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**Deliverable 5.3 and 6.3**

# PILOT DESCRIPTION AND ASSESSMENT

## Falster, Denmark


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[GEUS]



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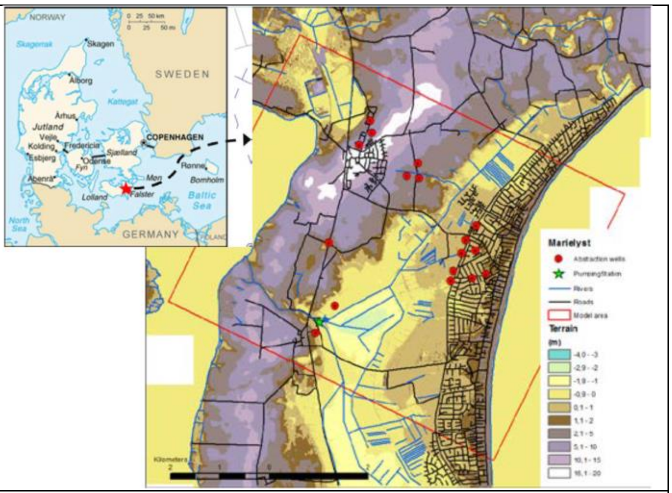
## LIST OF ABBREVIATIONS & ACRONYMS

## TABLE OF CONTENTS

# 1 EXECUTIVE SUMMARY

| | | |
|---|---|---|
| Pilot name | Falster |  |
| Country | Denmark | |
| EU-region | Central and eastern Europe | |
| Area (km$^2$) | 32 | |
| Aquifer geology and type classification | Chalk, fractured | |
| Primary water usage | Drinking water supply | |
| Main climate change issues | Increasing sea levels is expected to increase the risk of saltwater intrusion to the coastal confined chalk aquifer. Groundwater modeling studies have shown that a potential decrease in precipitation for extended periods may also increase the risk of saltwater intrusion to the local groundwater aquifer. Other effects of projected climate change impacts include an increase in the number and size of extreme rain events resulting in floodings along drainage canals if measures are not taken to avoid this. | |
| Models and methods used | Geophysical measurements (e.g. electromagnetic, both airborne and groundbased, as well as geophysical borehole logging) have been conducted to find the existing fresh-saltwater boundary and support the development of a geological and an integrated groundwater-surface water model for climate change impact assessment and adaptation. Field tracer experiments were completed in order to estimated dual-domain flow parameteres for density dependent groundwater modelling using MODFLOW, MT3DMS and SEAWAT. Analyses of groundwater and surface water including age dating and emerging contaminants were performed for characterization of water qualities.<br><br>Salinity sources were assessed by the use of self-organizing maps (SOM) for the analysis of the distribution of selected trace elements.<br><br>Natural backgroundwater values were furthermore estimated by different methods and used to assess groundwater threshold values and chemical status according to the Water Framework Directive. | |
| Key stakeholders | Marielyst Waterworks, Land Reclamation Society Bøtø Nor, Farmers, Dike Guild of Falster, Homeowners Association, tourist- and business associations, Gedser bird watching station. | |
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Saltwater intrusion to the coastal chalk aquifer on the southern part of the Falster island is a significant challenge and threat to water supply in the area in the near and far future (Rasmussen et al., 2013, 2015) as in many other coastal areas in Europe (Hinsby et al., 2011) and globally (Post and Abarca, 2010). The main climate change impact and adaptation issues with the Falster pilot area include potential saltwater intrusion from the Baltic Sea, deeper saline parts of the aquifer and other parts of the confined chalk aquifer and aquifer system (Hinsby et al., 2012), which locally seems not to have been completely freshened during the Pleistocene and Holocene (Knudsen et al., 2021). In addition flooding of low-lying areas and droughts during extreme events have occurred during recent years and is expected to increase in the area according to climate change projections for Northwestern Europe.

The upper part of the chalk aquifer at a depth between typically 15 – 25 meter below surface locally has elevated chloride contents to concentrations above the drinking water standard of 250 mg/l. Depending on location the observed elevated concentrations may originate from the aquifer itself as an old marine sediment, the Baltic Sea and Holocene marine sands above the aquifer (Hinsby et al., 2012, Rasmussen et al., 2013, Knudsen et al., 2021).

The understanding of the salinity sources and the migration of dissolved chloride in the chalk aquifer is important for developing efficient measures to control saltwater intrusion and protect water supply wells from increasing chloride e.g. by temporary groundwater storage / water banking and other subsurface water solutions (Hinsby et al., 2018), while potentially protecting the built environment in the area at the same time (Hinsby et al., 2015, 2016, 2019).

# 2 INTRODUCTION

Climate change (CC) already have widespread and significant impacts in Europe, which is expected to increase in the future. Groundwater plays a vital role for the land phase of the freshwater cycle and has the capability of buffering or enhancing the impact from extreme climate events causing droughts or floods, depending on the subsurface properties and the status of the system (dry/wet) prior to the climate event. Understanding and taking the hydrogeology into account is therefore essential in the assessment of climate change impacts. Providing harmonised results and products across Europe is further vital for supporting stakeholders, decision makers and EU policies makers.

The Geological Survey Organisations (GSOs) in Europe compile the necessary data and knowledge of the groundwater systems across Europe. In order to enhance the utilisation of these data and knowledge of the subsurface system in CC impact assessments the GSOs, in the framework of GeoERA, has established the project “Tools for Assessment of ClimaTe change ImpacT on Groundwater and Adaptation Strategies – TACTIC”. By collaboration among the involved partners, TACTIC aims to enhance and harmonise CC impact assessments and identification and analyses of potential adaptation strategies.

TACTIC is centered around 40 pilot studies covering a variety of CC challenges as well as different hydrogeological settings and different management systems found in Europe. Knowledge and experiences from the pilots will be synthesised and provide a basis for the development of an infrastructure on CC impact assessments and adaptation strategies. The final projects results will be made available through the common GeoERA Information Platform (http://www.europe-geology.eu).

The Falster pilot area in Southeastern Denmark has been investigated for about a decade to improve the understanding of salinity sources (Hinsby et al., 2012, Knudsen et al., 2021), climate impacts on salt water intrusion to a coastal aquifer that secure water supply for a summer housing areas in the southeastern part of the Falster Island (Marielyst), which experiences increasing salinity and risk of flooding.

# 3 PILOT AREA

The local waterworks, Marielyst Waterworks, located in the Falster pilot area has experienced problems with increasing salt (chloride) concentrations in water supply wells during the last two to three decades (Fig. 1). The waterworks have had to close several existing water supply wells due to chloride concentrations above the drinking water standard in the coastal aquifer. The main aquifer in the area is a shallow chalk aquifer highly fractured in the upper 10-20 meter. The land use in the study area is dominated by agriculture and settlements of summer cottages, although a few small permanent villages have developed on top of the push moraine hills in the western part of the area. Today there are more than 5000 summer cottages. Although most of these are built on the original barrier islands in the eastern part of the investigated area, the most recent housing areas have spread into the reclaimed areas and some of these are therefore located at or below mean sea level. The freshwater supply for the villages and the summer cottages is based solely on groundwater.

