D2.2 Road map for full scale implementation of SWS for fractured chalk aquifer.

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Executive Summary

The test site on the island of Falster, Denmark, was selected 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. Dual-porosity fractured carbonate aquifers occur in many coastal settings around the globe e.g. in the southeastern parts of the UK and northern parts of France. Efficient SWS techniques to control salt water intrusion and improve the access to high quality freshwater resources in such settings are called for globally.

Set-up

The exact location of the test site for assessment of SWS techniques at the Falster site was selected based on two Geoprobe HPT (Hydraulic profiling tool) soundings performed at two existing water supply wells in well field two of the Marielyst Water Works with increasing salinity approaching the drinking water standard. The selected location and design of the test site were agreed between Marielyst Water Works, GEUS, KWR and GEO (the drilling company selected to drill the wells in the test site) based on existing knowledge about the aquifer and previous tracer tests in a similar setting. The developed test site consists of six wells including two multi-level monitoring wells each with seven screens covering sections of one meter between 12 and 26 meter below the surface i.e. the upper 14 meter of the confined Chalk aquifer from where Marielyst Water Works abstracts water. Two potential “freshkeeper wells” screened in three different sections from 15 to 38 meter depths were also installed close to the water supply well. Geophysical borehole logging (including propeller flow logs) were performed in the freshkeeper wells and another well developed for water abstraction in order to design the pumping and tracer tests for assessment of the hydraulic characteristics of the site in a dipole set up with an abstraction and injection well in each end of the test site. The pumping and tracer tests were conducted during two separate field campaigns in December 2016 and April 2017.

Results field research

The original SubSol pilot test site was fully implemented ahead of time, but the two initial field tracer tests designed for estimation of the hydraulic properties of the chalk were not successful due to unforeseen geological complexity. The planned field investigations did not provide the expected and required data for detailed model assessments and recommendations for specific SWS designs on Falster.

Because of lack of data from the unsuccessful tracer tests it was decided to drill two additional wells in the test site in order to be able to conduct a successful tracer test. Permission for the two new wells were obtained in August 2017 and the new wells were completed in October 2017.

Detailed geological analyses during drilling of the two new wells showed that glacial impacts of last ice age glaciers heavily disturbed the upper approximately 30 meter of the

aquifer (Pedersen et al., 2018), and that chalk dominated glacitectonites and other glaciotectonic features affected the hydraulic behaviour of the Chalk. The glaciotectonic processes had significant and unpredictable impacts on the hydraulic properties between the wells established in the test site especially in the upper 10-15 meters of the aquifer from where the water works abstracts water.

The third and final tracer test was successfully conducted after the completion of the two new wells during the period 16.4 - 4.6 2018. The evaluation of the results from the tracer test demonstrate a significant effect of the glacitectonite (Pedersen et al., 2018) as it has a significantly higher hydraulic conductivity than surrounding parts of the Chalk. This has important implications for the assessment of different SWS techniques and the final design of and recommendations for SWS on Falster as it has to be included in the groundwater models. The location and extend of the glacitectonite and other glaciotectonic features are not known in detail and are difficult to predict. Unfortunately, time did not allow for detailed model studies based on the results from the third and final tracer test due to the geological complexity and the late completion of the test. Hence, preliminary and partly conceptual model assessments of the SWS possibilities on Falster were possible, and it was not possible to provide final and detailed recommendations for a SWS design on Falster.

Hydrochemical analyses of groundwater collected at different depths from the multilevel screens in the test field and geophysical borehole logs in a deep well close to the test field demonstrate that the salinity (electrical conductivity) is slowly increasing with depths from about 1100 µS/cm at 15 meters below surface (mbs) to 6000 µS/cm at a depth of 70 meter. Hydraulic active fractures exist to a depth of about 70 meter below which the increase in salinity is controlled by diffusion. The salinity reaches the salinity of the present day Baltic Sea around Falster at 80 meters depth and oceans at an estimated depth of about 150 m. Hence, there is no freshwater suitable for drinking water supply at depths below 15 meters at the investigated site.

The Chalk aquifer has the lowest salinity of 800-900 µS/cm around 15 mbs in the upper part of the identified glacitectonite, which has a relatively high permeability according to the field investigations. Electrical conductivity values of around 1200 µS/cm are found both above and below this part of the glacitectonite. Hence, only the upper part of the glacitectonite around 15 mbs yields water of drinking water quality although it still has elevated chloride concentrations compared to recent groundwater recharge. Groundwater in the Chalk above and below this level has a salinity (electrical conductivity) above the drinking water standard of 1000 µS/cm. This indicates that freshening of the Chalk aquifer after the last glaciation or later salt water intrusion from the Baltic Sea, which may have occurred during the Holocene, is incomplete in all of the Chalk aquifer. Tritium-analyses in groundwater from the water supply well show that present day recharge is very small as water from the well does not contain tritium. This is most probably the result of the land reclamation initiated in 1861 as most of the precipitation since then has been drained and pumped to the Baltic Sea on the western part of the island.

Preliminary feasibility assessment of SWS

The preliminary model assessments of the results obtained in the field studies on Falster indicate that the three SWS standard schemes described e.g. by Zuurbier et al. (2017) and applied at SubSol reference sites may require modifications before they can be applied to the Falster case. This is due to the rather different hydrogeological and hydraulic conditions between the sandy aquifers of the Netherlands and the fractured glacially disturbed chalk in Denmark, which resulted in a more complex distribution of hydraulic properties and salinity in the aquifer as described above. However, the conducted field tests and preliminary model assessments also indicate that modified versions of these methods e.g. combinations of the ASR-coastal and Freshkeeper concepts at least technically seem to have a potential on Falster and in similar hydrogeological settings globally.

Geochemical analyses of the Chalk show very low contents of pyrite and other reducing minerals and organic matter and that pyrite only contains small amount of arsenic and other toxic trace elements potentially threatening water supply. The assessments indicate that there is only little capacity to reduce oxygen and insignificant capacity for nitrate removal, and that oxidation of pyrite will not create unacceptable levels of trace elements. Hence, the geochemical assessments indicate that the Chalk aquifer is well suited for injection of properly treated and purified drainage water from the nearby drainage canal and/or desalinized brackish water from a freshkeeper well. Water pumped from a freshkeeper well below the water supply well would have the additional benefit of removing up-coning saline water from the deeper parts of the chalk aquifer and reduce the salinity of the water supply well. Analyses of trace elements and strontium isotopes indicate that up-coning from deeper parts of the chalk aquifer is responsible for the increasing salinity of the water supply well rather than recent salt water intrusion from the Baltic Sea.

Injection of purified water types enables subsurface storage from winter to summer, freshening of the aquifer and hence the possibility of increasing the available freshwater resource in the summer period where water abstraction is peaking with nearly 10 times the winter abstraction. Considering the long dry period in most parts of Europe in the summer of 2018 (including Falster, which suffered severely from a lack of precipitation), such SWS techniques may be required to maintain a sustainable use of groundwater in the investigated chalk aquifer in a future climate.

The subsurface water solutions (SWS) seem to have a significant potential at the investigated site and at other similar sites with coastal carbonate aquifers, globally, for storing excess precipitation during wintertime for the summer with much higher demands, especially where no other options are available. The required more detailed geological and hydraulical investigations of the subsurface due to the complexity of sites with glaciotectonical impacts, however, may make the actual implementation more difficult.

Currently, the added costs for: (1) detailed site assessment studies, (2) treatment and purification of either freshwater from nearby drain ditches or brackish waters from deeper parts of the chalk before injection or reuse and (3) maintenance of the water treatment systems seem in combination to be too high to be an attractive solution for Marielyst Water Works in the near future. Additional obstacles include difficulties obtaining permissions for injection of treated water types in aquifers used for drinking water supply. However, our conducted investigations also indicate that it may only be a matter of time before salt water intrusion issues becomes so severe that the application of SWS techniques is the only option if the local authorities and the water works want to keep the water supply within the area.

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Introduction and previous studies in the Falster case study area

The Falster test site area was studied in two previous EU and National research projects "BaltCICA" (www.baltcica.org) part-funded by the BONUS programme on the Baltic Sea (www.bonusportal.org) and "Water4Coasts" part-funded by the Ecoinnovation program of the Danish Ministry of Environment and Food (http://eng.ecoinnovation.dk/). Main results from the two projects can be found in Rasmussen et al. (2013) and Hinsby et al. (2016). The main objective of the studies conducted in BaltCICA was to assess climate change impacts on the fresh- saltwater boundary in the Chalk aquifer in the investigated area. Geophysical measurements (e.g. electromagnetic, both airborne and groundbased, as well as geophysical borehole logging) were 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. The location of the test site is shown in Figure 1.

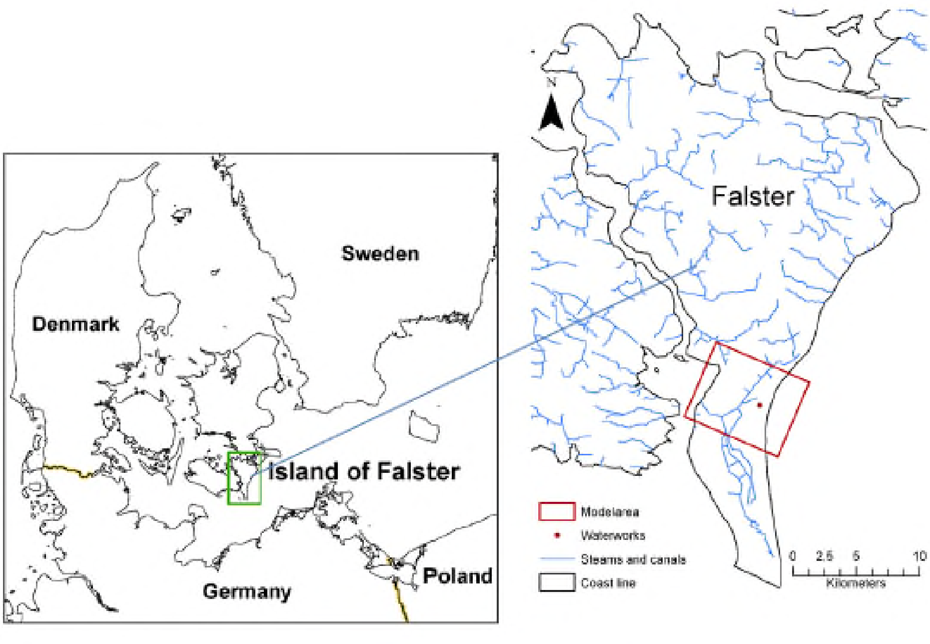


Figure 1. Location of SubSol Study site on the Island of Falster, Denmark, western Baltic Sea.

