302.41 km^2 and 3372.882 km^2 respectively. These data form the baseline for assessing the value of crops at risk to increasing rates of salinity.

Figure 4.15. Land use in Oudlandpolder in 2017. Source: own elaboration based on landbouwgegevens 2017



4.4.1. Germany

In Northern Germany geogenic salinization of groundwater resources is a growing problem for the public water supply. In comparison with the direct anthropogenic influences (e.g. nitrates, pesticides, ammonium and sulphate accumulations) on the quality of groundwater, salinization is less critical. However, groundwater salinization is a threat to the long-term utilisation of ground water resources, which has not yet sufficiently been taken into account in scientific investigations and developments. The massive influence of ground water salinization on public water supply has already been seen in the past when more than 15 water works in Northern Germany had to be shut down, with salinization being a major factor; more than 80 water works were influenced negatively by salinization (e.g. closure of production wells) (Grube, 2000).

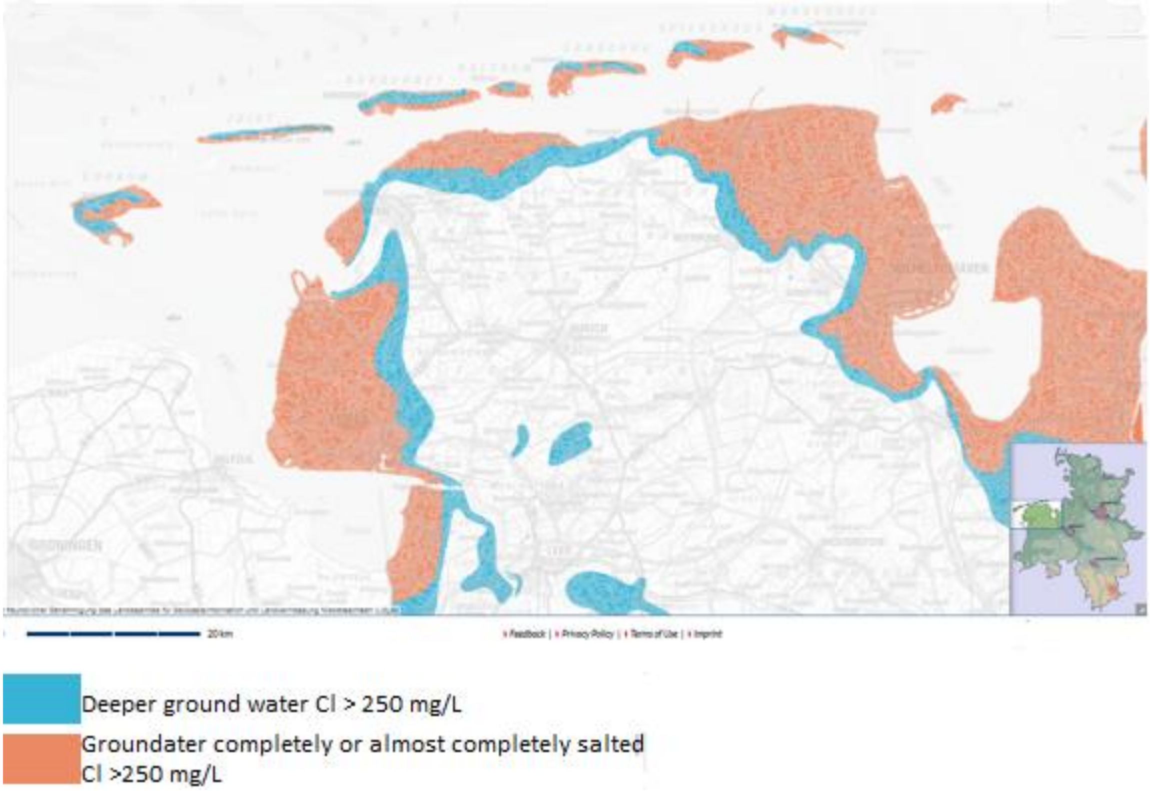
In Lower Saxony Fresh water aquifers are only encountered to maximum depths of 300 m. They are limited to regions in which the water is constantly replenished by infiltrating precipitation (active water exchange zone). Below this, increasingly salinized groundwater is observed (delayed water exchange zone) and at greater depths a zone of predominantly stagnating groundwater is observed.

In large watercourses (e.g. Elbe, Weser and Aller lowlands), where the hydrostatics pressure is suddenly dissipated as a result of the movement of large volumes of groundwater into the watercourse, widespread pressure drops can occur. This may lead to infiltration of deep, salinized water into shallow aquifers.

The global sea level rise along the North Sea coast, after the last ice age, caused the entrance of sea water to inland aquifers (coastal salinization), and hence affecting the existing fresh water. A coastal strip 20 km deep, covering a total of 2,500 km², was impacted by this type of groundwater salinization, making it predominantly unsuitable for groundwater exploitation. Only on the coastal islands have fresh water lenses formed beneath the dunes as a result of infiltrating precipitation, allowing limited potable water production. In total, regions in Lower Saxony with an overall area of around 6,500 km² are affected by groundwater salinization, making groundwater exploitation either difficult or impossible.

The regions with salinized groundwater are delineated in Figure 4.16. The map was developed based on results of water analyses, geoeletric soundings and exploration wells with geophysical down-the-hole logging. A body of water is referred to as salinized if the chloride content exceeds 250 mg/l. In unconsolidated rock the map differentiates between completely salinized groundwater bodies (orange in Figure 4.16) or whether salt water was only encountered in part of the groundwater (blue in Figure 4.14Figure). Areas in blue show that there are restrictions on possible production of drinking water (NIBIS, 1987).

Figure 4.16. Generalised hydrogeological map of Lower Saxony, 1:200 000 - Groundwater salinization. Source: *NIBIS (1987)*



Increased sea level rise in coastal estuaries are anticipated to affect the water balance because saline water continues to rise upstream as the sea level rises. This effect not only works in the estuaries themselves, but also affects the tributaries and groundwater at the estuaries. The possibility of future salt water flooding is very difficult to assess since the coastal protection is also advancing. All along the East Frisian coasts dykes are protecting the land. The dykes are constantly being reinforced and built higher. Dykes and other coastal structures are usually well built, but it is questionable whether they will withstand the effects of climatic change. In addition, reinforcement has a limit. If the dykes are overtopped, resulting increased salinity levels can last for many years in the shallow aquifers.

4.4.3. England

Predictions for future sea-level rise along the UK coasts are based on IPCC values for global mean sea-level change (*Table*). The coastlines of southern Britain, which were outside the limits of former glaciations, are slowly sinking due to the lowering of the earth surface associated with these ice sheets. This exacerbates the effects of any future sea-level rise (Gehrels and Long, 2008).

Table 4.1 Estimates of UK sea-level rise by Defra to AD 2115 based on estimates provided by UKCIP

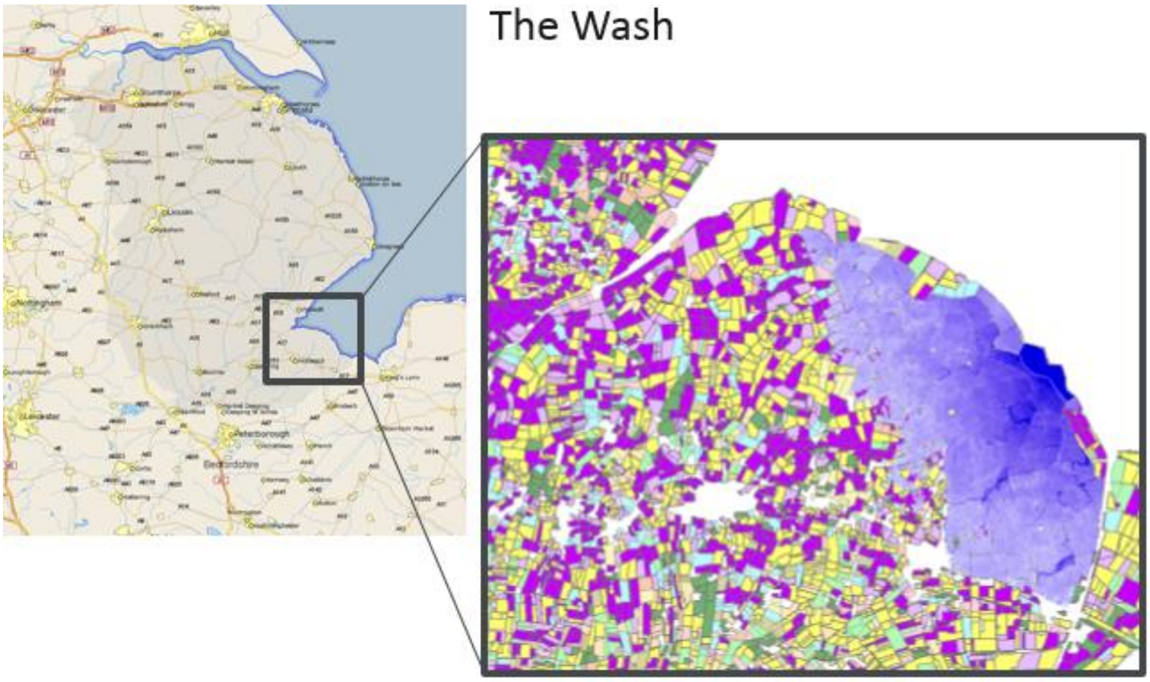
Administrative or devolved region	**Net sea-level rise (mm per year) 1990-2025**	**Net sea-level rise (mm per year) 2025-2055**	**Net sea-level rise (mm per year) 2055-2085**	**Net sea-level rise (mm per year) 2085-2115**
East of England, East Midlands, London, SE England	4.0	8.5	12.0	15.0
South West and Wales	3.5	8.0	11.5	14.5
NW England, NE England, Scotland	2.5	7.0	10.0	13.0