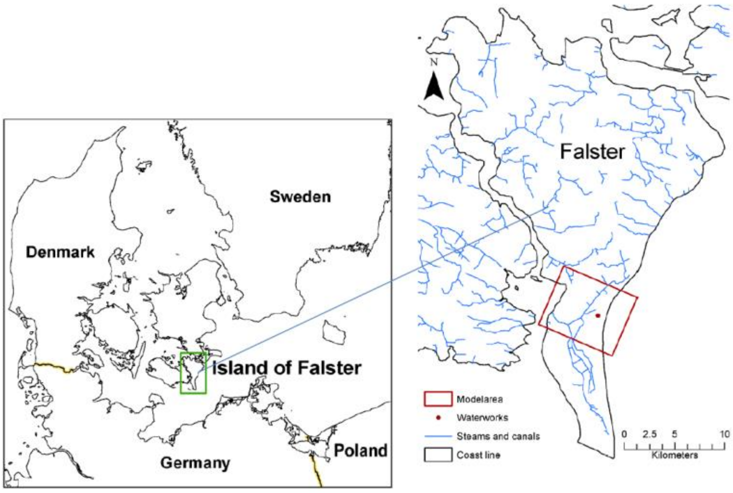


Fig. 1. Location of Falster pilot area

The Falster test site area was studied in the three previous EU and National research projects: “BaltCICA” (www.baltcica.org) was part-funded by the BONUS programme on the Baltic Sea (www.bonusportal.org), “Water4Coasts” was part-funded by the Ecoinnovation program of the Danish Ministry of Environment and Food (http://eng.ecoinnovation.dk/), and “SUBSOL” (www.subsol.org) received funding from the European Union’s Horizon 2020 research and innovation programme (https://ec.europa.eu/programmes/horizon2020/en). Main results from the three projects can be found in Rasmussen et al. (2013), Hinsby et al. (2016), and Hinsby et al. (2018).

The main objective of the studies conducted in BaltCICA was to assess climate change impacts on the freshwater-saltwater boundary in the Chalk aquifer in the investigated area. Geophysical measurements (e.g. electromagnetic, both airborne (SkyTEM) and ground based, as well as geophysical borehole logging) were conducted to find the existing freshwater-saltwater boundary and to support the development of a geological and an integrated groundwater-surface water model for climate change impact assessment and adaptation (Fig 2 and 3).

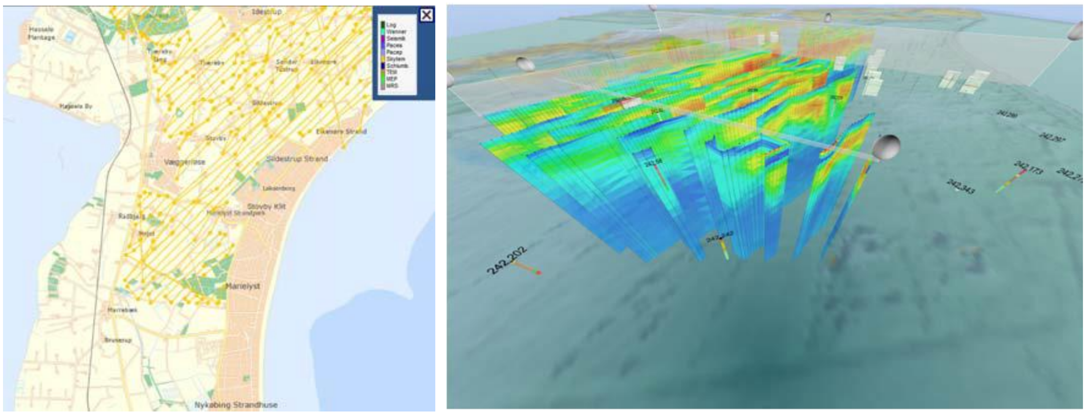

Fig. 2. SkyTEM flight lines (left). SkyTEM resistivities displayed in 3D (right)

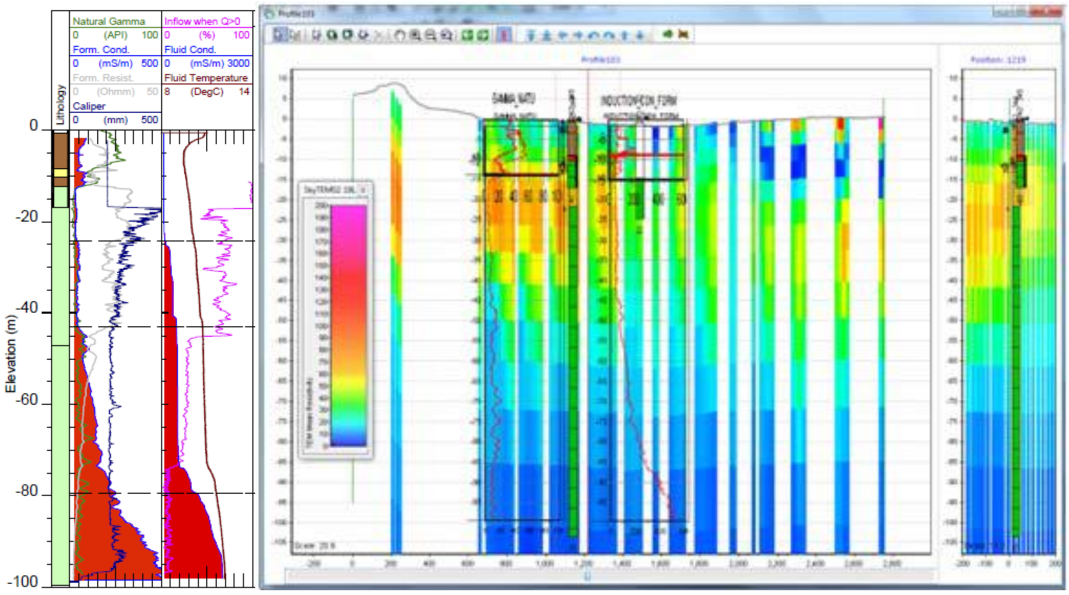


Fig. 3. Geophysical borehole logs (left). Combined plot of formation conductivity from wireline logging and SkyTEM resistivities (right)

The main objective of the Water4Coasts study was to initiate the assessment of the potential application of new innovative techniques to control saltwater intrusion and protect freshwater resources in the fractured Chalk aquifer of the Falster Island and similar settings, globally (Hinsby et al, 2016). The studies demonstrated that several issues needed to be investigated further before concrete solutions could be recommended. The recommendations included more detailed analyses of the hydraulic properties of the fractured chalk aquifer. Other suggestions dealt with further analysis of water quality of groundwater and surface waters. Surface water could potentially be used after treatment for injection and water banking e.g. between wet winter periods with low demands and abstraction and dry summer periods with high demands and abstraction.