The main objective of the Water4Coasts study was to initiate the assessment of the potential application of new innovative techniques to control salt water intrusion and protect fresh water 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 including more detailed analyses of the hydraulic properties near the protected wells / well fields and the geochemistry and quality of the Chalk aquifer as well as groundwater and surface waters, which potentially could 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.

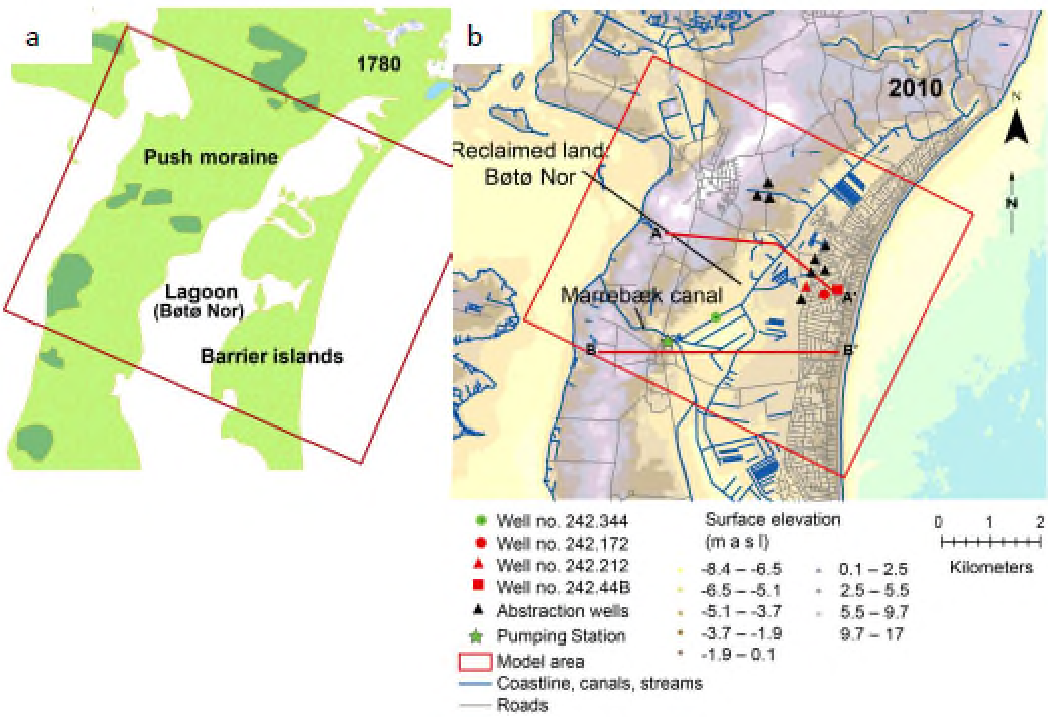


Figure 2. a) The Falster case study area in the year 1780 with a natural lagoon between a Pleistocene push moraine and Holocene barrier islands and b) The same area in 2010 with indication of drainage canals, reclaimed land and a highly developed summer housing area, and the location of the geological cross sections shown in figure 3. Note! The location of the red triangle (well 242.212) where the test site is developed.

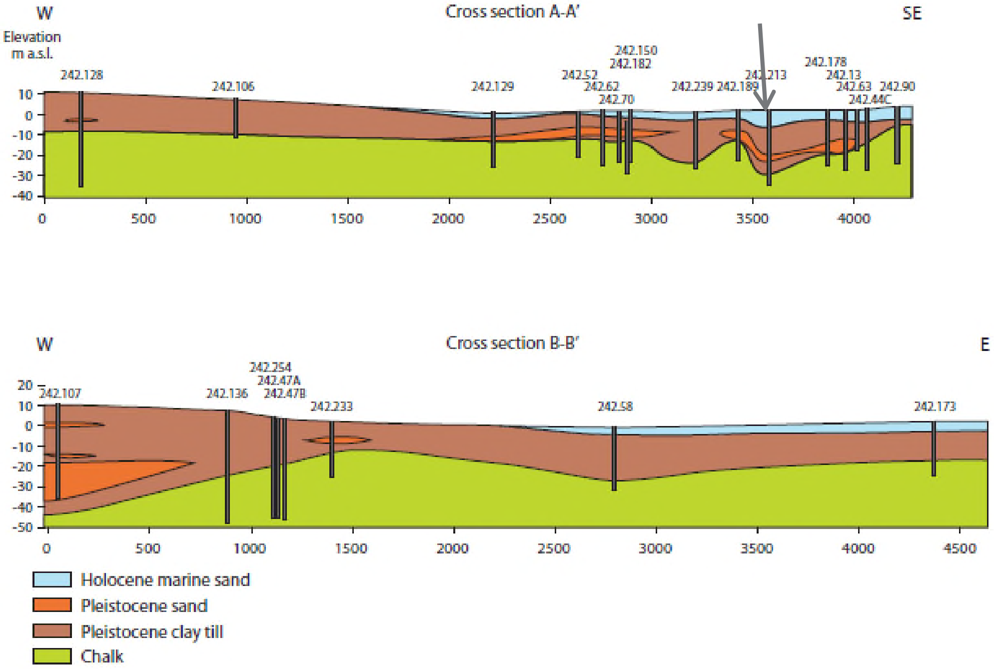


Figure 3. Geological cross sections through the Falster study area. Locations are shown in Figure 2. The test site is located about 100 m to the south of well 242.213 marked with the grey arrow in the upper cross section (A-A´).

Locating and developing the SubSol Falster test site

Assessment of existing data

Data from the area from previous investigations and the Marielyst Water Works were included in the assessment of suitable test sites for detailed analyses of the hydraulic and chemical characteristics of the Chalk aquifer. The data from the detailed analyses are required in order to develop and assess different tailored site specific subsurface solutions to control salt water intrusion and protect the existing freshwater resource towards increasing chloride concentrations. GEUS identified three water supply wells together with the Water Works potentially suited for further investigations. The location of these are shown in Figure 4.

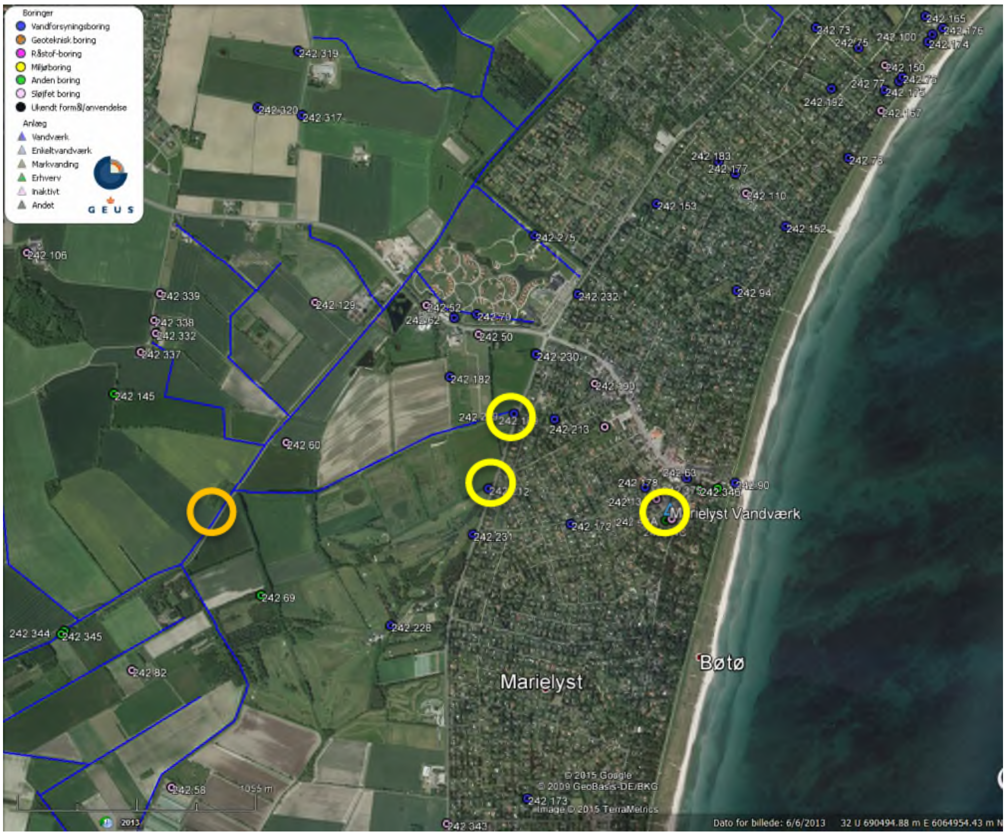


Figure 4. Location of potential water supply wells for detailed investigation of SubSol subsurface water solutions (SWS) indicated with yellow circles, and the investigation well shown in Figure 5 indicated with orange circle.