Source: DEFRA (2006)

To reduce the incidence of coastal flooding in the United Kingdom, Shoreline Management Plans (SMPs) have been implemented by the Environment Agency (EA) and analogous approaches are undertaken globally. Given future climate scenarios, significant areas of agricultural land are at increased risk from coastal flooding, notably in the case study are of Lincolnshire,

Flooding risk is presented in Figure by existing flood models; a flood scenario based on a 1 in 200 year sea flood whereby the protection offered by coastal defences is ignored (Environment Agency, 2018). Hard data on groundwater salinity is less available but there are growing pressures on farmers to irrigate more in drier summers.

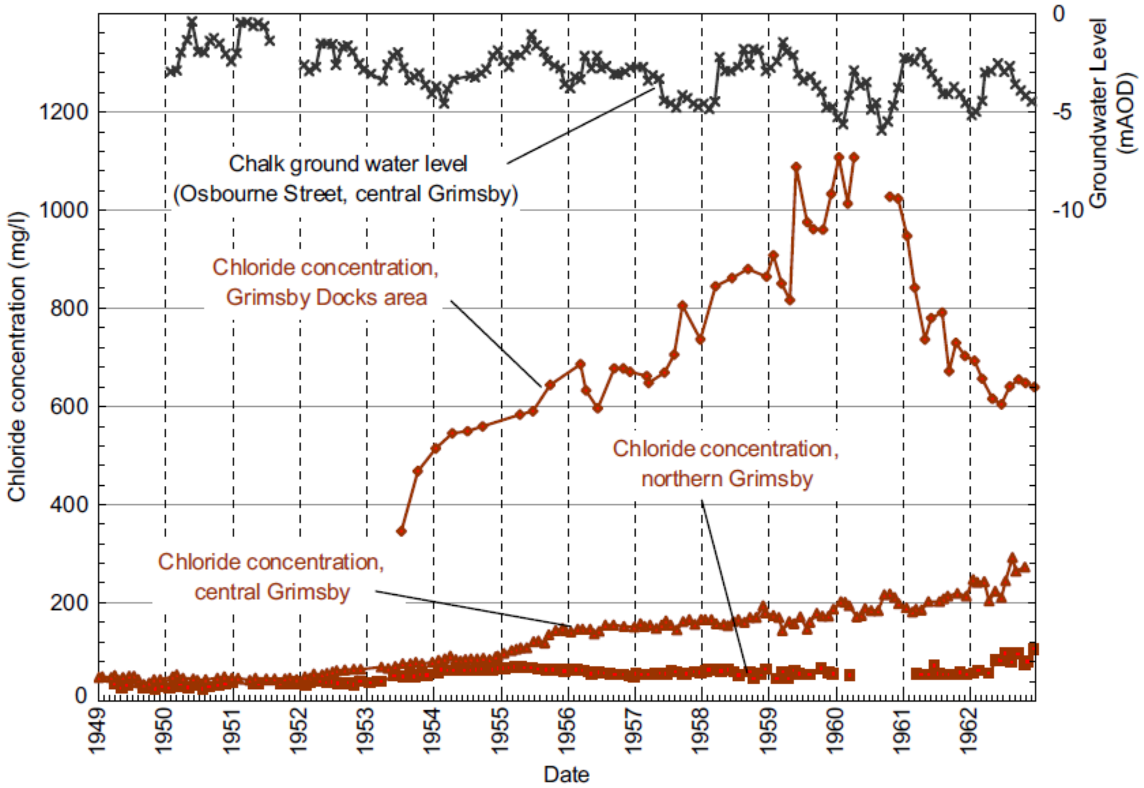
Figure 4.17 Flood scenario based on 1 in 200-year sea flood. Source; (Environment Agency, 2018)



The chalk aquifer of NE Lincolnshire has a long history of exploitation for public water supply and industrial use since the middle of the nineteenth century. In the 1960s the rate at which groundwater was abstracted had approached the rate of recharge to the aquifer over the Chalk outcrop of the Lincolnshire Wolds. Due to the this change in hydraulic conditions, groundwater levels lowered to the point that they were below sea level leading to the intrusion of saline water from the Humber estuary (Hutchinson et al., 2012).

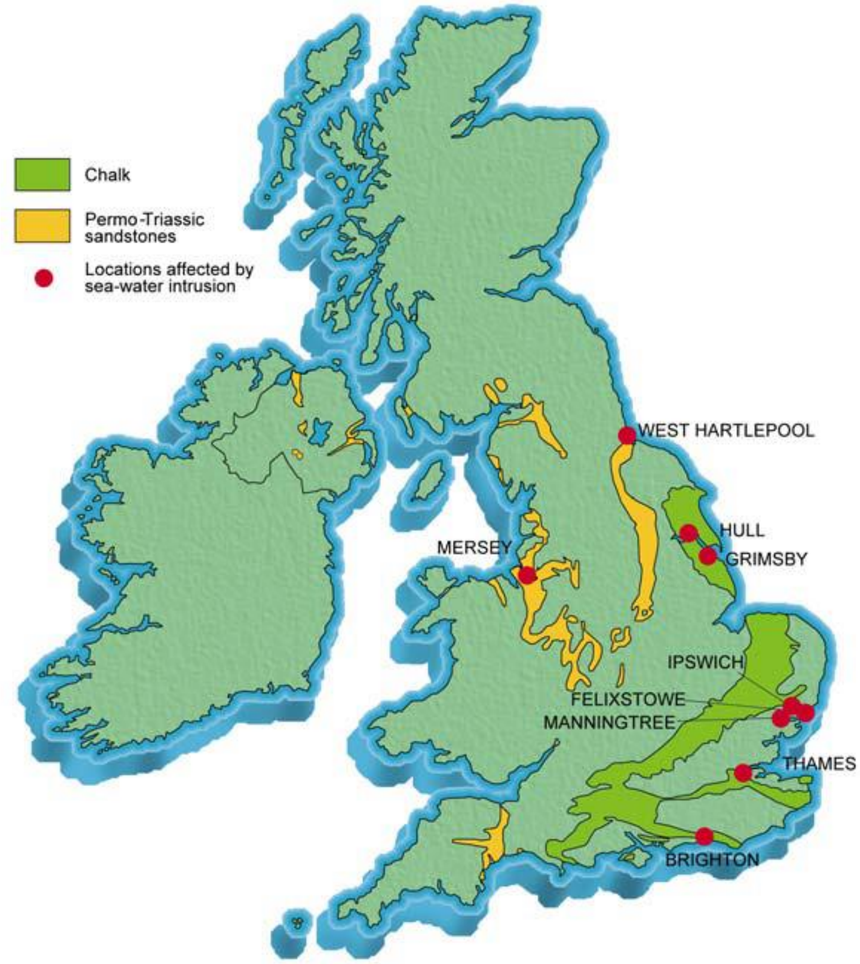
High Cl concentrations recorded in the Grimsby docks area, located in the Humber estuary, are shown in Figure 4.18. The graph shows that, the general long-term trend in the heavily pumped coastal area as a whole is one of gradually falling groundwater levels and gradually increasing Cl (Gray, 1964).

Figure 4.18. Groundwater Cl concentrations and levels in Grimsby, 1949–1963 (Gray, 1964). mAOD, Metres above Ordnance Datum (elevation in metres relative to the UK national sea level reference datum).