In the SUBSOL project, the Falster area was selected as one of the areas to assess whether the subsurface water solutions (SWS) developed for single porosity granular aquifers in the Netherlands may be applied with similar success and designs in dual-porosity fractured carbonate aquifers. The conducted investigations indicate that dual porosity systems are very well suited for the application of SWS techniques, globally, but that fracture distributions and e.g. glaciotectonical impacts affects the hydraulic behaviour in complicated ways that require additional investigations and assessments (Fig. 4).

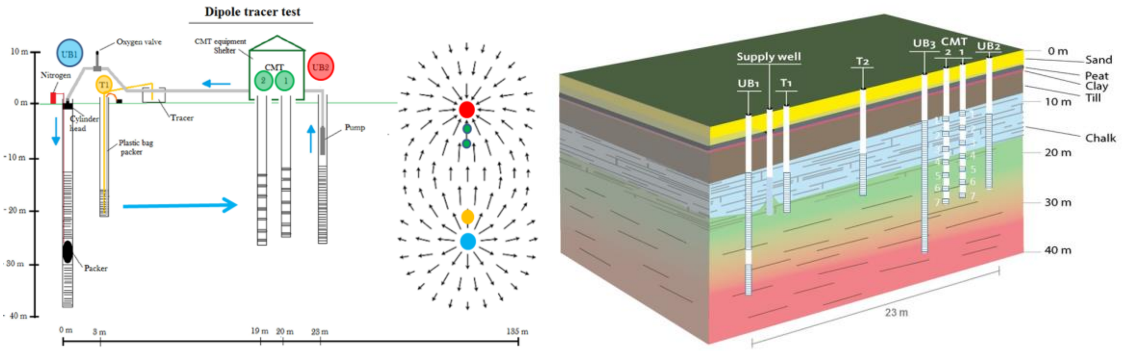

Fig. 4. The developed dipole tracer test setup in the SUBSOL project, blue arrows in the left diagram show the water movement. Tracer was injected in T1 or T2 (right diagram) and tracer breakthroughs were observed in the multi-level screens of CMT1 and 2

The aim of this case study was to further assess the salt-/seawater intrusion status and vulnerability in the shallow fractured chalk aquifer in Falster. The vulnerability assessments of the aquifer includeed effects of future climate predictions concerning risks of a drier climate with less precipitation resulting in reduced groundwater recharge, increased frequency and intensity of intense rainfall resulting in flooding. The aim was also to look at the possibility for using MAR (Managed Aquifer Recharge) as a tool for the long-term protection, sustainable management and improvement of local groundwater resources.

## 3.1 Site description and data

***Location of pilot area***

The pilot area is located in the south-eastern part of Denmark on the island of Falster. Towards the east the area is bounded by the Baltic Sea and towards the west of the strait of Guldborgsund (Fig. 5). The local waterworks are abstracting groundwater from the shallow Chalk aquifer overlain by quaternary and post glacial sediments of mainly clayey tills and sands. The well fields located closest to the Baltic Sea coast have seen an increasing chloride concentration in the abstracted groundwater during the last decades.

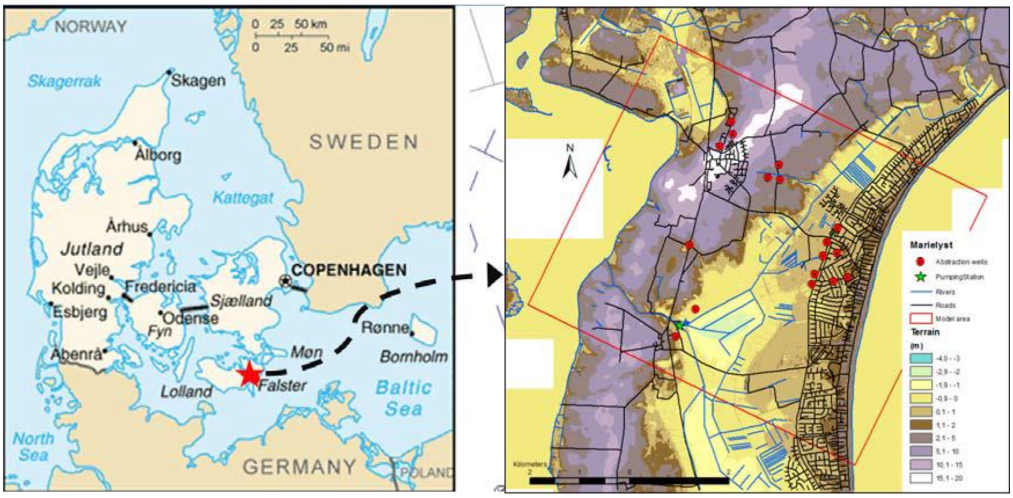

Fig. 5. Location of pilot area, abstraction wells, drainage canals and pumping station

***Climate***

The climate in Denmark is characterized by the country's close location to the Atlantic Ocean and the Gulf Stream. The predominant occurrence of western winds means that the coastal climate is dominant. The coastal climate and the location in the west wind belt mean that Denmark usually has relatively cool summers and mild winters. However, when the wind comes from the continent, periods of continental climate (hot summers and cold winters) can occur.

The sea is surrounding Denmark, which also means that the temperature difference between night and day is relatively small.

The average daily temperature in Denmark is around 15-16 degrees in summer and around or just above the freezing point in winter. Winters with a prolonged supply of cold air from the continent occasionally give rise to hard winters, where the inland waters freeze.

The average annual precipitation in the area is approximately 700 mm and the actual evapotranspiration is approximately 450 mm.

***Topography***

The elevation varies from 19 m a.s.l. (above sea level) in the west to -3 m a.s.l. in the central eastern part of the area. The landscape is mainly developed from north-south trending push moraine hills of clayey tills along the coast in the western part of the island, which were formed during the last glaciation by an east to west moving glacier. During the Holocene, small barrier islands with eolian sand dunes, which constitute the eastern part of the island and a lagoon developed in front of the glacial moraine hills. As the barrier islands grew it became possible to reclaim the low-lying wetland area between the push moraine and the barrier islands in the central part of the study area.

***Land use***

The land use in the study area is dominated by agriculture and settlements of summer cottages, although a few small permanent villages have developed on top of the push moraine hills in the western part of the area.

### *Soil types*

The dominant soil types in the Falster pilot area are clayey till, marine sand, and eolian sand dunes (Fig. 6).