The two western most water supply wells were finally selected for further studies for practical reasons as the easternmost well is located on the Water Works itself and investigations here would disturb the daily work at the Water Works.

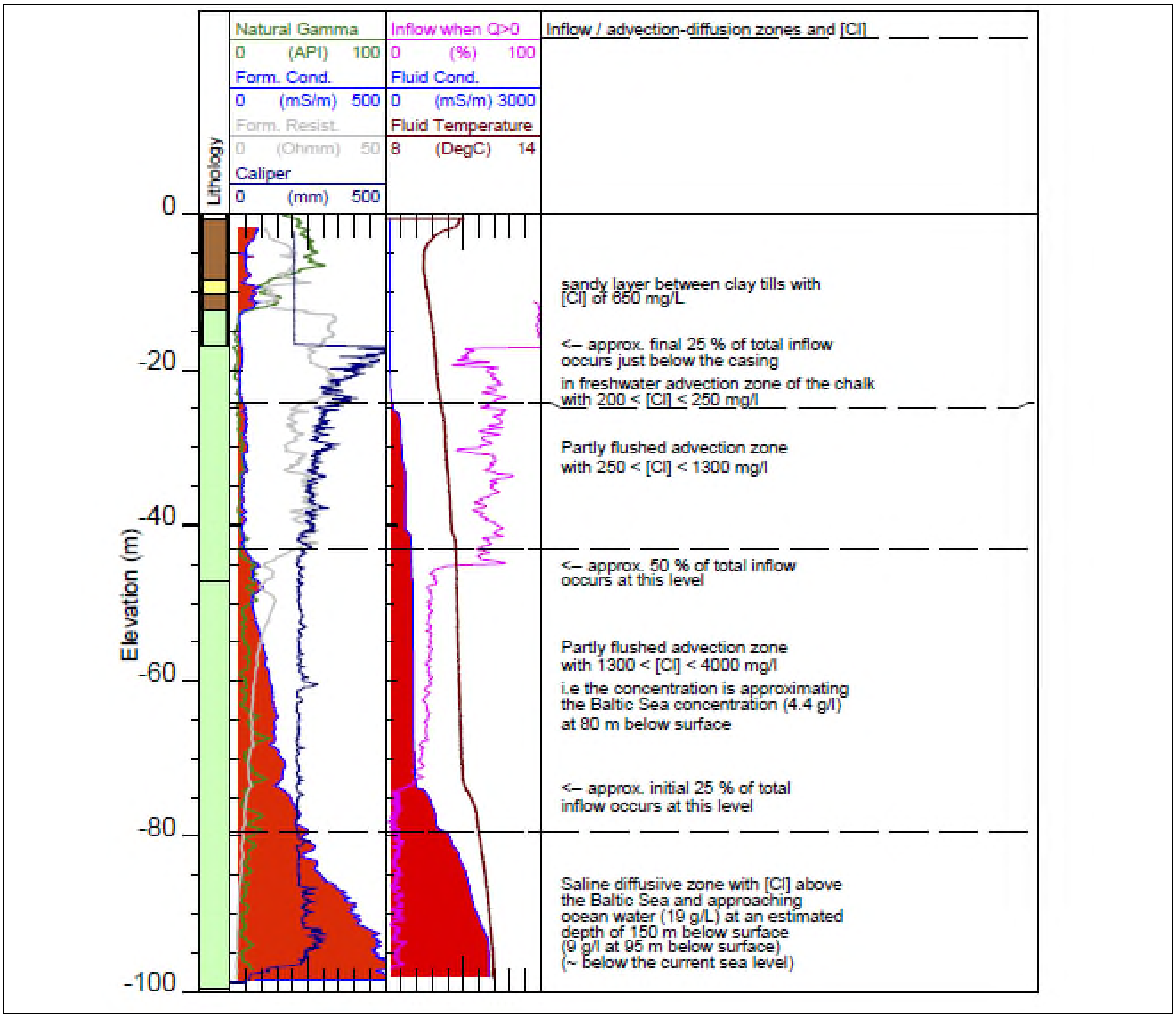


Figure 5. Geophysical borehole log in investigation well no. 242.344 about 1.2km southwest of the water supply wells 7 and 9 (Figure 4). The well clearly show the increasing salinity with depth and that only the upper 10-20 meters of the Chalk apparently contains freshwater suitable for drinking water supply.

Figure 6a and b show the evolution of the chloride concentration since 1990 in the two wells 242.212 and 242.231 or well 9 and 7, respectively of the Marielyst Water Works. Well 9 is rapidly approaching the drinking water standard of 250 mg/l, while the concentrations and increase is somewhat lower in well no. 7 (242.231).

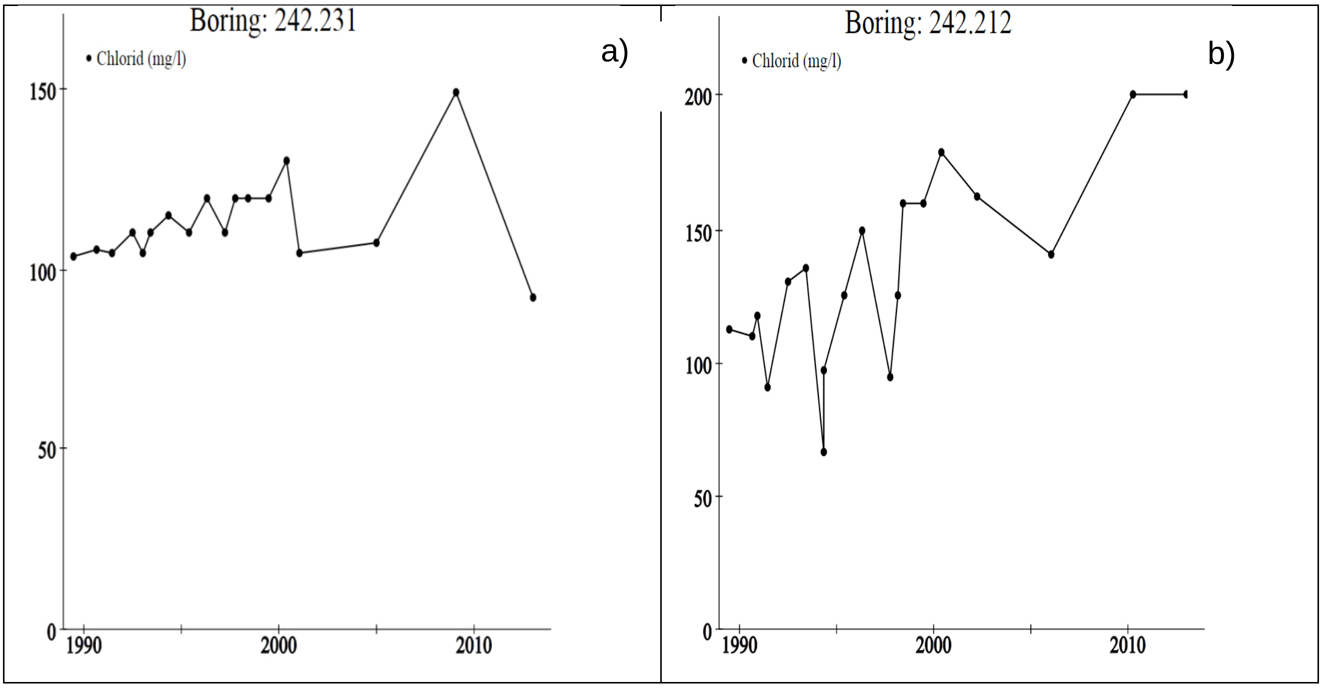


Figure 6. The chloride evolution in (a) water supply well no. 7 (242.231) (b) water supply well no. 9 (242.212) of Marielyst Water Works

Well no. 7 is screened in the upper 11 m of the Chalk with a 200 mm pvc screen, while well no. 9 has an unscreened open section in the Chalk. Geophysical borehole logging conducted by GEUS showed that well no. 9 had "collapsed" and could not be logged in the Chalk. The log of well no. 7 (Appendix 1) showed that the whole upper screened section of the Chalk contained freshwater with an electrical conductivity of around 500 µS/cm (well below the drinking water standard of 1000 µS/cm). Although well no. 9 had collapsed it still had a reasonable yield, and it was therefore decided to conduct further investigations close to the two wells in order to assess, which location would be best suited for the development of the final SubSol-SWS test site.

Conducted investigations for location of test site for detailed studies

It was decided to conduct Geoprobe HPT soundings as close to the two drinking water wells as possible to measure detailed high-resolution vertical variations of both the hydraulic and the electrical conductivity at the two wells. The results from the HPT soundings are shown in Figure 7a and b.