Saline intrusion has occurred in Britain at a limited number of locations where the Chalk and Permo-Triassic sandstones have been extensively exploited. The cause is usually industrial abstraction concentrated in coastal areas of large towns. The volume of water pumped is generally limited by the chloride concentration and, if the increase in salinity cannot be controlled, the boreholes are eventually abandoned. In many sandstones, where the flow is mainly intergranular, saline intrusion moves slowly inland on a broad front, but in fractured aquifers, such as the Chalk, intrusion can be rapid along individual fractures and extend inland for considerable distances. Figure 4.19 shows the main areas of sea water intrusion. Apart from West Hartlepool, the aquifers affected are the Chalk and Permo-Triassic sandstones. At West Hartlepool the aquifer affected is the Permian Magnesian Limestone (UK Groundwater Forum, nd).

Figure 4.19 Main areas of sea-water intrusion in the UK. Source: UK Groundwater Forum

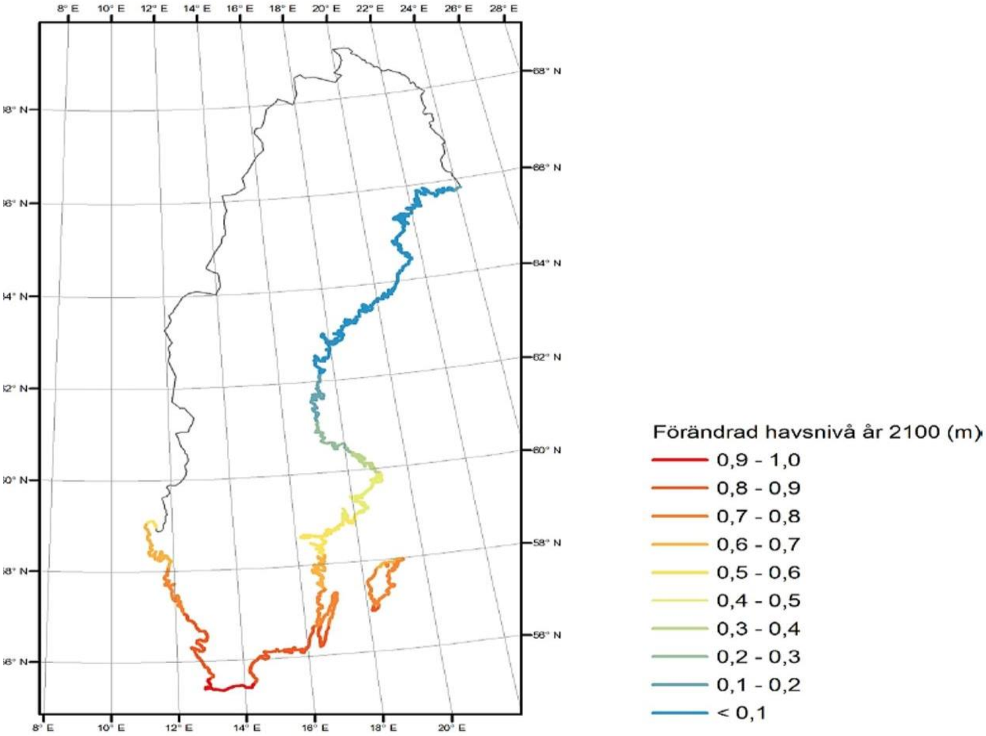


4.4.4. Sweden

In Sweden, sea level rise in combination with increasing demand on groundwater might induce the salinization of groundwater along the coastal areas of Sweden bordering with North Sea. Post-glacial rebound or land subsidence affect the local effects of rising sea. Sweden is still undergoing a post-glacial rebound after the Weichselian ice age, which varies between 1.05 m per century in northern Sweden (North of Skellefteå), to 0.08m per century in southernmost part of Sweden (Trelleborg). In other coastal areas such as Stockholm, it is 0.53 m per century, in Göteborg 0.31 m/century and in Malmö it is 0.10 m/century. Therefore, in big parts of Sweden, mostly in the North, the effects of global sea level rise are mitigated because of the post-glacial rebound (SeaLevelRise, 2017).

Figure 4.20 shows the net effect of sea level rise minus land uplift along the coast of Sweden, subject to a global sea level rise of 1 metre in 100 years. The calculation of uplift is based on the Swedish National Land Survey uplift model NKG2005LU.

Figure 4.20. Estimated Net sea level rise for 2100 (m)



The Swedish case study region is Halland, a county on the western coast of Sweden (Figure 4.21). The climate in Halland is mild and humid, with high precipitation and favours the growth of forests, although soils are not the optimal for forest cultivation. The southeastern part of Halland, receives more than 1000mm rainfall per year, which is the largest in Sweden outside the mountain region, due to orographic lifting. The large amount of water is suitable for the growth of spruce, but also contributes to bog expansion associated with rising water tables (Crawford et al, 2003). The topography and soils are very much a result of the latest ice age and consist of till in the higher parts and glaciofluvial material in the lower parts (Blennow and Hammarlund, 1993). To date, soil salinity has not been considered a significant risk in the region.

Figure 4.21 Halland, the case study of Sweden

In the case study of Sweden, Halland, there is not enough information on the salinization of groundwater. However, an older research has shown evidence of ground water salinity (Lindewald, 1981). According to this study, each year about 80 wells (1% of the total water wells drilled in Sweden, were reported to be salt-water wells. By the time of Lindewald’s (1981) study, 780 wells were identified as salinized, with Cl concentrations between 300 to 7,000 mg per litre. The main part of the salt-water wells could be found in four areas along the coast (the Southern part of Sweden, South-East, Gotland and the area near Stockholm, see Lindewald, 1981, p29). These areas coincide with the densely populated areas in Sweden. Saline groundwater occurred in different aquifers in Sweden and could be found in sedimentary as well as in crystalline bedrock as well as in sand and gravel deposits (Lindewald, 1981).

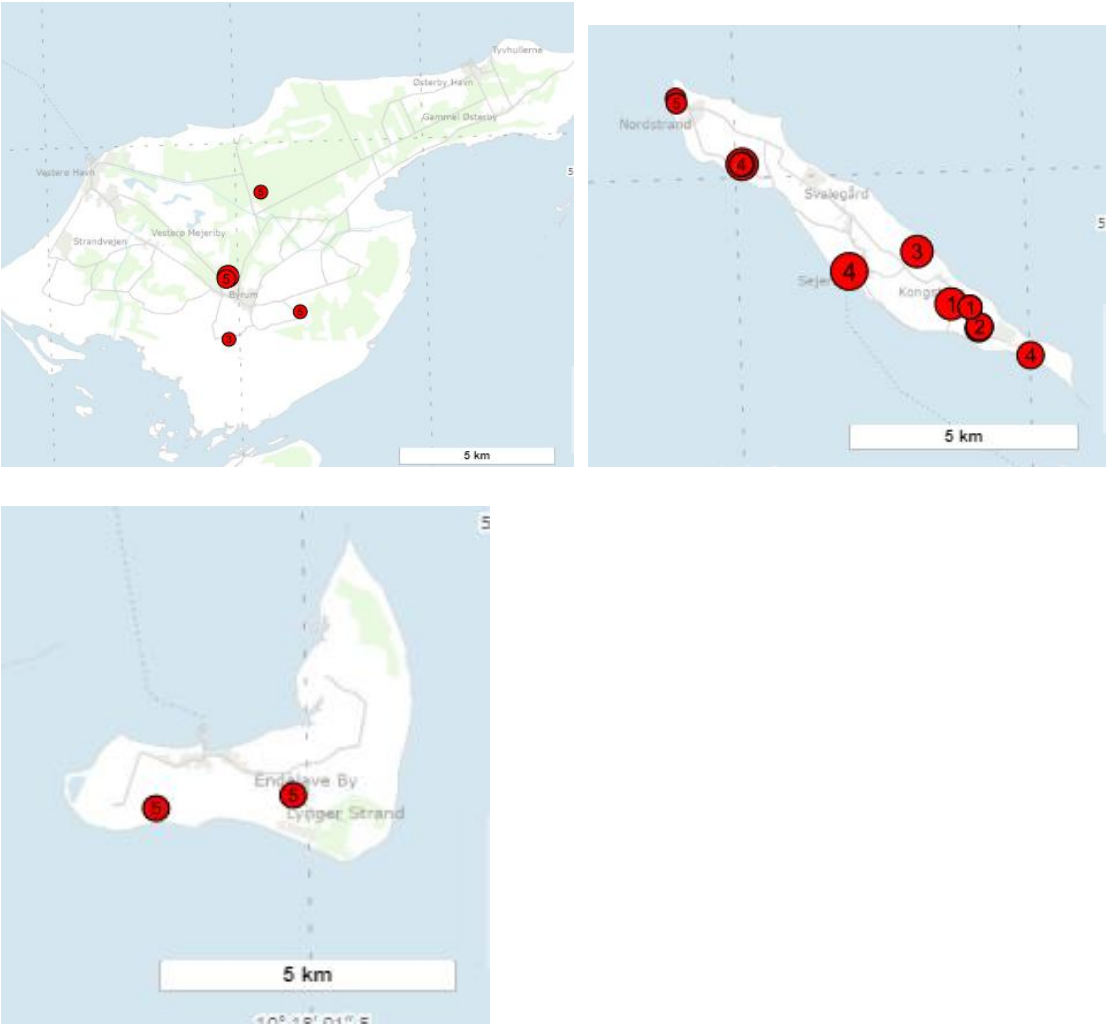
The origin of the high Cl contents in middle and east Sweden was estimated in most cases to be from the earlier salt-water periods of the Baltic Sea, as the salt water wells were characterised by their location to elevations below the Holocene marine limit. The cause of salinization on the west coast has probably been because of the transgression from the Atlantic Ocean (Lindewald, 1981).