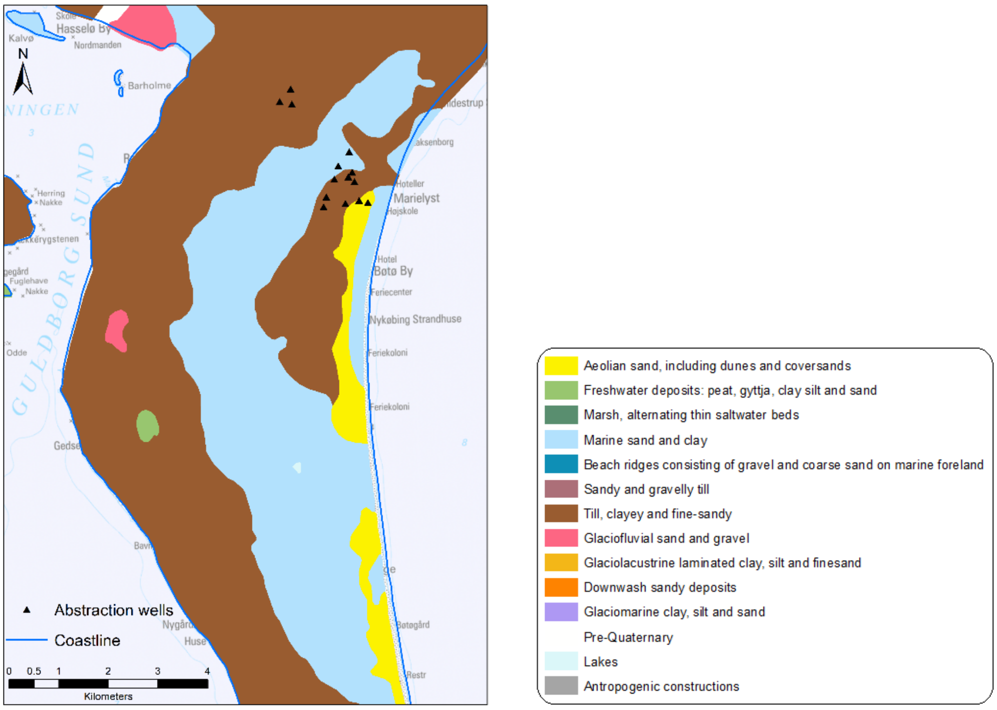


Fig. 6. Soil types (location map, see Fig. 7 A)

### *Geology/Aquifer type*

In the pilot area, the top surface of the Upper Cretaceous chalk aquifer is situated at about 10 m below the surface. It is overlain by a 5 m thick unit of glacial sediments and 5 m marine sand. However, at a depth of 15 to 18 m there is a layer of chalk with gravel and pebbles of basement rocks.

Based on an evaluation of data from other wells in the area, it has become evident that another zone with basement gravel and pebbles existed even deeper at a level from 30 to 40 m below the surface. These findings have implications for the understanding of groundwater flow around the wells as the complexity of the hydraulic characteristics markedly changes the aquifer's behaviour. A model of the glaciotectonite occurrence was established based on a glaciodynamic concept of the area (Pedersen et al., 2018) (Fig. 7).

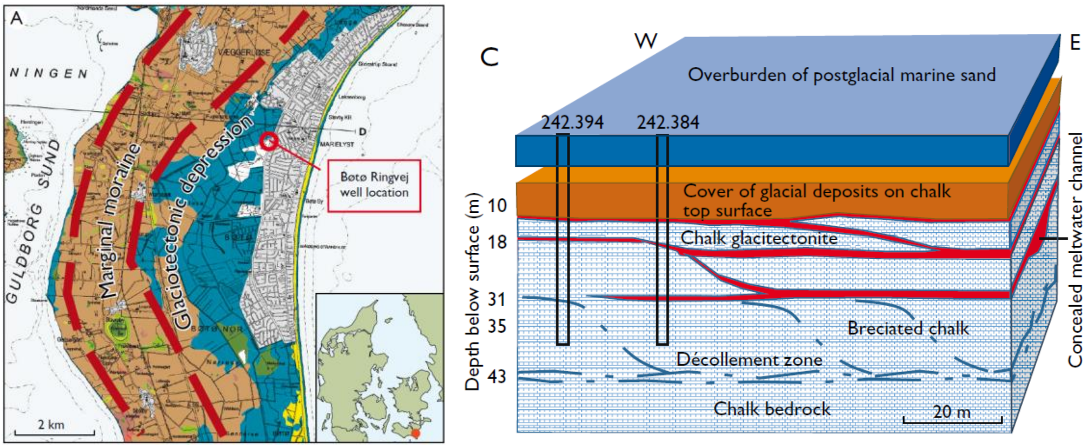


Fig. 7. Hydrogeological investigation site on Falster: A: geological map of the area demonstrating the glacial geological setting. C: block diagram illustrating the features and glacitectonites in the Upper Cretaceous beds (Pedersen et al., 2018)

The main aquifer for water supply in the area is the upper chalk. The Quaternary glaciations have caused fracturing of the upper 20–30m of the chalk. In this part, the chalk is fully or partly refreshed due to fast advective groundwater flow through the fractures. Previous studies of chalk aquifers in Denmark have shown that the residual saltwater typically is completely flushed out in the upper 50–80m of the chalk by infiltrating freshwater. Below this zone a mixing zone with elevated chloride concentrations is seen, where the number of fractures and the effective hydraulic conductivity is gradually decreasing compared to the fully refreshed zone above. Below this depth, matrix diffusion is the dominating transport process for saltwater. At depth below 150–200m the saltwater is of oceanic concentration with total dissolved solids (TDS) concentrations above 35 000 mg/l and chloride concentrations above 19 000 mg/l.

***Surface water bodies***

The surface water system is dominated by the artificial drainage canal system. A few minor creeks flow towards the drainage system or towards Guldborgsund. The drainage system is lowering the water table in the area where the ground surface has elevations between +1 and −3 m a.s.l. The pumping station is aiming at keeping a constant water level in the drainage canals.

***Groundwater abstractions/irrigation***

The Marielyst Waterworks supplies water to 5200 households. Due to the high percentage of summer cottages in the area, the groundwater supply varies considerably during the year with a maximum of 2000 $m^3$/day in July to a minimum of 300 $m^3$/day in January. The waterworks has 12 active abstraction wells, which are located in three separate well fields. The oldest well field is located about 0.5 km from the coast, a second group of wells are approximately 1 km from the coast (established 1975–1990) and both well fields are located on one of the former barrier islands. The newest well field is located in the central part of the island 2.5 km from the coastline. It was established in 2005 in or very close to the main groundwater recharge area in the push moraine hills.

All 12 groundwater abstraction wells of Marielyst Waterworks are drilled to a depth of 10–15m into the upper fractured chalk aquifer. Significant groundwater abstraction has taken place since the 1960s. The annual groundwater production reached its maximum around 470 000 m$^3$/year in the beginning of the 1980s and has since then decreased to the present level of around 250.000 m$^3$/year, mainly due to repair of leaky water pipes. Additionally, groundwater abstraction takes place from two other minor waterworks and a few irrigation wells, which add up to approximately 150.000 m$^3$/year.