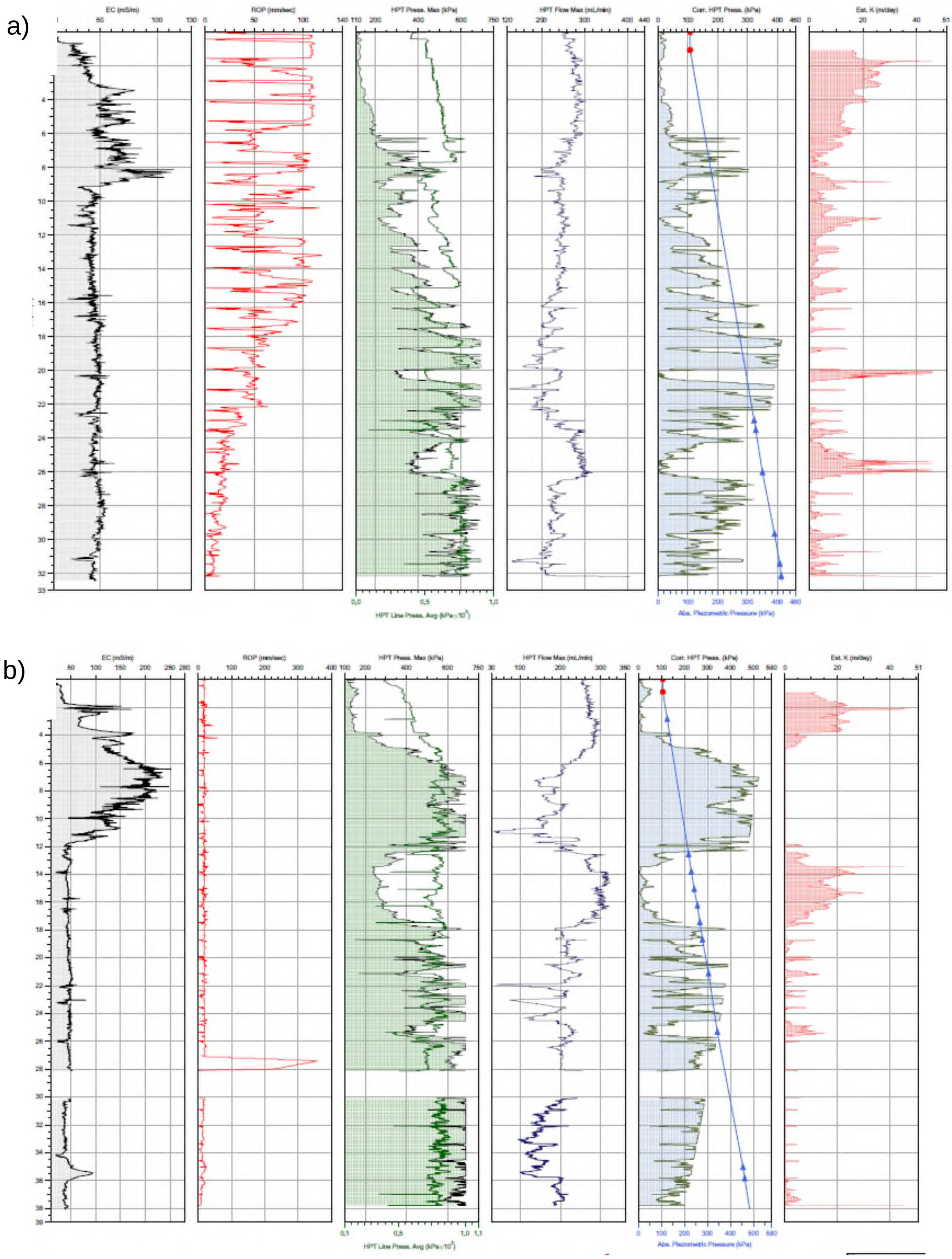


Figure 7. a) HPT log of well no. 7 (242.231) and b) HPT log of well 9 (242.212)

The HPT profiles from both wells indicates that fracture flow dominates in most of the Chalk section in both wells. However, in well 9 in the section 12-18 m below surface, the HPT log indicates a continuous, relatively high hydraulic conductivity. This only agrees partly with the flow log conducted in well T1 about 1 meter from HPT 9 where the flow log indicates relative high hydraulic conductivities from 16-20 m below surface especially at the bottom and top of this section. The flow log indicate small conductivities in the Chalk above 16 m below surface.

Final selection of study site location

Based on the conducted HPT soundings and the existing data for the investigated wells including the higher chloride concentrations in well no. 9 GEUS decided, in collaboration with the Water Works, to develop the test site for detailed SubSol / SWS studies at well no. 9 .

Development of study site for detailed evaluation of potential subsurface water solutions.

After requesting offers from three different Danish drilling companies, GEUS decided to use the drilling section of the company GEO (http://www.en.geo.dk/front-page/) as a subcontractor for drilling and developing the wells of the test site. GEO is a highly respected geotechnical company in Denmark, and it has the largest experience in drilling and installation of monitoring wells in the investigated area.

It was decided to start by cleaning up well no. 9 and install a screen to prevent that the well collapsed again, and then conduct borehole logging in the “new” well. However, this work failed as the well kept collapsing, and it was not possible to install a screen without drilling a new well inside the old one.

GEUS discussed the possibilities and purpose of the test site, and the most suitable drilling procedures and well development etc. with GEO and decided to give up reestablishing well no. 9, and instead drill a total of 6 new wells at the test site around well no. 9 as indicated in Figure 7. The CMT wells are intended for sampling at specific depths.

Each well has 7 screens of 1 m, installed interleaved with the other CMT well and separated by bentonite seals.

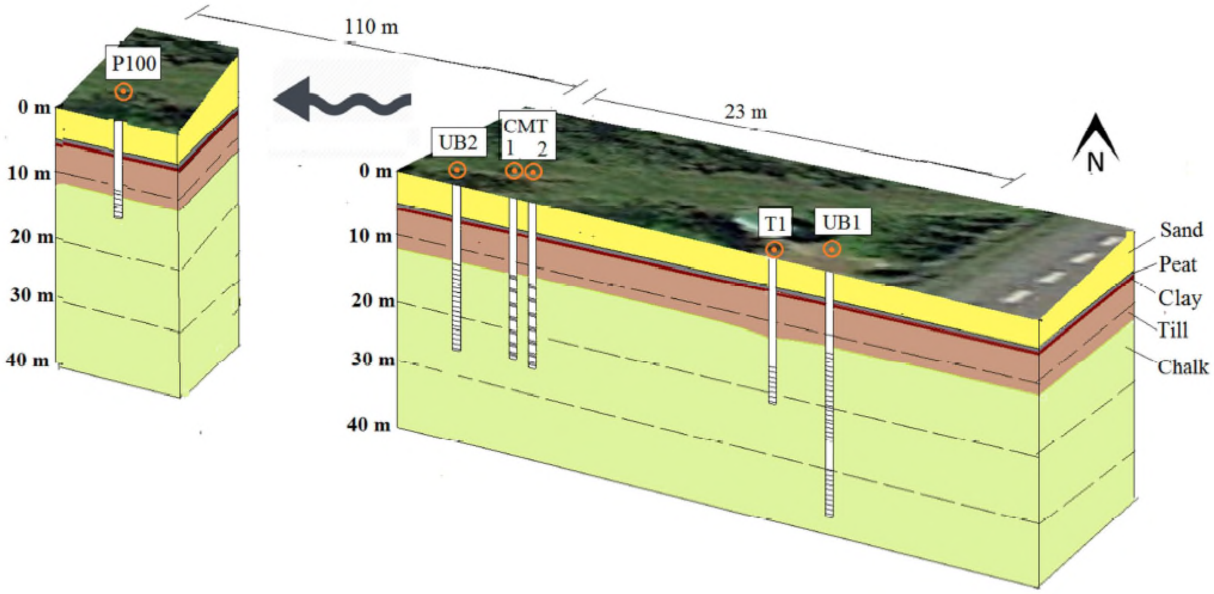


Figure 7. The developed test site at water supply well no. 9. Well no. 9 is located between the new wells T1 (developed for tracer injection) and well UB1 potentially part of SubSol solutions for protection of the fresh water resource during the continued operation of well no. 9 (Kolind-Hansen, 2017).

Results of initial investigations in developed test site

Borehole geological and geophysical logs

After completion of the test site, sediment samples collected during drilling were described in the laboratory (Appendix 1) and geophysical borehole logging was conducted in wells UB1, UB2 and T1 (CMT 1 and 2 cannot be logged). The logging included propeller flow logging to evaluate the hydraulics of the boreholes. The geological logs are shown in Appendix 2. Generally 2-5 meters of Holocene mainly marine sands are found in the top of the profile followed by 4-8 meters of Quaternary clay (mainly tills) underlain by Cretaceous Chalk to the bottom of the borehole. In the investigated area the Chalk continues for several hundred meters below surface. In several of the boreholes the flow-log showed distinct inflow zones indicating the fractures in the chalk aquifer.

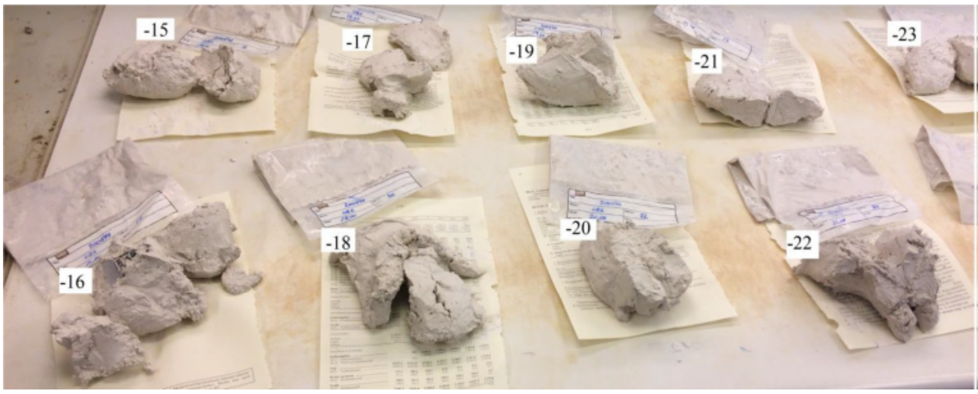


Figure 8. Selection of Chalk samples from depths between 15 and 23 meters collected during drilling of well no. CMT1. Kolind-Hansen, 2017.