4.4.5. Denmark

For the case study of Denmark there is data available on salinity only in drinking water sources. Figure 4.22 displays Cl concentrations larger than 250 mg/l, which is above the accepted threshold of drinking water in Denmark.

There is no information on the correlation of groundwater affected with salinity and soil salinity in these areas there is a correlation, however, between groundwater salinity with the proximity to the sea as well as to terrain above sea level. Thus, the areas of salinity in ground water sources are also among candidate areas of saline soil.

Figure 4.22 Location points where ground water Cl concentrations are higher than 250 mg/l. Numbers in dots show the number of years measurements were taken. Source: GEUS (2014)



4.4.6. Norway

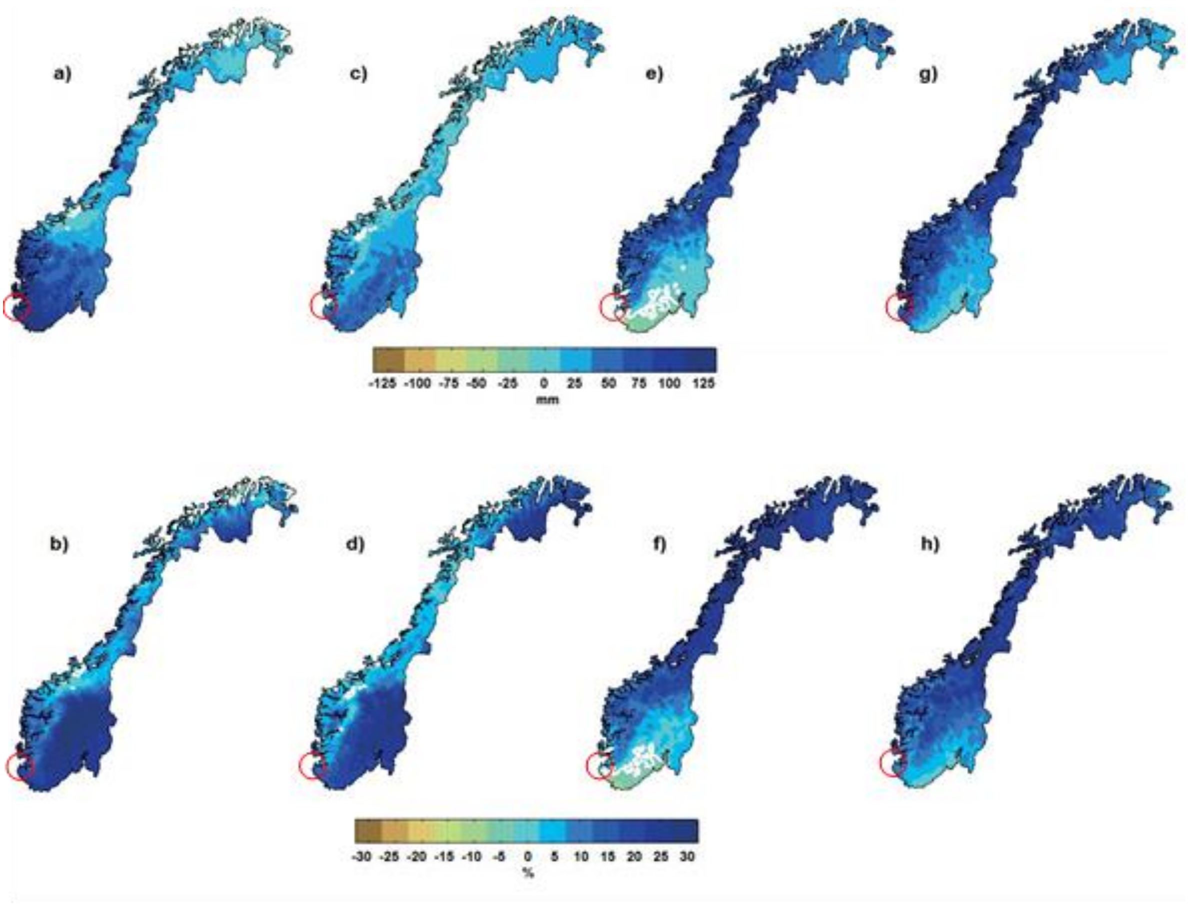
Unlike many other countries, groundwater only plays a small role in drinking water supply in Norway. Due to large surface water supplies, only about 15 % of the drinking water in Norway come from groundwater. This may be the main reason why groundwater has not been mapped and monitored in detail. However, since 1977 a national groundwater network (LGN) has existed that collects reference data on groundwater including temperature, groundwater level and chemistry in places that are assumed to be little affected by human activity, rivers or lakes. In 1989, a national monitoring network on soil water (NOM) was established in order to follow regional and temporal variations in amounts and quality of soil water. In 2010, both monitoring networks were combined (Norges Geologiske Undersokelse (NGU), 2018).

A first national survey on groundwater was carried out in 2005 with a focus on groundwater in glacial river deposits. In that survey, potential main contamination sources were identified, i.e. agriculture, development, industry, mining, landfill sites and transport. Seawater intrusion into groundwater has been considered of less importance. This may be the reason why there is relatively little information on groundwater quality in coastal areas.

However, despite a generally low awareness concerning potential agricultural problems related to seawater intrusion, the Geological Survey of Norway (NGU) lists reducing groundwater removal in order to avoid saltwater intrusion in coastal areas among possible measures to maintain good groundwater quality.

Climate change scenario for Norway predict increased temperatures and thus a longer growing season, but also more precipitation in general and more extreme weather events in most parts of the country (Hanssen-Bauer et al., 2017). Temperature in Norway is predicted to increase substantially over the 21st century, with largest increases in the north and smallest in the west of the country. While precipitation in the winter and spring is expected to increase along the Norwegian North Sea coast, summer precipitation, and in parts also autumn (the south-eastern coast) is likely to decrease slightly in large parts of the southern and south-western coast. Further north along the west coast of Norway and along the Norwegian Sea coast, the opposite pattern may occur, with somewhat decreasing precipitation (Figure 4.23).

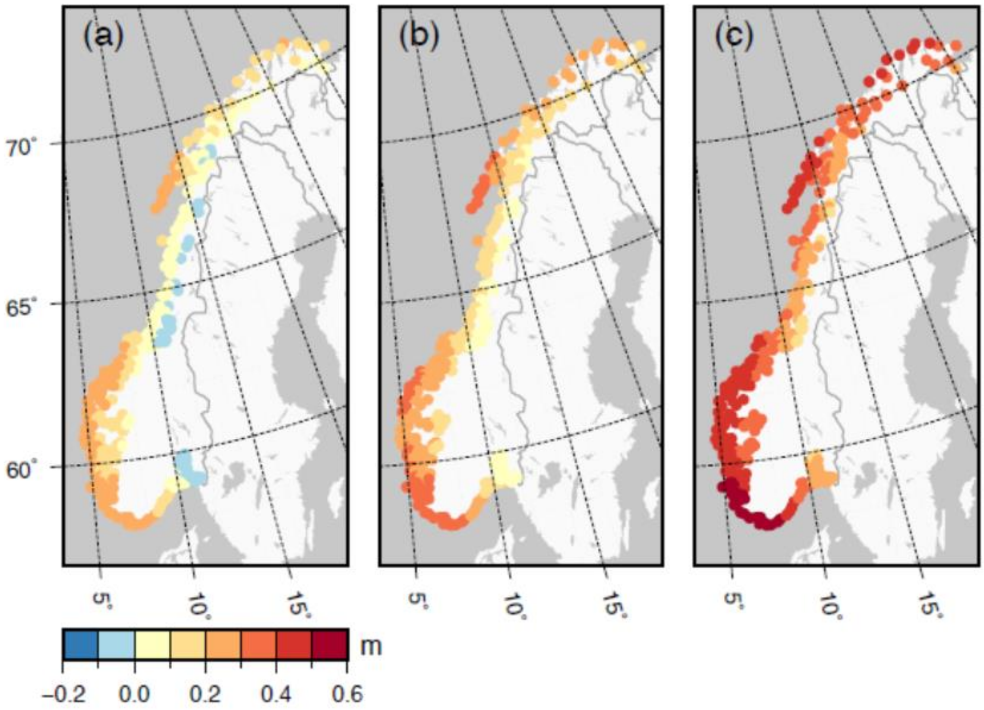
Figure 4.23. Absolute (mm) and relative (%) change in seasonal precipitation (median) from 1971-2000 to 2071-2100 for the concentration pathway RCP8.5. Winter (DJF) in a) and b), spring (MAM) in c) and d), summer (JJA) in e) and f) and autumn (SON) in g) and h). Source: Hanssen-Bauer et al. (2015)



The projections for sea level change are also based on the representative concentration pathways (RCP) that were adopted by the IPCC for its fifth Assessment Report. For the projections of sea level change along the Norwegian coast, three RCPs were used, i.e. RCP 2.6, RCP 4.5 and RCP 8.5. The lowest pathway, RCP 2.6, assumes a peak in global annual GHG emissions between 2010 and 2020, and a substantial decline thereafter, while emissions in RCP 4.5 peak around 2040, then decline. In RCP 8.5, emissions continue to rise throughout the 21st century.