## 3.2 Climate change challenge

The Falster pilot area is located in the Central and Eastern Europe climate zone (EEA map Fig. 8) where a decrease in summer precipitation is expected along with an increase in warm temperature extremes. In the Falster pilot area higher summer temperatures and lower precipitation will most probably result in a higher demand for groundwater, both for domestic use and for irrigation of e.g. golf courses. Lower summer precipitation will also affect the surface water bodies being subject to more water stress. A decrease in summer precipitation is not expected to affect the groundwater recharge that is mainly taken place from October to April.

The most likely climate scenario for the pilot area also predicts an increase in sea level, and an increase in winter precipitation, which will most probably result in an increase in groundwater recharge. Rising sea level will most probably result in further seawater intrusion into the coastal Chalk aquifer, causing a reduction in the available groundwater resource for the local freshwater supply. In addition, an increase in the frequency and the intensity rainfall is predicted, which might result in more severe flooding events.

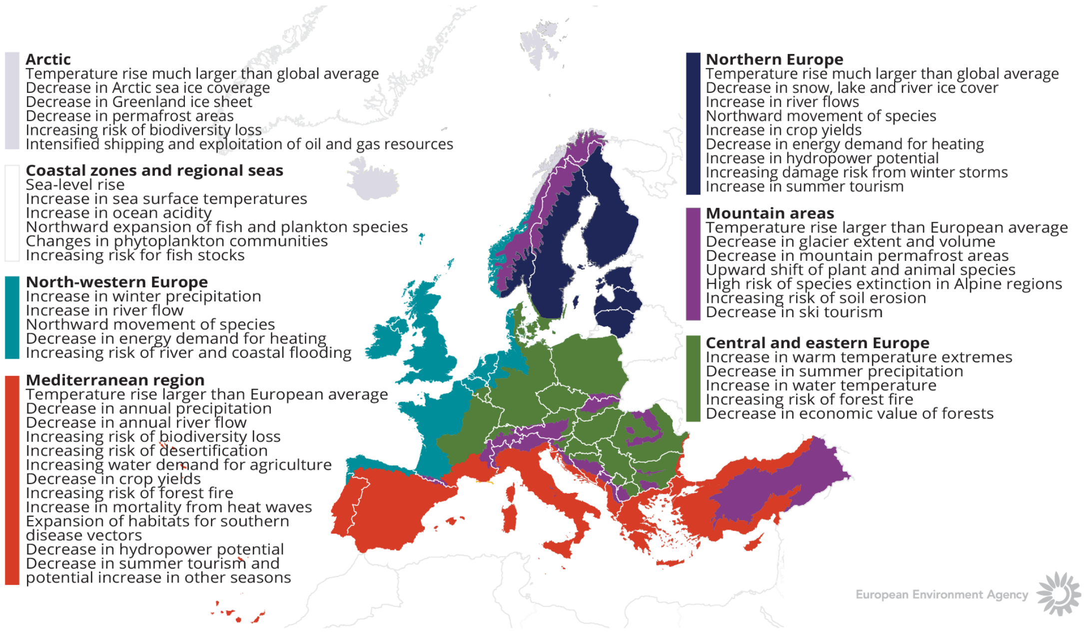


Fig. 8. Observed and projected climate change and impacts for the main biogeographical regions in Europe (European Environmental Agency)

# 4 METHODOLOGY

## 4.1 Methodology and climate data

### *4.1.1 Tools/ model description*

For the pilot area on the island of Falster a 3D variable density groundwater model has been setup with the aim of analysing actual and future risk of saltwater intrusion to the local coastal aquifer. The modelling packages MODFLOW, MT3D, and SEAWAT were used. The setup of the MODFLOW/MT3D/SEAWAT model, its functionalities, applications and basic assumptions are described by Rasmussen et al. 2013, which can be found in a special issue of Hydrology and Earth System Sciences (Hinsby et al. 2011). Focus of the modelling were on 1) getting the initial saltwater concentrations right by modelling the transition of part of the pilot area, which over the last two to three centuries has changed from a saltwater lagoon to reclaimed land, 2) the increase in groundwater abstraction from the costal aquifer due to a significant development of summer cottages and the possible effect of seawater intrusion, 3) and impacts of climate change, change in precipitation and sea level rise, on seawater intrusion.

A minor local and simplified 3D variable density model based on the above described model has been setup with the purpose of analysing the applicability and effectiveness of subsurface water solutions (SWS) in a fractured chalk aquifer. The SWS "Freshkeeper" was tested, where freshwater is injected in to the aquifer with the aim of storing freshwater from winter to summer were, and at the same time prevent saltwater from entering the aquifer by creating a freshwater lens in the aquifer around the groundwater abstraction wells (Hinsby et al. 2018).

### *4.1.2 Climate data*

The model scenarios on future risk of saltwater intrusion to coastal aquifer were based on predictions of sea level rise and on change in groundwater recharge due to projected changes in precipitation for the Danish area. The expected change in groundwater recharge for the Pilot Falster was based on the predicted change in groundwater recharge for a comparable area in Denmark (van Roosmalen et al. (2007). These studies used output from regional climate models representing IPCC (2000) scenarios A2 and B2.

The tested climate change effects of sea level rise and changes in groundwater recharge were gradually implemented in the groundwater model over a simulation period of 90 years. For an additional 200-year simulation period both recharge and sea level were kept constant in order to assess the long-term effects of the imposed climate changes (Rasmussen et al. 2013).

The groundwater model could be improved in a couple of ways, e.g. by including 1) an ensemble of the latest climate models for different emission scenarios including downscaling (see www.aquaclew.eu), 2) the latest predictions for expected sea level rise, and 3) the expected change in the demand for groundwater with predicted longer and warmer summer periods with less precipitation than today.

## 4.2 Tool(s) / Model set-up

The groundwater model was based on the large scale Danish national hydrological model, the DK-Model (Henriksen et al. 2003) with later updates. The geological information in the model was refined using data from geological soil maps, and from various types of borehole tests and borehole wireline logs. The canal and drainage system were refined using local maps and field surveys.

## 4.3 Tool(s)/ Model calibration/ test

The groundwater model was calibrated using groundwater head observations and discharge data from the main drainage canal. The variable density model simulations of saltwater intrusion were validated against groundwater chemical data and geophysical data (borehole logging data and data from both ground and airborne transient electromagnetic surveys).

### *4.3.1 Observation data*

Time series of groundwater head, groundwater chemistry and river discharge were available for model calibration and validation. Some of the historical data series up to or more than 30 years long. During the resent project periods more intensive monitoring programmes were organised.

## 4.4 Uncertainty

The geological uncertainty was the major source of uncertainty for the groundwater density model. The knowledge in general and also site-specific knowledge about flow and transport characterises for the fractured and double porosity chalk aquifer was limited. The geological interpretation and the implemented geological model for the coastal zone was uncertain, there were only limit geological available in the coastal zone, few boreholes exist as groundwater interests are limited and geological information collected for exploration for off-shore raw material exist only further out in the sea. The degree and the extent of the refreshening of saline water in the chalk aquifer by fresh groundwater recharge was also a source of uncertainty.