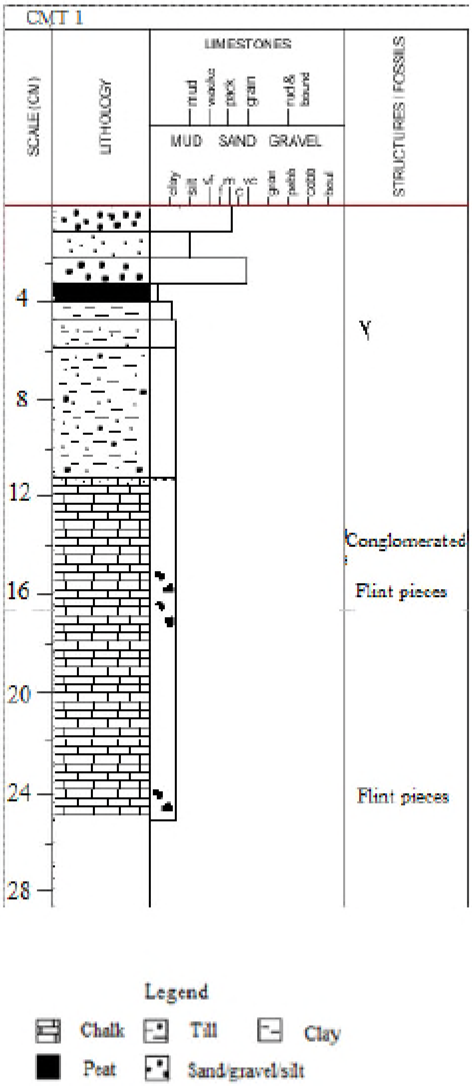


Figure 9. Geological log of CMT 1 developed based on the collected samples from the well during drilling (figure 8), (Kolind-Hansen, 2017).

Geochemistry of the Chalk and potential geochemical reactions for nitrate reduction/risk of clogging

Chalk samples were also collected for analysis of the content of reducing minerals, pyrite and harmful trace metals such as As and Ni in the pyrite. The content of reducing minerals was measured by titrating with Ce (the reduction capacity). The content of pyrite and the related trace metals was measured by first dissolving the Chalk in boiling 20% HCl, rinse the remaining material and boil it in concentrated HNO_3. The supernatant was analyzed for Fe by AAS and trace metals by ICP-MS. It was generally impossible to get core samples from the upper part of the Chalk where the water supply wells are located because it was very soft due to glaciotectonic impact. In this part of the Chalk material was collected in plastic bags and stored at room temperature until analysis. Due to the sampling and storage of the bag samples they have not been shielded from oxygen and pyrite oxidation might have occurred between sampling and analysis thereby underestimating the amount of pyrite in the Chalk aquifer. Figure 10 show the content of pyrite (FeS_2) and the reduction capacity of the upper Chalk and the lower till mixed with chalk from the study site.

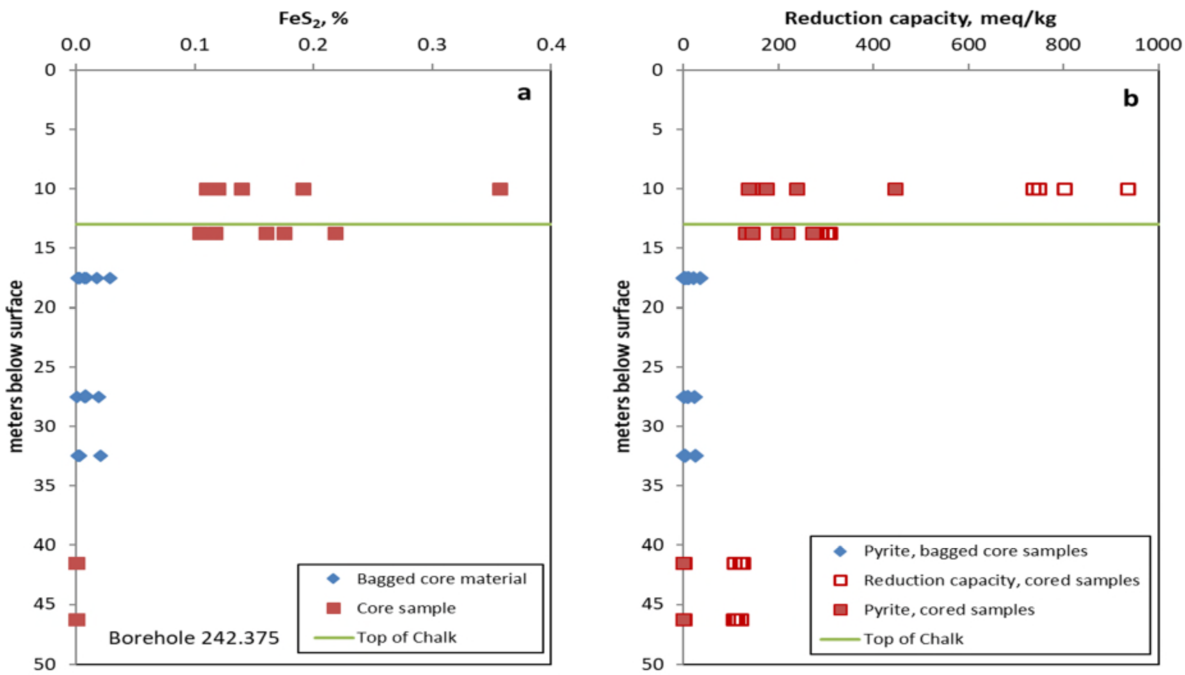


Figure 10. a) Percentage (weight) of pyrite (FeS_2) in Chalk samples collected from a research well in the Falster study area (DGU no. 242.375). Red squares indicate results from core samples, blue diamonds are from bag samples. b) Reduction capacity in Chalk samples measured with the Ce-metode (empty squares) and reduction capacity from complete oxidation of pyrite calculated from the measured amount of pyrite shown in Figure 10a. It was generally impossible to get core samples in the upper part of the Chalk where the water supply wells are located because it was very soft.

The results show that pyrite is mainly found in the till and the very top of the Chalk and that decreasing amounts of pyrite is found with depth. Measurements of the sediment reduction capacity by the Ce-method show a higher reduction capacity compared to the content of pyrite, indicating that reducing components as organic matter and other Fe(II) minerals are present, especially in the till and upper Chalk. Below 40 m the very low content of pyrite around 1 ppm indicate that injection of oxidized water will not be influences significantly by pyrite oxidation.The contents of some of the potentially problematic trace elements related to the pyrite content is shown in Figure 11. The amounts correlate well with the measured pyrite content, indicating that most of the trace element content is derived from the pyrite during the extraction. The content of trace elements in the pyrite in the Chalk is low, even for the highest As where the content in pyrite is only 0.5 ‰ by weight. In the Chalk as such, the maximum content of As in pyrite is 1 ppm. These low contents indicate that the release of problematic trace elements due to injection of oxidized water will be small.

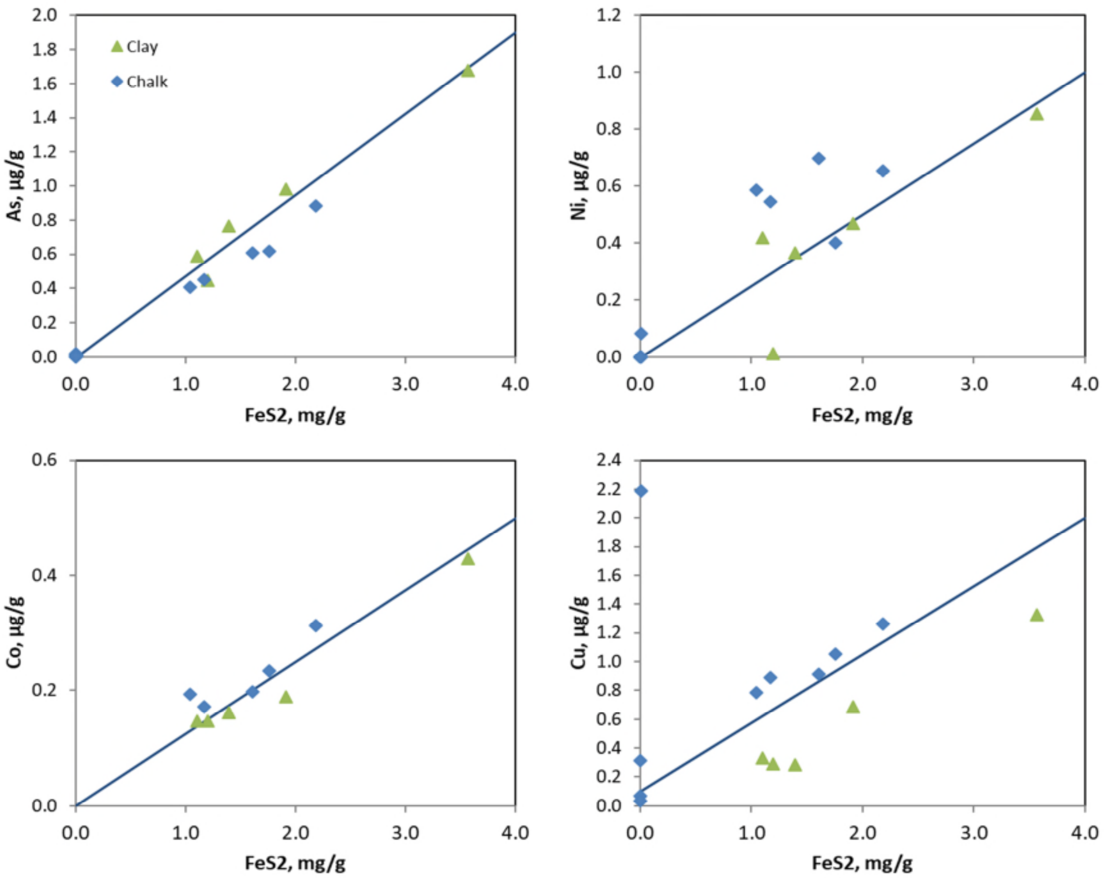


Figure 11. Concentration of As, Ni Co and Cu in pyrite from clay till (green triangle) and Chalk (blue diamond) as a function of the FeS_2 content.