For Norway, climate driven sea level rise will dominate over land motion changes over the next 100 years but predicted sea level changes are expected to be below the global mean (Simpson et al. 2015). The predictions indicate only small differences between the RCPs until 2050, with uncertainties of approximately ±0.1 m. In the second half of the 21st century, the predicted sea level rise is increasingly different between the RCPs. Figure 4.24 shows that the coastal areas in south-western and western Norway will most likely experience larger sea level increases than in more northerly areas (with the exceptions of some islands) or in the Skagerrak strait. The chosen area for the field experiment (Jæren) is within the area that can expect highest sea level rises.

Figure 4.24. Projected ensemble mean regional relative sea level change (m) over the period 1986– 2005 to 2081–2100 for (a) RCP2.6 (b) RCP4.5 and (c) RCP8.5. Source: Simpson et al. (2015)



4.5. Extent of Salinization along the North Sea Region

The collation and consideration of the information received from the project's partnering countries led to the creation of the following map (Fig. 4.25). The salinization map was developed based on the climate change and sea level rise scenarios for each case study and considering the latest salinity measurements or evidence of salinity provided by public or private bodies in each case study. Figure 4.25 delineates the areas with high, medium and low ground water salinity levels. The classification of saline water in high, medium, low is taken from the study of de Vos et al. (2016). Assuming that these areas are using groundwater irrigation we could point to these areas as areas at high, medium or low salinity risk for growing crops. Taking into consideration that summers in the North Sea region will become dryer and warmer, water demand for irrigation will increase. It is hard to make any speculations regarding groundwater's intrusion to the root zone, as these studies demand rigorous hydrological modelling, where salinity data is required.

The levels of groundwater salinity were classified in low, medium, high because there was not consistency in the salinity units used in each study area. Most of the case studies were using Cl, while

EC was also used to measure water salinity. Therefore, this map can be used as an indicator for areas where crop yields can be at risk due to saline water used for irrigation particularly during warm and dry summers.

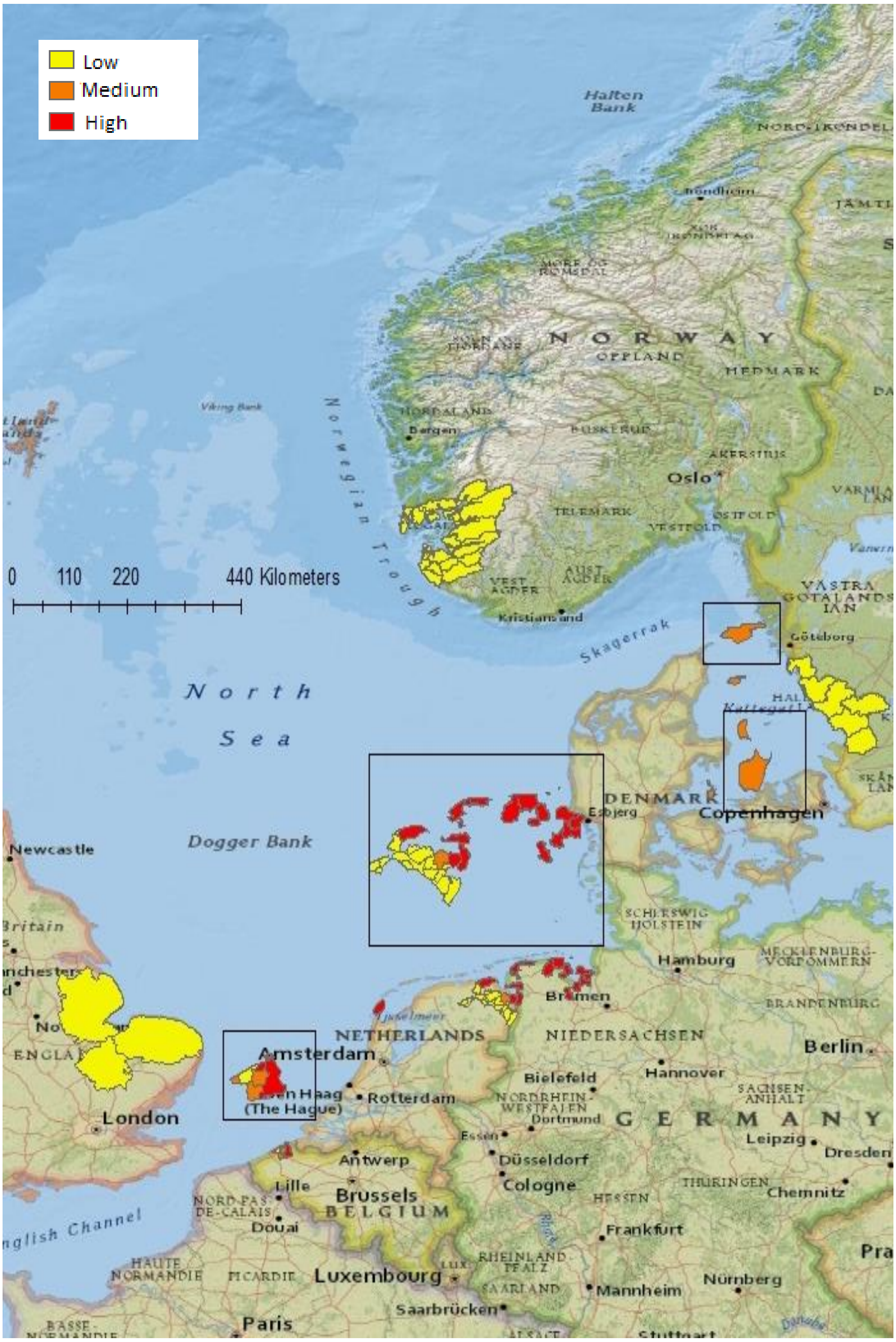


Figure 4.25. Ground water salinity levels in the North Sea Region. Nb: Salinity in Texel Island refers to surface water (The boxes are magnified illustrations of the Belgian, Dutch/German & Danish areas). Note, only case study areas are coloured as data is not available for other regions)