These uncertainties were to some extent addressed by field campaigns including borehole wire logging, electromagnetic surveys, both airborne (SkyTEM) and ground based, and onsite field tracer tests. More investigations are needed to really improve the flow and transport processes in the double fractured chalk aquifer.

## 4.5 Saltwater intrusion and groundwater chemical status

The national Threshold Value (TV) for Cl is set to 250 mg/l, which is the same as the drinking water quality standard. The natural background levels (NBL) for Cl were estimated at the national scale for different types of aquifers and locations. However, because these NBLs were lower than the national TV, they were not used in the chemical status assessment of the Danish groundwater bodies.

The NBL for Cl relevant to Falster is for the carbonated aquifers on Sjælland, which was estimated to be 157.2 mg/l, based on the representative Cl values for 1283 sampling points. The representative value was determined as the mean of the annual mean concentrations for the period 2000-2018 (incl.).

## 5 MODELLING AND MONITORING RESULTS

### 5.1 Modelling results and climate change impact assessments

#### *5.1.1 Performance to historical data*

The calibration results for the groundwater heads for the steady-state models were are regarded as satisfactory with a RMS value of 1.53 m. The used groundwater heads for model calibration were all measured in boreholes with low salinity and density effects on hydraulic heads are insignificant. For the transient calibration a $R^2$-value (the Nash–Suthcliffe coefficient) of 0.88 was found for the drainage canal main gauging station based on monthly data, which in general is an acceptable calibration result (Rasmussen et al. 2013).

A comparison between the modelled saltwater distribution and SkyTEM surveys showed both good agreement in some areas and areas with some discrepancy (Fig. 9). See Rasmussen et al. 2013 for further discussions of the model validation and the electromagnetic surveys.

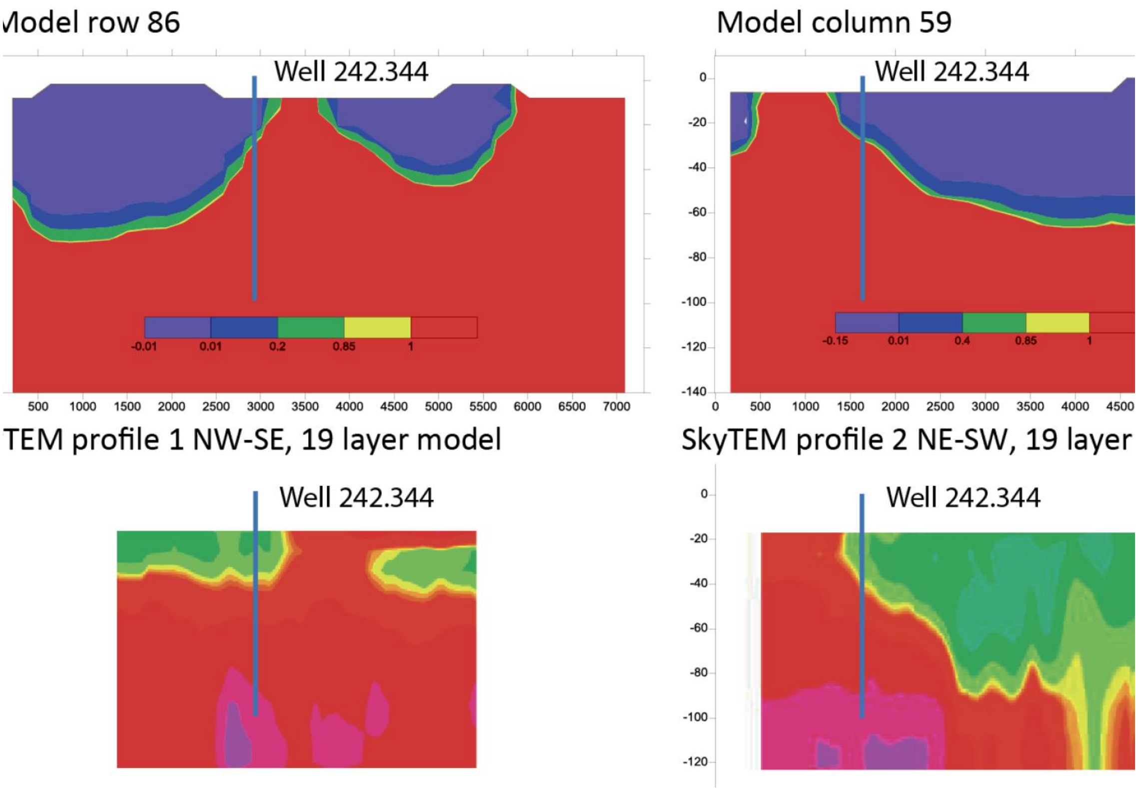


Fig 9. Comparison between the results of model simulations (upper cross sections) and SkyTEM surveys (lower cross sections). The colour scales are defined such that blue/green colours indicate freshwater of drinking water quality ([Cl−]<250 mg L−1). Yellow is breaching a threshold value of 150 mg L−1, and red breaches the drinking water guideline (Rasmussen et al. 2013)

### *5.1.2 Results of assessments*

The study shows that saltwater intrusion in the Falster Pilot is sensitive to changes in sea level, groundwater recharge and stage of the drainage canals. The changes in recharge were found to be the most important factor, whereas minor sea level rises do not seem to affect the sea water intrusion as much. For the abstraction wells at risk the model studies show that the chloride concentrations are most sensitive to the stage of the drainage canals and to the groundwater recharge. However, the combination of significant changes in groundwater recharge, sea level rise, groundwater abstraction, and canal maintenance are crucial for the development of the groundwater quality (Rasmussen et al. 2013).

## 5.2 Monitoring data and chemical status assessments

### *5.2.1 Time series of chloride concentrations*

The dataset covers the period 1985 to 2020 and includes groundwater Cl samples taken at 14 abstraction wells used by Marienlyst Vandværk for drinking water production (Table 1 and Figure 10 and 11). In addition, the Cl samples of the treated drinking water taken at the exit of Marienlyst Vandværk (after all treatment) are also presented for comparison purposes.