Geochemical reactions and the potential for nitrate reduction

The reduction capacity of the Chalk was investigated further in batch experiments at GEUS. The experiments were set up to study the rates of oxygen and nitrate reduction by the upper Chalk and to elucidate which minerals contribute to the reduction. Batches was set up inside an anaerobic glovebox with sediment from 14 meters below surface (research well DGU no. 242.375). The sediment primarily consist of Chalk and the core material at this depth have a higher reduction capacity compared to deeper parts of the Chalk aquifer (Figure 10). Water was added to the batches with either 10 mg O2/L or 20 mg NO3/L + 10 mg O2/L. In parallel, control-batches was run without sediment. The concentration of oxygen was monitored daily and samples were taken four times during the 147 days long experiment (at the end of each cycle). The supernatant was analyzed for Fe2+ (spectroscopy), anions (ion-chromatography), cations and trace elements (ICP-MS) and alkalinity (gran titration). Water with either 10 mg O2/L or 20 mg NO3/L + 10 mg O2/L was added to the batches after sampling to minimize the headspace, except after the third sampling, were the headspace was filled with atmospheric air to introduce a large oxygen pool to the batch experiment. The first cycle was conducted at 4°C (24 days) and the remaining cycles at 10°C (14, 34 and 75 days respectively).

The result of the batch experiment show that oxygen is consumed in the batches while the nitrate concentration remains stable throughout the experiment (Figure 12). It can also be noted that the reduction rate of oxygen is faster at 10°C than 4°C.

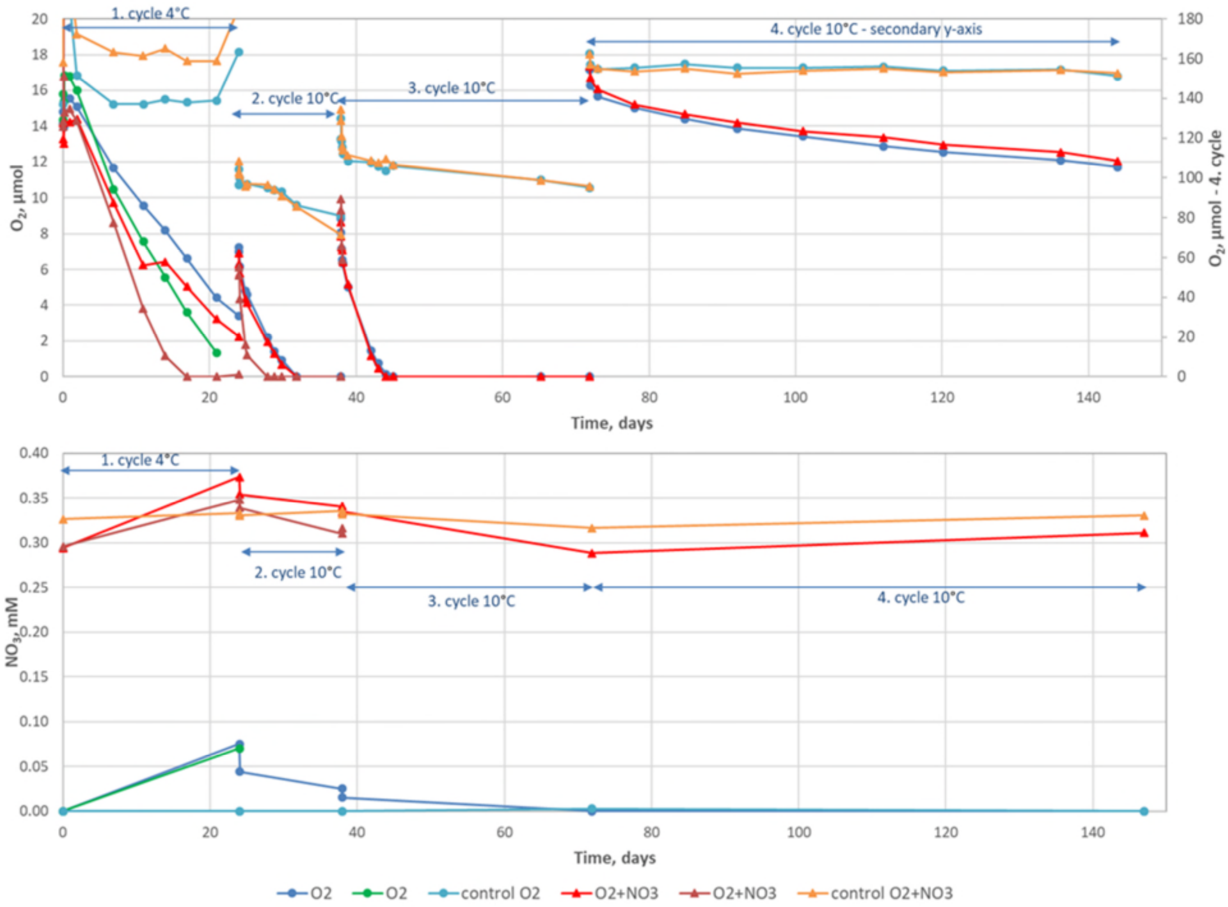


Figure 12. Oxygen (O2) and nitrate (NO3) in batch experiments with Chalk from 14 meters below surface in well 242.375. Batches amended with either O2 or O2+NO3. The oxygen is consumed during each cycle while nitrate remains stable.

The reduction potential of the Chalk is larger than the pyrite content, indicating that reducing components as organic matter and Fe(II) minerals are present in the chalk (Figure 10). Complete oxidation of pyrite with oxygen produces sulfate and iron oxides:

The sulfate concentration increases throughout the experiment as seen in Figure 13. The increase in sulfate concentration during the 2nd and 3rd cycle matches the consumption of oxygen in a ratio of 2 SO4 to 15/4 O2 in accordance with the equation above. Fe(II) was not detected throughout the experiment, supporting that oxygen was reduced by complete pyrite oxidation.

In the 4th cycle less sulfate is released than expected from pyrite oxidation. At the end of the experiment roughly 10% of the pyrite initially present in the sample was oxidized. Thus, the lower sulfate concentration is not due to lack of pyrite. Precipitation of sulfate containing minerals as gypsum (CaSO4) would reduce the sulfate concentration, but the water is sub saturated with respect to gypsum. The lower sulfate concentration in the 4th cycle could indicate that other minerals than pyrite contributes to the reduction of oxygen.

At the end of the 1st cycle the concentration of sulfate is much higher than can be related to pyrite oxidation with the oxygen consumed. The initial concentration of sulfate is not known, but calculations of the expected concentration based on the sulfate concentration in the groundwater estimates a staring sulfate concentration of 0.006 mM. It is speculated that the initial sulfate concentration might have been significantly higher than the 0.006 mM due to pyrite oxidation in the core between sampling and setup of the batch experiment.

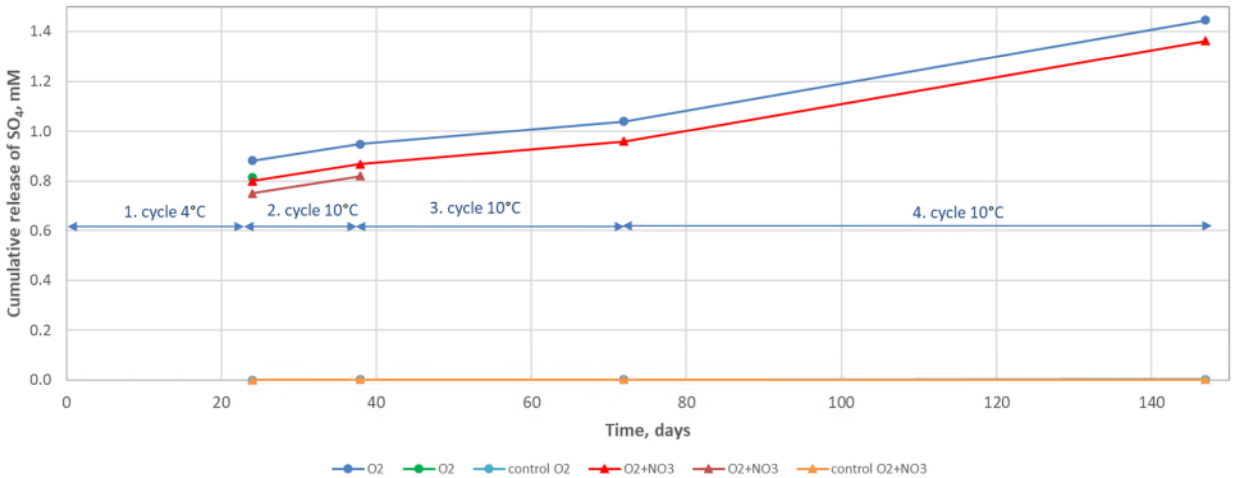


Figure 13. Cumulative release of sulfate (SO4) during batch experiments with chalk amended with either O2 or O2+NO3. Similar release of sulfate is seen in the batch with O2 and the batch with both O2 and NO3

During the batch experiments the concentration of trace metals was measured (Figure 14). Dissolution of pyrite indicate that As, Co and Ni is related to the pyrite content (Figure 11). In the batch experiments the concentration of As, Co and Ni are all below the guideline limit for drinking water. The concentration of Ni and Co decreases during the experiment, while the As concentration increases. The formation of iron oxides as a result of the complete pyrite oxidation likely acts as a sorbate for the trace metals thus lowering the concentration of trace metals in the water.