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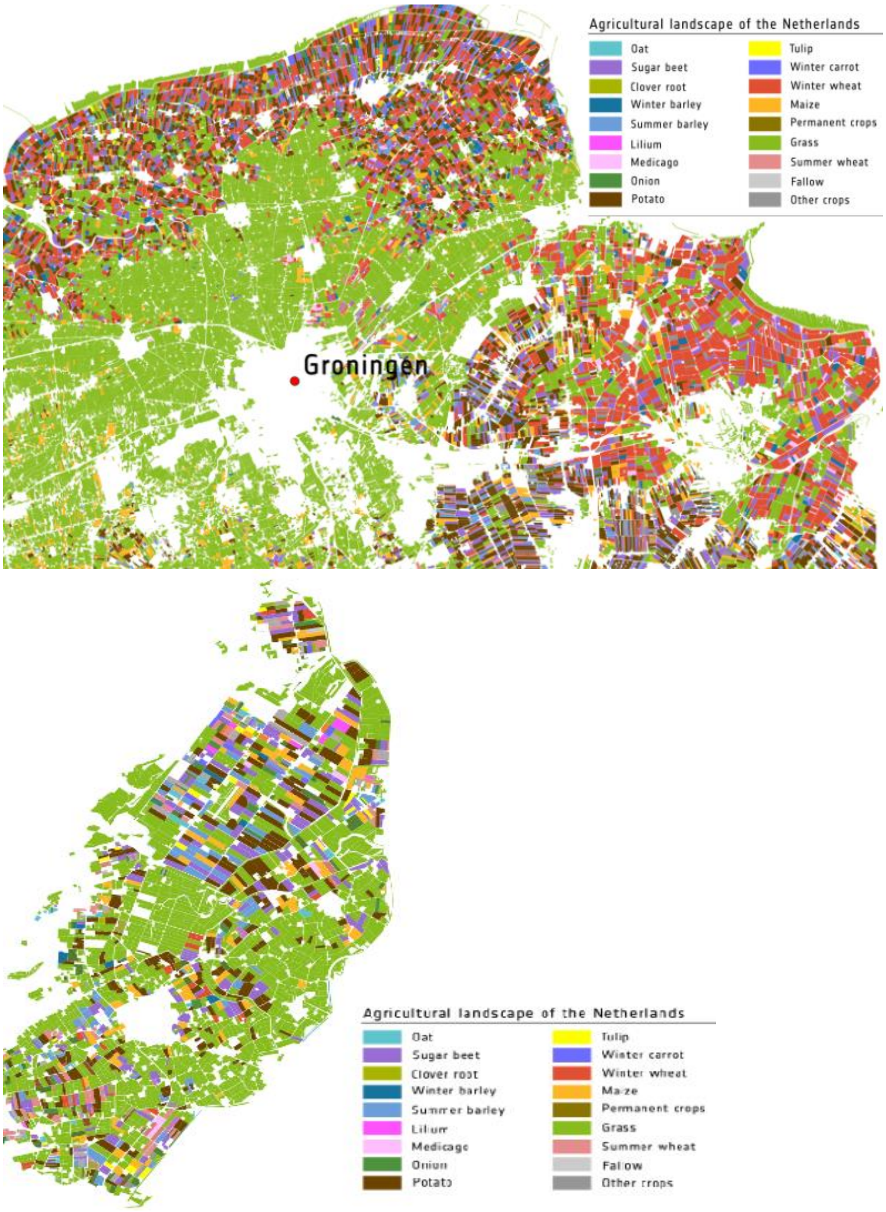
Appendix. Land uses in the case study areas

A1. Agricultural land use in the province of Groningen and Texel

The agricultural land in the province of Groningen closer to the North Sea is mainly covered by winter wheat, potatoes and sugar beet (Figure A1). To a lesser extent winter barley and maize are also grown in this area. The land around the city of Groningen is mainly used for grass, while in the west of the province of Groningen the agricultural land is mostly used for the cultivation of winter wheat. The second map in Figure A1 delineates the agricultural land use in the Island of Texel, where most of the agricultural area is used as grassland and growing sugar beets, potatoes and maize. The exact amount of land used to grow each agricultural crop is not publicly available.

Figure A1. Crop-type map of Texel based on a time series of 2017 data during the growing season from the Copernicus Sentinel-1 and Sentinel-2 missions. Source: ESA–Sen4CAP (2018)



A2. East Frisia – Germany

Groundwater in coastal areas in Germany along the North Sea, East and North Frisia are currently affected by salinity (Daliakopoulos et al., 2016), however the focus of this report is on East Frisia, a part of the state Lower Saxony in North-West Germany (Figure A2). Lower Saxony is located in the northern part of Germany and it has an area of approximately 48,000 km^2. It is considered as an extensive region containing a large proportion (over 75%) of land used for agriculture and forestry (Gunreben, 2005). The soil type on the higher "Geest" areas is mainly sandy, while mostly clay soil is found in the "Marsch" areas close to the coast, which is built from marine sediments. Most of the SALFAR work will be carried out in Emden, which is located in the western part of East Frisia. The soils close to Emden where the SalFar trials are being conducted belong to the "Marsch" and are heavy clay soils.

Figure A2 Case study region: East Frisia (light and dark green areas). Source: *Wikimedia Commons*

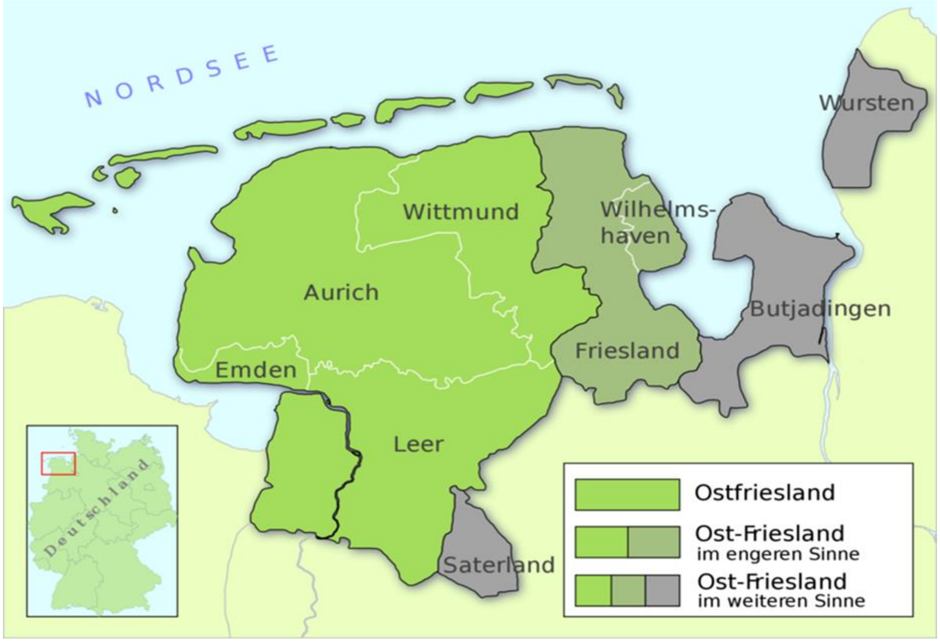
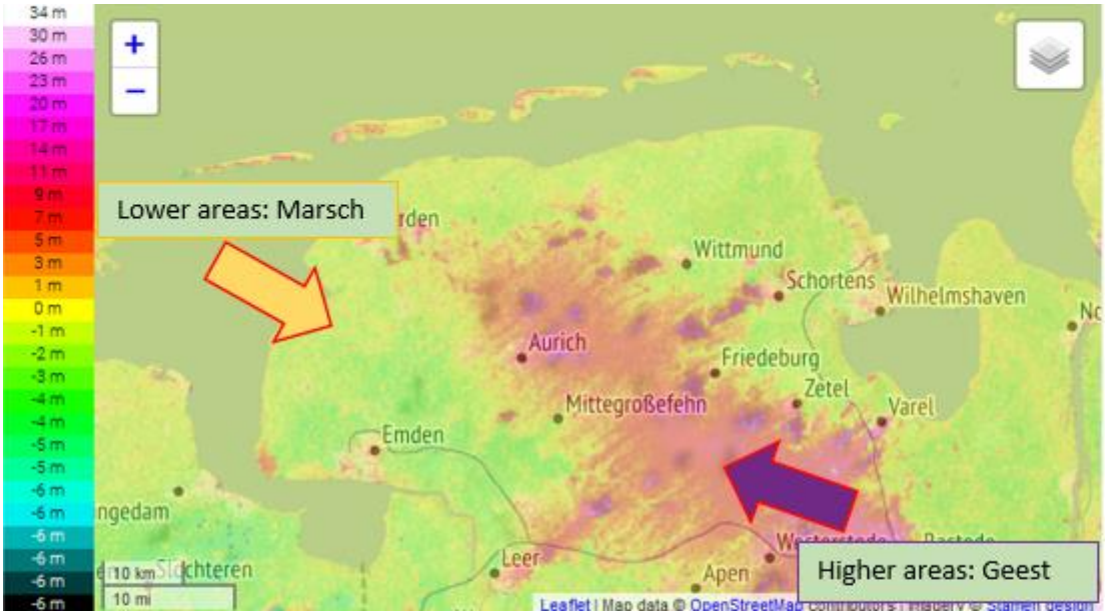


Figure A3 delineates that the higher Geest areas are located in the centre of East Frisia surrounded by the lower Marsch areas which are extended across the coastline.