Table 1. Summary statistics for the Cl dataset with information on the number of samples, the sampling period, the minimum, 10$^{th}$ and 50$^{th}$ percentiles (p10 and p50 respectively), maximum, mean and standard deviation (SD)

| Sampling point | | Samples | Period | | Cl concentrations (mg/l) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **DGU number** | VV Boring | n | $y_1$ | $y_n$ | min | p10 | p50 | max | mean | SD |
| **242. 172** | 3 | 115 | 1985 | 2020 | 60 | 120 | 160 | **260** | 156.8 | 39.3 |
| **242. 178** | 2 | 115 | 1985 | 2020 | 190 | 208 | **280** | **300** | **262.8** | 33.2 |
| **242. 189** | 5 | 115 | 1985 | 2020 | 40 | 70.8 | 176 | 250 | 162.2 | 55.4 |
| **242. 190** | 4 | 57 | 1985 | **2005** | 156 | 238 | **270** | **316** | **267.2** | 29.2 |
| **242. 212** | 9 | 112 | 1985 | 2020 | 76 | 110 | 140 | 236 | 148.4 | 34.5 |
| **242. 213** | 10 | 57 | 1985 | **2005** | 195 | 204 | 220 | **260** | 221.5 | 15.1 |
| **242. 230** | 6 | 115 | 1985 | 2020 | 39 | 54 | 80 | 144 | 86.3 | 30.2 |
| **242. 231** | 7 | 115 | 1985 | 2020 | 60 | 70 | 104 | 180 | 102.1 | 28 |
| **242. 239** | 11 | 107 | **1993** | 2020 | 11 | 39.2 | 78 | 160 | 74.7 | 33.1 |
| **242. 317** | new 4 | 58 | **2005** | 2020 | 32 | 35 | 40 | 50 | 40.7 | 5.1 |
| **242. 319** | 12 | 58 | **2005** | 2020 | 34 | 38 | 40 | 60 | 42.1 | 5.3 |
| **242. 320** | new 10 | 58 | **2005** | 2020 | 26 | 30 | 40 | 52 | 39.7 | 7.7 |
| **242. 332** | 8 | 115 | 1985 | 2020 | 76 | 116 | 148 | 180 | 144.7 | 21.7 |
| **242. 44B_1** | 1 | 59 | 1985 | **2006** | 130 | 239 | **280** | **320** | **271.3** | 37.9 |
| **242. 44B_2** | 1 | 44 | **2009** | 2020 | 20 | 32 | 40 | 80 | 41.9 | 13.9 |
| **Marielyst Vandværk** | | 115 | 1985 | 2020 | 40 | 105 | 124 | 186 | 126.5 | 26 |

Seven of the wells have been used in the entire period (1985 – 2020). Two (242. 190 and 242. 213) were used until 2005 and after that they were replaced by other two new wells (242. 317 and 242. 320) (Figure 10)

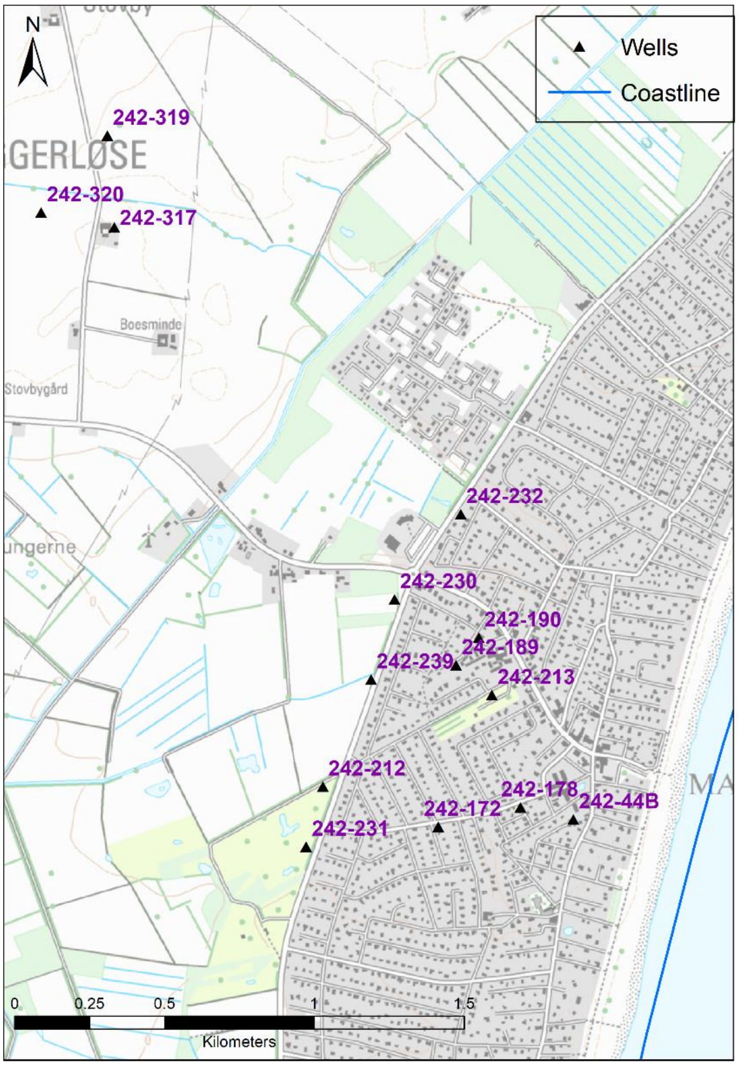


Fig. 10. Location of sampling wells

Well 242. 44B was re-established (deepened) in 26 Jan 2007, so the time-series have a gap from 2006 to 2009. The concentration before and after this intervention differ significantly, so in both Table 1 and Figure 11 those are shown separately and are treated as different sampling points. In the first period, the Cl concentrations were showing an increasing trend with concentrations exceeding the national TV of 250 mg/l, while after the intervention the median Cl concentration was 40 mg/l (max concentration 80 mg/l).