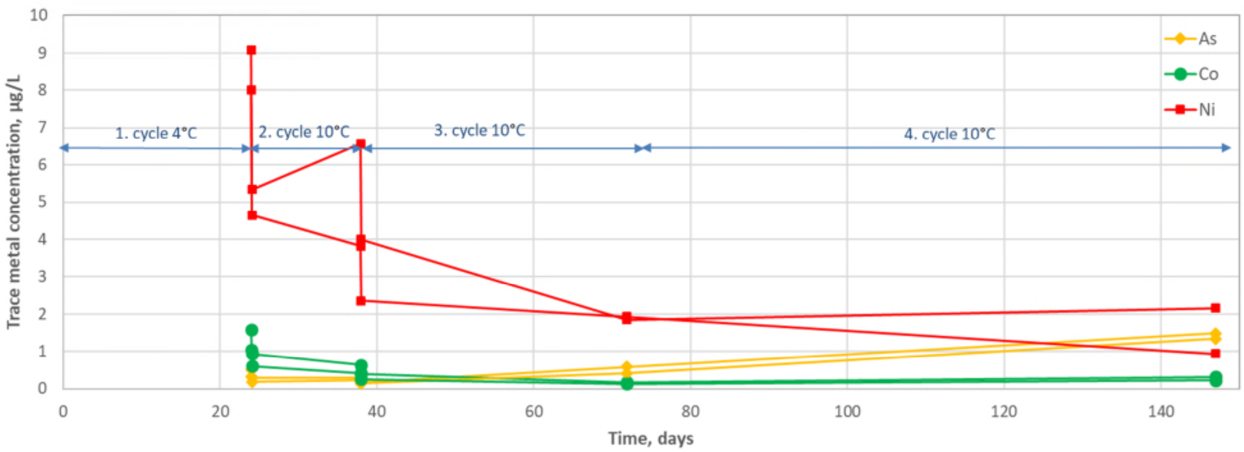


Figure 14. Concentration of As, Co and Ni in the batch experiments.

The batch experiments were conducted with core material from the upper Chalk, where the last glacial advance in the area strongly affected the upper part of the Chalk. This part of the Chalk have a higher reduction potential than deeper parts of the Chalk (Figure 10). Oxygen, but not nitrate, is reduced by minerals in the Chalk, primarily pyrite. There is no significant capacity for nitrate reduction in the Chalk in the Marielyst area (Figure 12). Hence, the aquifer does not seem to constitute a potential mitigation measure for excess nitrate loadings from agriculture e.g. by injecting nitrate containing surface waters in the deeper brackish coastal part of the Chalk before discharge to the sea.

Risk of clogging

The geochemical analyses of the chalk and the batch experiments have identified pyrite as the reductant responsible for oxygen reduction in the Chalk. The pyrite does not seem to have a nitrate reduction potential (Figure 12), but reduction of pyrite produces iron oxides - Fe(OH)3, which on the long term may cause clogging problems in the screen of the injection well. Further studies are however needed to estimate the time scale for this process.

Pumping tests

Several short and long term pumping tests have been conducted in at the test site in November/December 2016, January 2017 and April 2017. The conducted pumping tests indicate conductivities that vary significantly from a few meters /day and up to 172 meters/day most probably dependent on the amount of hydraulic active fractures affecting the water flow in the tested volume. New wells drilled later revealed a glacitectonite with a high hydraulic conductivity around 15 m depths. The pumping tests indicate K-values both higher and lower than the results obtained from the Geoprobe test mentioned in section 2 (up 30 m/day).

Tracer tests

The Setup applied for the performed tracer tests are illustrated in Figure 15. The idea in the setup is to contain the injected tracer within a surrounding dipole flow field, enabling experiments with different flow velocities to assess the interaction between transport in fractures and diffusion into the surrounding matrix.

The tracer tests were conducted with NaBr and NaCl in separate tests. NaBr and NaCl were added to an approximately 600 l container to obtain electrical conductivities of around 5000 and 7000 µS/cm, respectively. The temperature of the injected water was increased to 27/29°C in order to minimize the density effect of the increased salinity. The temperature needed to obtain the same density as the water in the aquifer was calculated using the geochemical program PHREEQC. The CMT 1 and CMT 2 wells (Figure 16) were pumped continuously at a low flow rate of 20-60 ml/min from all 14 screened intervals during the entire tracer test.

Figure 15. Injection of tracer into T1 just left of the green cover, through thin white hose – about 1 meter from the WSP no. 9 below the green cover. Blue hose injects water pumped from UB2 into UB1 to create the dipole flow field between UB1 and 2 Illustrated in Figure 14. The manifold on top of the green cover is for removing air from the water prior to injecting it. The transparent plastic tube going into T1 was filled with water after the tracer injection to expel the volume of water in the well to avoid effects of the borehole during the tracer movement.

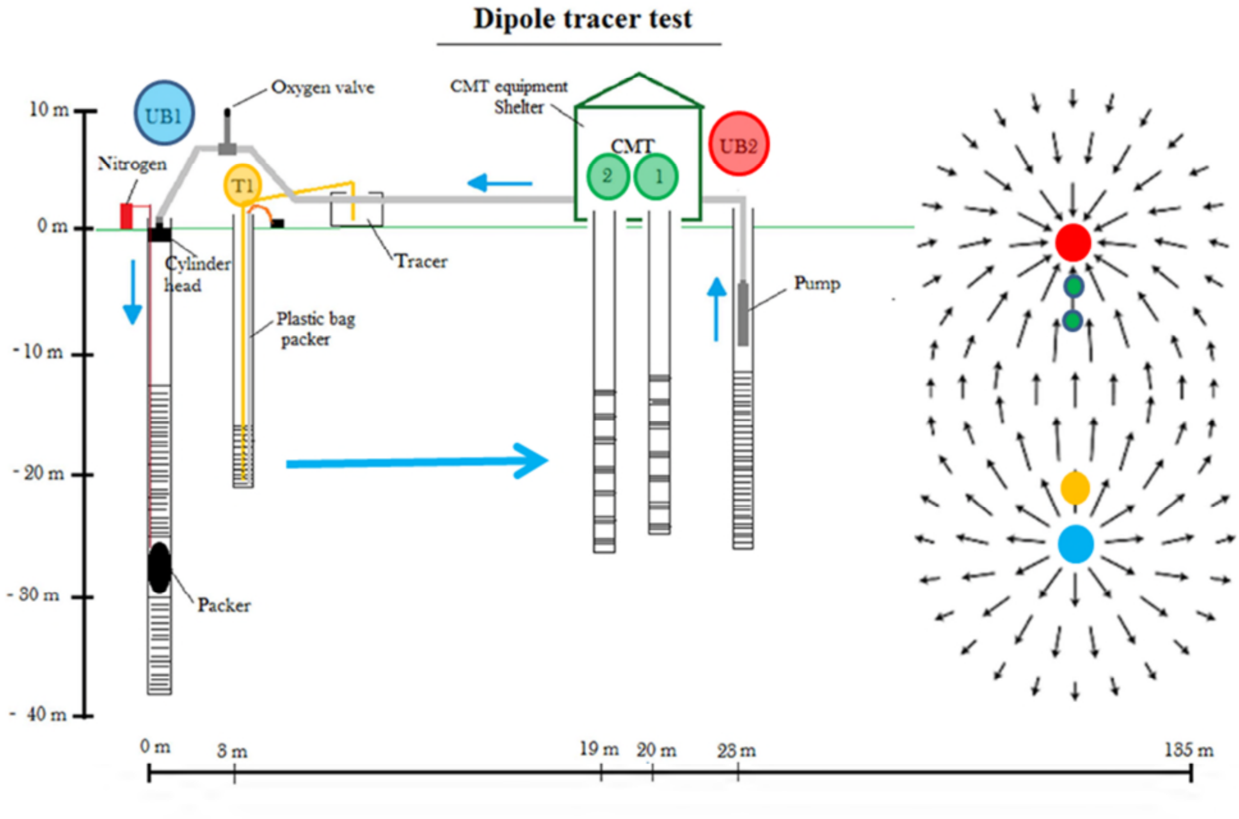


Figure 16. The developed test site indicating the setup for the conducted dipole tracer tests using NaBr, NaCl and tempe rature as tracers. Color markings on the wells in the cros-section to the left corresponds to the plan view of the intended flow field on the right. Blue arrows in the left diagram show the water movement. The water supply well of Marielyst Waterworks is situated between UB1 and T1 in the left side of the figure.

The results from the tracer tests indicate that most of the tracer diffuses into the matrix making it difficult to say whether we succeeded in actually seeing the tracer as it passed by wells CMT 1 and CMT 2.

On-line monitoring of salt water intrusion ("salinity") and SCADA/PLS

The SubSol project is currently testing on-line monitoring systems delivered by two different environmental consulting companies COWI (www.cowi.com) and We-teco (www.we-teco.com). The two monitoring systems monitored salinity, temperature and water table variations in the tracer injection well (T1) at a depth of 17 m, and in the deepest monitoring well (UB1) at a depth of 35 m; 1 and 3 meter from the water supply well, respectively. The monitoring station for T1 was established by COWI in November 2016, while the We-teco station has been monitoring since April 2017. Results from the the monitoring station in T1 can be found at:

http://www.gwm.cowi.dk/GWM/Projects/GEUS/index.htm , (brugernavn = GWM_GEUS, password = Fa_Con_1415)

while the data from the station in UB1 are shown here: https://thingspeak.com/channels/250041.

The monitoring station established by COWI above was terminated during spring 2017 due to relatively high costs and little flexibility (it was not possible to download data on-line etc.).

Data from and similar to the data from the two stations are required for developing the automated control system for controlling the investigated SWS techniques. Development of the planned SCADA/PLS system by the company Blue Control (in collaboration with Orbicon and GEUS) is somewhat delayed due to loss of key employees at both Blue Control and Orbicon (see remaning work section).