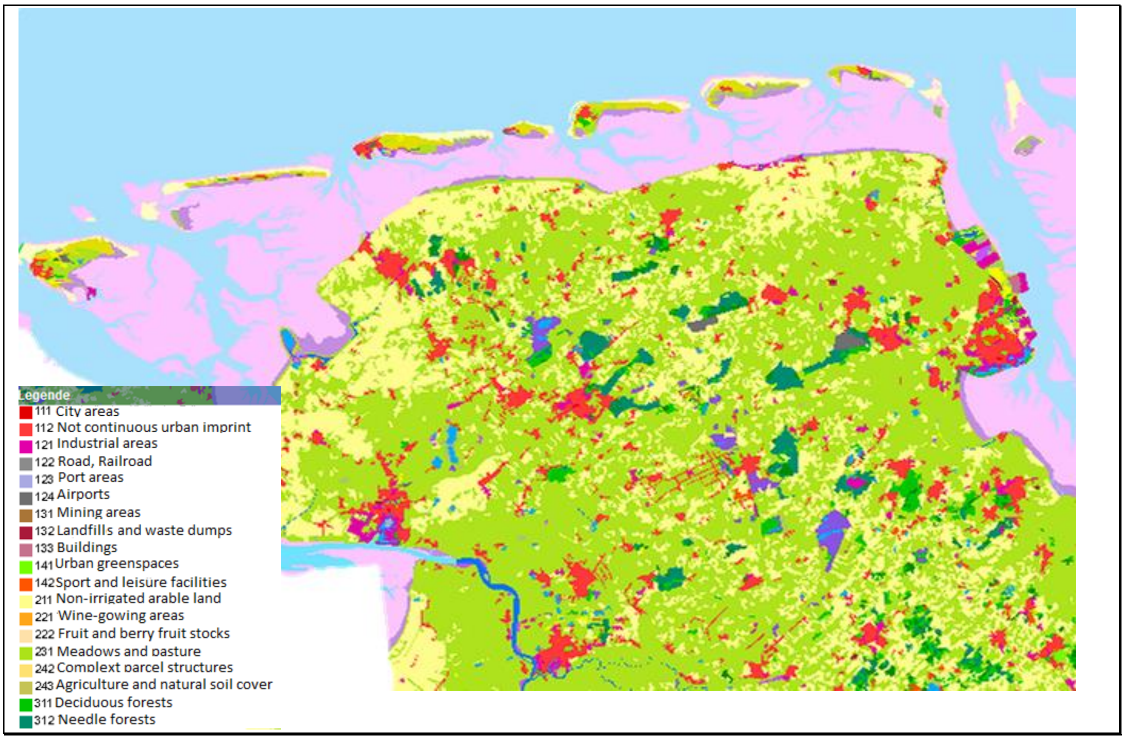
Figure A3 Topographic map of East Frisia.



The East Frisian Islands lack natural drainage systems on the surface, therefore most of the rainfall flows in the sands. This results in filling with fresh water the groundwater reservoirs underneath the dunes. The top of the fresh water lenses can be found up to 1-2 m in the dune areas and the base at -30 to -40 m, while in the Norderney island it can reach -70 m. Beside the fresh water lenses there is a permanent drainage of the fresh water to the North Sea. The fresh water reservoir in the islands is sufficient to cover the daily need of drinking water. The only islands that have a fresh water pipeline connection to the mainland are the Baltrum and Wangerooge (Bungenstock and Enters, 2010).

The total utilised agricultural area (UAA) in East Frisia is 196,869 ha out of which 38.65% is farmland and 60.65% is permanent grassland. Therefore, the largest area of the land in East Frisia is covered by meadows and pasture and followed by non-irrigated arable crops located closer to the coast (Figure A). Permanent grassland is mainly grazed by cattle cows (385,445) for meat production and dairy cows (160,378). Followed by pigs (141,458). The largest area of crops is occupied by maize for silage and consumption (28,883 ha) followed by wheat (21,318 ha) and barley (7,086 ha) (Agricultural Union of East frisia, 2016). Along the coastline, coastal saltmarshes are displayed in light violet, while moors and swamps are mainly seen inland.

Figure A4: Land cover in East Frisia. Source*: Bundesamt für Kartographie and Geodäsie (2012)*



A3 Lincolnshire, The Wash – England

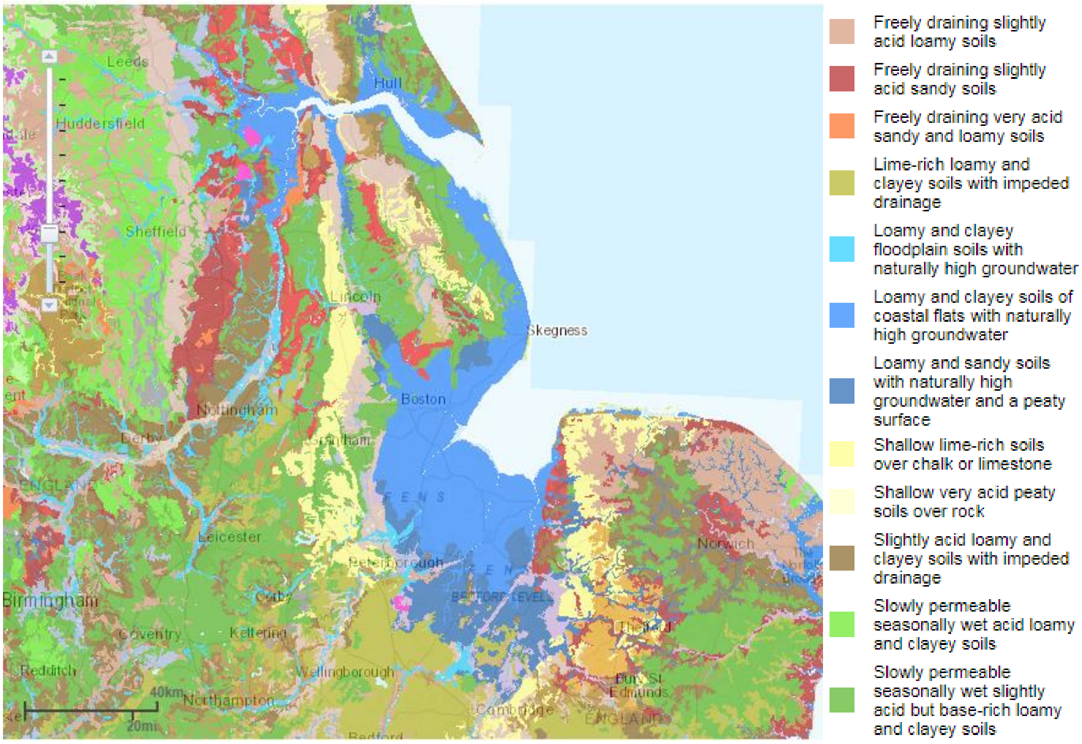
Lincolnshire consists of a wide coastal plain which is bounded by the North Sea along its eastern edge and by the Lincolnshire Wolds to the west. The wide coastal plain incorporates three main different areas; the Middle marsh, the Outmarsh and the coast itself. The Middle Marsh lies to the west and comprises an arable landscape with a greater number of woodlands and hedgerows than other areas. To the east lies the Outmarsh, an open landscape of arable land, mixed with rich pasture divided by narrow dykes. The Outmarsh has changed in character and while it used to be as grassy as Romney Marsh or the Somerset Levels, it has gradually turned into an area which is predominately arable, particularly since effective pump drainage was introduced in the second half of the 20th century, following the 1953 floods. The coast itself has extensive areas of intertidal habitats including salt marsh, coastal dunes and wetlands and is continually changing (Figure A5). In the norther side of the coast, the offshore gradient is so gentle that at low tide extensive sand flats and mudflats are exposed. Half of the coast is rich in biodiversity and the bird species in particular. Bordering estuaries, like the Humber Estuary to the north and the Wash to the south comprise designated areas as a Special Protection area for the large flocks of overwintering migratory and breeding birds (Natural England, 2015).

The Lincolnshire Coast and Marshes, Lincolnshire Wolds and Holderness national character areas share a major chalk aquifer which is used extensively for the supply of water in the region. A number of rivers (the Great Eau and River Freshney) flow through the coastal plain of Lincolnshire via catch water drains and dykes. *A series of catch water drains and dykes are pumped into the Steeping which follows a canalised channel before discharging into the large Wash Estuary, thus providing an important fluvial and ecological link to The Wash* (Natural England, 2015).

Groundwater, which is defined by the European Union as the saturated zone below the ground surface, and is in direct contact with the ground or subsoils (European Union, 2000), is the second largest reservoir of freshwater, following snow, glaciers and ice caps and represents 30% of available freshwater (Fitts, 2002). In the UK, ground water is a crucial resource; three quarters of which is abstracted from boreholes and springs use for public supply.

Most of the Wash area is covered by alluvial silts with naturally high groundwater (Figure). These soils are mostly drained. Shallow groundwater and marginal ditches to most fields mean that the water resource is vulnerable to pollution from nutrients, pesticides and wastes applied to the land. These soils support a wide range of crops and are highly productive as they contain much available water and are stoneless and flat, and as such are considered to make up a significant proportion of the Grade 1 agricultural land of England. Heavier soils are less easily worked and favour grass. The land cover in this area is mainly arable and some grassland.

Figure A5. Soil types in the Wash and Lincolnshire. Source: *Cranfield Soil and Agrifood Institute (2018)*



In Lincolnshire the largest type of farm is represented by cereal holdings. The area used to grow winter wheat in 2014 was 6,398.34 ha, followed by winter oilseeds (2,227.43 ha) and sugar beets (1,249.76 ha) (FBS, 2014). Pigs are the most numerous livestock with 31,500 animals, followed by sheep (28,200) and cattle (12,200). In the areas adjacent to the Wash however, crop composition focusses mainly on high value productions, such as brassicas.