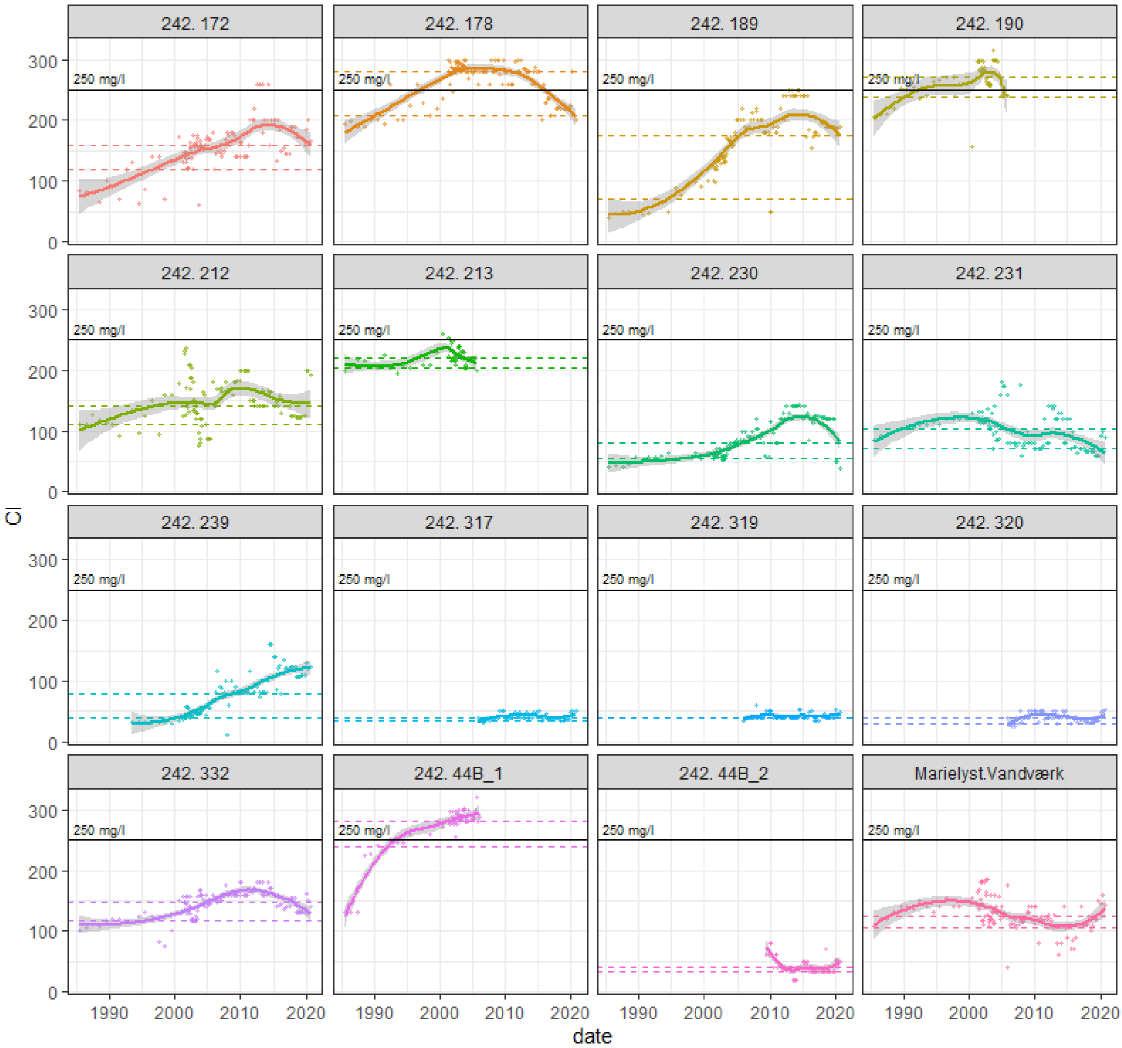


Fig. 11. Time-series of Cl concentrations (mg/l) (y-axis) in groundwater samples for the period1985-2020 at the abstraction wells of Marielyst Vandværk; Each measurement is visualized with a point, the trend is shown with a loess (local polynomial regression) and its 95% confidence interval. The DGU numbers of the abstraction wells are provided above each panel. The Marielyst Vandværk panel shows the Cl concentrations in the treated drinking water at exit waterworks. The national Threshold Value (250 mg/l) is drawn with a black horizontal line, while the representative value for each sampling point based on the 10$^{th}$ and 50$^{th}$ percentiles are shown with dashed lines; DGU n. 242.44B was re-established (deepened) in 26 Jan 2007, so the time-series are split for the two periods (before and after)

### *5.2.2 Natural background levels (NBLs) for Chloride based on time series data*

In order to calculate NBLs (based on the 90$^{th}$ percentile), first a representative concentration level should be chosen for each sampling point. The representative concentration level for a specific period can be calculated based on different summary statistics. For example, in the River Basin Management Plan, the mean of the annual mean concentrations is used to account for the irregularity of the time-series, so each year is weighed equally. The mean is however very sensitive to outliers, so the median has been suggested by the BRIDGE method. In the recent work done in TACTIC, both the median (50$^{th}$ percentile, p50) and the 10$^{th}$ percentile were tested. Table 1 presents both p10 and p50 for each of the sampling points, both of which are considered here as “representative” levels. These sampling-point specific levels are also shown in Figure 11 together with the time-series and the national TV level.

The p10 representative level for all abstraction wells is below the national TV (250 mg/l). Two sampling points have high p10 (238-239 mg/l), but both of these are no longer in use (242. 190 was replaced, and 242. 44B was deepened).

The p50 representative level, however, is higher than the TV (250 mg/l) for:

- DGU n. 242. 178 (1985-2020), p50 is 280 mg/l and the max Cl concentration is 300 mg/l
- DGU n. 242. 190 (1985-2005), p50 is 270 mg/l and the max Cl concentration is 316 mg/l
- DGU n. 242. 44B (before intervention, 1985-2006), p50 is 280 mg/l and the max Cl is 320 mg/l

The NBL (90$^{th}$ percentile) calculated based on the abstraction wells of Marienlyst Vandværk (15 sampling points with data in the study period) are:

- 226 mg/l with p10 as a representative value
- 276 mg/l with p50 as a representative value (> national TV of 250 mg/l)

Both of these NBLs are higher than the NBL calculated for the carbonated aquifers on Sjælland as part of the River Basin Management Plan (157.2 mg/l). This could indicate that the Cl concentrations observed in these sampling points are influenced by saltwater intrusion due to groundwater abstraction. However, the time-series also show that for most of these sampling points there is a trend-reversal in the last 5-10 years. The new wells established after 2005 have generally low median Cl concentrations (40 mg/l), which could be considered as the natural background at this part of the aquifer.

It could be argued that in general p10 represents better the “natural” background at each of the sampling locations, because the medians at some of the sampling points are influenced by the increasing trends or the trend-reversals. Future work should include detrending of the time-series before estimating NBLs.

Even though the Cl concentrations at some of the abstraction wells of Marienlyst Vandværk are elevated, the drinking water produced at the waterworks has relatively low levels of Cl (median 124 mg/l) which has never exceeded the drinking water standard (250 mg/l) in the study period.

# 6 CLIMATE CHANGE ADAPTATION STRATEGIES

Saltwater intrusion in coastal aquifers is an increasing problem, and increasing sea levels increase the concern and need for protecting groundwater resources in coastal regions, globally. Hence, efficient adaptation strategies are of increasing importance for projection of the water supply of small cities as well as metropolis in coastal areas around the world. Managed aquifer recharge and other subsurface water solutions provides many options for protecting coastal freshwater resources and temporarily store water e.g. from wet winters to dry summers (Hinsby et al. 2015, 2016, 2018; Zuurbier et al., 2014, 2015, 2017). Sources of fresh water to be stored in groundwater reservoirs / aquifers include desalinized deep brackish groundwater (less energy demanding than seawater desalinization) and purified rain and drainage waters.

The Falster pilot area with its test site facilities for tracer test studies provide excellent opportunities for studying and analysing the efficiency and impact of temporarily storing different types of freshwaters in fractured carbonate aquifer to control salt water intrusion and protect groundwater resources in coastal regions. Studies of climate change impacts in the area (Rasmussen et al., 2013; Hinsby et al., 2018) indicate that such subsurface water solutions may be the only efficient way to protect groundwater resources in similar areas. Hence, such solutions should be more widely tested and optimized in coastal areas around the world.

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