Table A1. Crop production in Lincolnshire in 2014

Crops	Area (ha)	Yield (t/ha)	Value (£)	Value/production
Winter barley	416.21	93.3	108,871	141.17
Winter wheat	6,398.34	553.3	2,437,230	158.87
Spring barley	609.5	147.9	46,244	142.64
Spring wheat	118.24	50.5	28,194	157.86
Spring oats	54.16	22.5	24,390	143.47
Dry beans	367.04	43.5	61,641	231.99
Winter oilseeds	2,227.43	142.2	425,611	322.33
Sugar beets	1,249.76	2,524.6	55,734	34.14

Source: Own elaboration based on the UK Farm Business Survey 2014

A4. Læsø, Endelave, Sejeroe - Denmark

In Denmark areas under Natura 2000, such as the areas of marshland along the coast of West Jutland are currently affected by salinity but the focus of this report is the Islands of Læsø, Endelave, Sejerø, where field experiments will be conducted throughout the duration of this project.

Figure A6. a) Læsø Island left, Endelave Island top right, Sejerø Island bottom right, and below, identified on the Danish map.

When the last ice sheet retreated from Sjælland about 16 to 15 thousand years ago (Houmark-Nielsen and Henrik Kjær, 2003), the coastline around Denmark was located several hundred kilometres west of the present-day coastline. The distribution and formation of land and sea changed significantly and so did the life conditions of man and fauna, during the following global and regional sea-level rise. During the early Holocene the islands which now belong to Denmark, as well as, Sweden and England were united and belonged to the northwest European continent (Noe-Nygaard and Hede, 2006).

During the Atlantic period the global sea level rose fast, resulting in coastal flooding and strong tidal amplitude of 4 m in the North Sea and Kattegat areas. During the Atlantic and the Subboreal periods, several transgressions occurred in Denmark.

Læsø is the largest island of the Kattegat-Skagerrak region and is characterised by a number of sea level rise indicators, such as raised beach ridges, swales, lagoons and saltmarshes. It is extended to an area of 118 km^2 in northern Kattegat and is in the normal marine to brackish, low-tide zone transition between the Baltic Sea and the North Sea.

Shallow saline groundwater has been known for several hundred years at the southern shores of the Island of Læsø (Vellev, 1991). Since the Middle Ages, the saline groundwater, with salinities up to 17%, contributed to large-scale production of commercial salt. Salt production reached its peak at the period between 12th and 15th centuries, when several hundreds of small salt works were established in the coastal meadows and salt marshes at the south coast of the island. The main process used to extract salt from brine was fizzing, and dug wells were used to extract groundwater (Jorgensen, 2002). High demand in firewood associated with the salt production resulted in increasing deforestation of the island, therefore the salt production was forbidden by law in 1652 (Vellev, 1991).

The vast open nature areas on Læsø have been created through many years of grazing with cattle, sheep and horses. Meadows, marshes, heaths, dunes have been created by animals grazing and roaming. Animals grazing also contributes to keep the areas without trees and to the encroachment of shrubs (Layman, 2018).

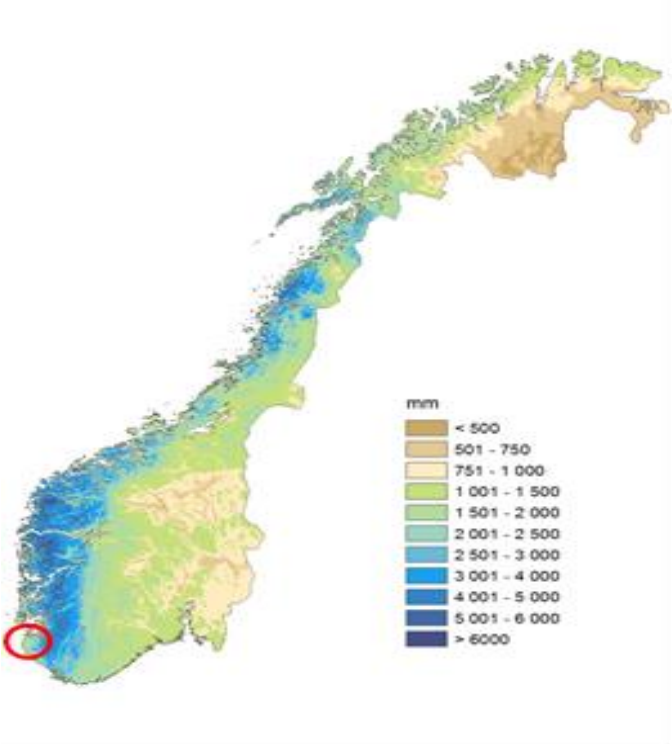
Sejerø with its 400 inhabitants, is part of Kalundborg Municipality and covers an area of 12.55 square kilometres. The largest village on Sejerø is Sejerby, housing half of the island's population.

Endelave extends over 13.20 km^2 and is quite diverse. Large protected nature areas are extended in the north and south where a great a great variety of rare plants are grown and the wildlife is plentiful. On the northernmost part of the island, Øvre, is a large preserved nature area. In this area, heather, pine thickets and small lakes shape the landscape, which attracts large colonies of seabirds, such as terns and gulls. To the south, there is another preserved nature area, Lynger Hage, dominated by heather, rowan berries, pine and oak trees (VisitDenmark).

A5. Jæren – Norway

The coastal area of Jæren in south-western Norway was chosen as the location for the field experiment to be carried out within the SalFar project.
Figure delineates the location of the study area circled in red and the average annual precipitation in Norway. Precipitation varies greatly along the Norwegian coast, with large amounts in the western parts of the country and less precipitation towards north and east. Precipitation west of the mountains in the southern parts of Norway may be well above 2000 mm per year (
Figure), due to predominantly westerly winds and mountain ranges inland. The areas right at the coast in western Norway, where Jæren is located, receive less precipitation (between 1000 and 2000 mm per year) than the areas slightly further inland.

Figure A7. Average yearly sum of precipitation for the period 1985-2014. Source: (Norsk Klimaservicesenter, nd)



In Norway, land suitable for agriculture is scarce and constitutes only about 3 % of the total area. With a mild climate due to the vicinity of the Golf stream, Jæren is one of the most productive agricultural areas in Norway. Some of the agricultural land along the coast lies in immediate proximity to the sea only a few metres above sea level (Figure A7), in large parts without a buffer zone of sand dunes. Sandy, light soils are typical for the coastal area, but there are also some fields with loam or organic soils on Jæren (Kilden; https://kilden.nibio.no/).

The eight municipalities in Jæren cover only 0.5 % of Norway's land area but 4.7 % of the agricultural area. Most of this is used for roughage production, whereas cereal area amounts to only 0.9 % of the national area. The livestock population is very large, with 22.4 % of the breeding pigs, 16.7 % of the chickens and 10.3 % of the livestock in Norway (SSB 2016). The region is also important for vegetable and (early) potato production. The crops per unit area and the yield per animal are generally higher than elsewhere in the country.

Table A2 shows agricultural area in the coastal municipalities on Jæren, divided by use. The municipalities with biggest agricultural areas are Hå, Time, Sandnes and Klepp. Like all municipalities in Jæren, the main use of land is for grasslands while cereals and other crops are grown on 4 to 24 % of the agricultural land.

Table A2. Agricultural area per coastal municipality in Jæren 2017 (in daa)

Municipality	Hå	Time	Sandnes	Klepp	Sola	Randaberg	Stavanger
Agricultural area in use, total	120 071	80 663	75 382	73 006	32 300	11 917	11 057
Cultivated land	84 897	42 611	45 918	66 224	26 790	10 231	8 995
Field & permanent horticultural crops	7 089	3 293	4 740	15 380	7 897	2 672	2 199
Cereal and oil seed crops	3 003	2 255	2 017	9 184	5 698	1 181	1 446
Wheat	..	..	0	..	..	..	0
Barley	2 794	2 010	1 824	8 715	4 668	1 033	1 389
Oats	100	..	193	371	996		..
Potatoes	1 426	85	655	1 744	1 135	979	372
Green fodder and silage crops	647	827	228	343	197	..	..
Field grown vegetables	1 984	..	..	3 835	484	294	197
Total grassland	112 982	77 370	70 642	57 626	24 403	9 245	8 858
Cultivated meadows	77 808	39 318	41 178	50 844	18 893	7 559	6 796
Other grassland	35 174	38 052	29 464	6 782	5 510	1 686	2 062

Source: Statistics Norway (SSB); https://www.ssb.no/statbank/table/06462/