Chloride sensors have not been deployed in this study although it was anticipated in the original application as 1) previous test of these were not satisfying (Hinsby et al., 2016), 2) the developer has left his university position and 3) electrical conductivity sensors generally suffice for salt water intrusion monitoring.

Discussion and conclusion on preliminary results

The conducted investigations show that the upper 10-20 meters of the chalk where the water supply wells abstracts water for the water works are strongly affected (crushed and displaced) by glaciotectonics at the study site. The preliminary results indicate that these processes have a strong influence on the hydraulic characteristics of the Chalk in a way that makes the variation of the hydraulic conductivity highly unpredictable and also that the upper Chalk may be divided into two domains with different hydraulic characteristics. It seems that parts of the upper 10-20 meters may behave similar to a single porosity medium and that other parts behave in the expected way as a dual-porosity fractured media as the Chalk generally does in North-Western Europe (Downing et al. 2005). From the assessments of the currently conducted investigations we believe that the location of these two domains are highly unpredictable and variable both horizontally and vertically due to the character of the glacial dislocations and erosion. Further studies in SubSol will evaluate the effects and significance of the glaciotectonical impacts, and explore effective solutions to deal with this complicating factor.

Hydrogeology, final test site design and tracer tests

Due to the difficulties in getting clear data from the first tracer tests it was concluded that it would be necessary to install 1-2 new tracer injection/observation wells closer to the two CMT wells and carry out an additional tracer experiment. This was required to obtain results, which can be used for assessment of the hydraulic conditions of the part of the chalk, which was most impacted by glaciotectonics. The best location of these wells was discussed and evaluated, resulting in the drilling of two new investigation wells that reduce tracer travel distances and increase the chance of recording tracer breakthroughs.

Design of final test site with two new investigation wells

The final design of the test site is illustrated in Figure 17

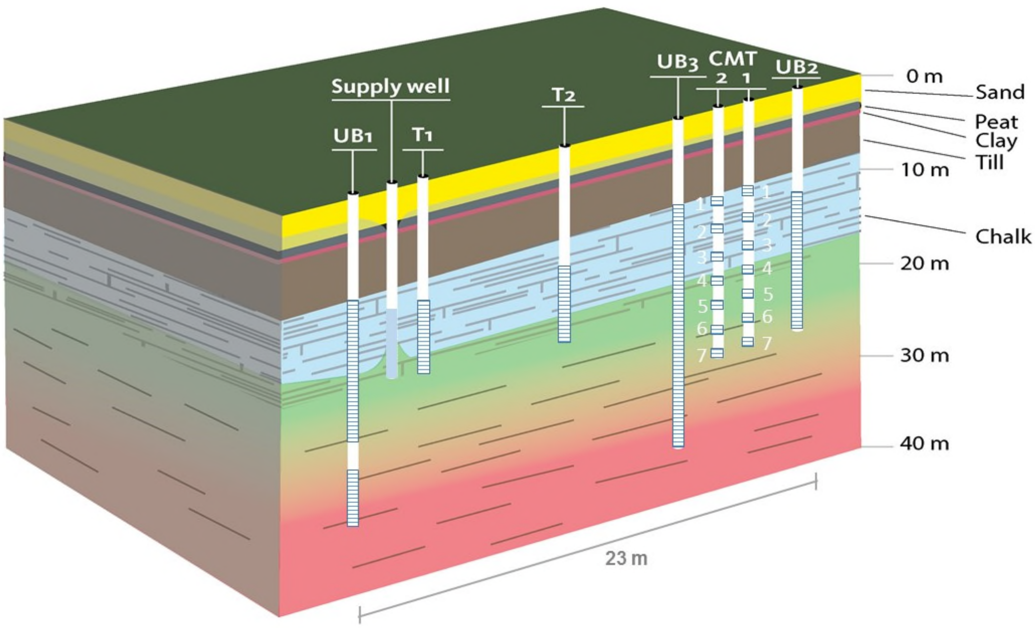


Figure 17. Design of the final test site. The NaCl tracer solution heated to 27 degrees Celsius to compensate for density differences was injected in T2 in the dipole set up illustrated in Figure 16 and tracer breakthroughs were observed in the multi-level screens of CMT1 and 2.

Glaciotectonics, geological complexity and interpretation of new wells

Detailed descriptions of the collected geological samples were made during the drilling of the two new wells in the test site, T2 and UB3, located as indicated in Figure 17.

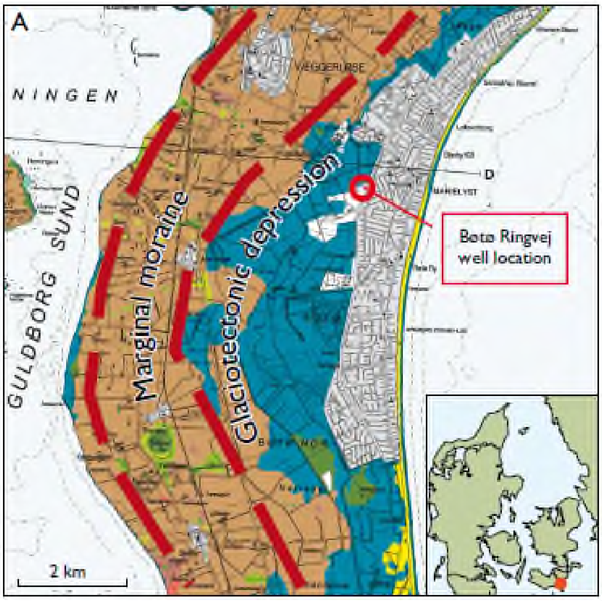


Figure 18. Geological map around the test site and new well locations (red circle) demonstrating the geological glacial geological setting (Pedersen et al., 2018).

The geological descriptions performed during drilling of the two new wells clearly identified glaciotectonical impacts on the Chalk aquifer and the presence of a Chalk-glacitectonite at 15-18 meter below surface strongly affecting the hydraulic characteristics of the upper approximately 30 meters of the Chalk in an unpredictable way without very detailed investigations of numerous wells.

Figure 19 shows geological logs of the two new wells with indication of the glacitectonite, which according to the latest tracer test have significantly higher hydraulic conductivity than the surrounding layers.

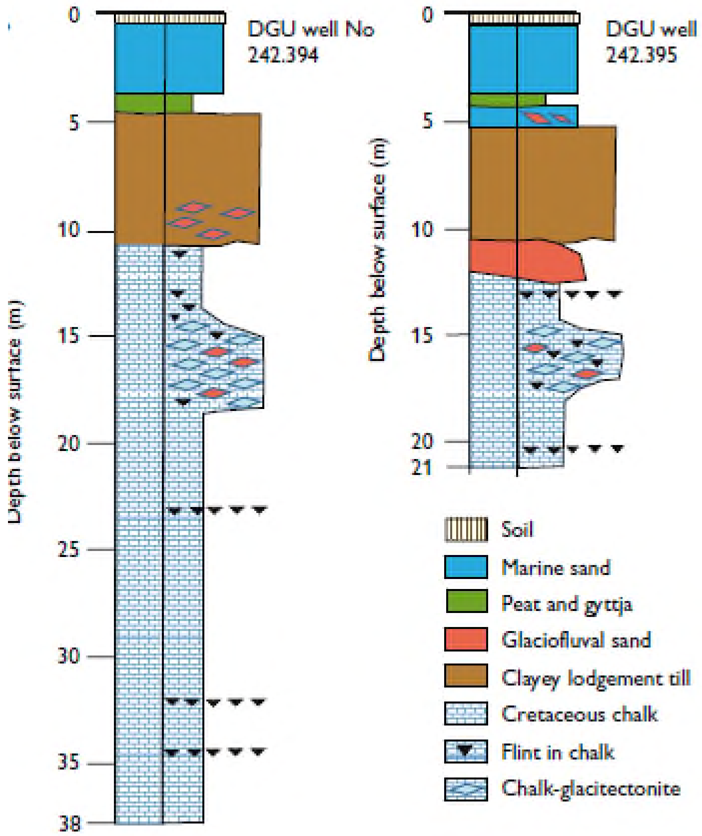


Figure 19. Geological logs of the two new wells drilled in the test site. The location of the glacitectonite at about 15-18 meter below surface is indicated.

Final tracer tests

The tracer tests were carried out inside a surrounding dipole flow field (Figure 16) as the first test, using the same two wells for pumping and injection, but the tracer was injected closer to the CMT sampling wells at a distance of 9 m. In addition to being closer, this position should also bring the tracer injection into the converging part of the flowfield, further decreasing the chance of tracer leaving the test field. However, on the background of the first tests it was assumed that it might still be difficult to see a clear breakthrough, so it was chosen to use a NaCl solution, giving a higher electrical conductive (EC) signal at the same concentration (by weight) than NaBr. As previously, the injected water was heated to 27 °C to compensate for the density effect and a long plastic tube in the tracer injection well was filled with water after the tracer injection to limit effects of the borehole as the upstream part of the plume moves past the borehole.

During the tests the EC was logged in 12 of the 14 screens in the two CMT wells. All the screens were pumped continuously during the tests using two multi-channel peristaltic pumps. Logging of EC was done on water from all the pumped screens at 30 minute intervals using a Campbell Scientific logger that also controlled a manifold with 3-way valves. The manifold made it possible to sequentially direct water from the individual pump channels (well screens) to the EC-meter and evacuate the manifold tubing between samples to avoid carry over effects.

Water samples were taken from the screens giving the most prominent EC breakthrough. The sampling intervals were adjusted in response to the EC readings. All samples were analyzed for anions by ion-chromatography and most samples for cations by ion-chromatography, Fe on atomic absorption spectroscopy and trace elements on ICP-MS. In addition, for some samples the alkalinity was determined by Gran titration and selected samples are analyzed for water-isotopes by Cavity Ring-down Spectroscopy (Picarro).

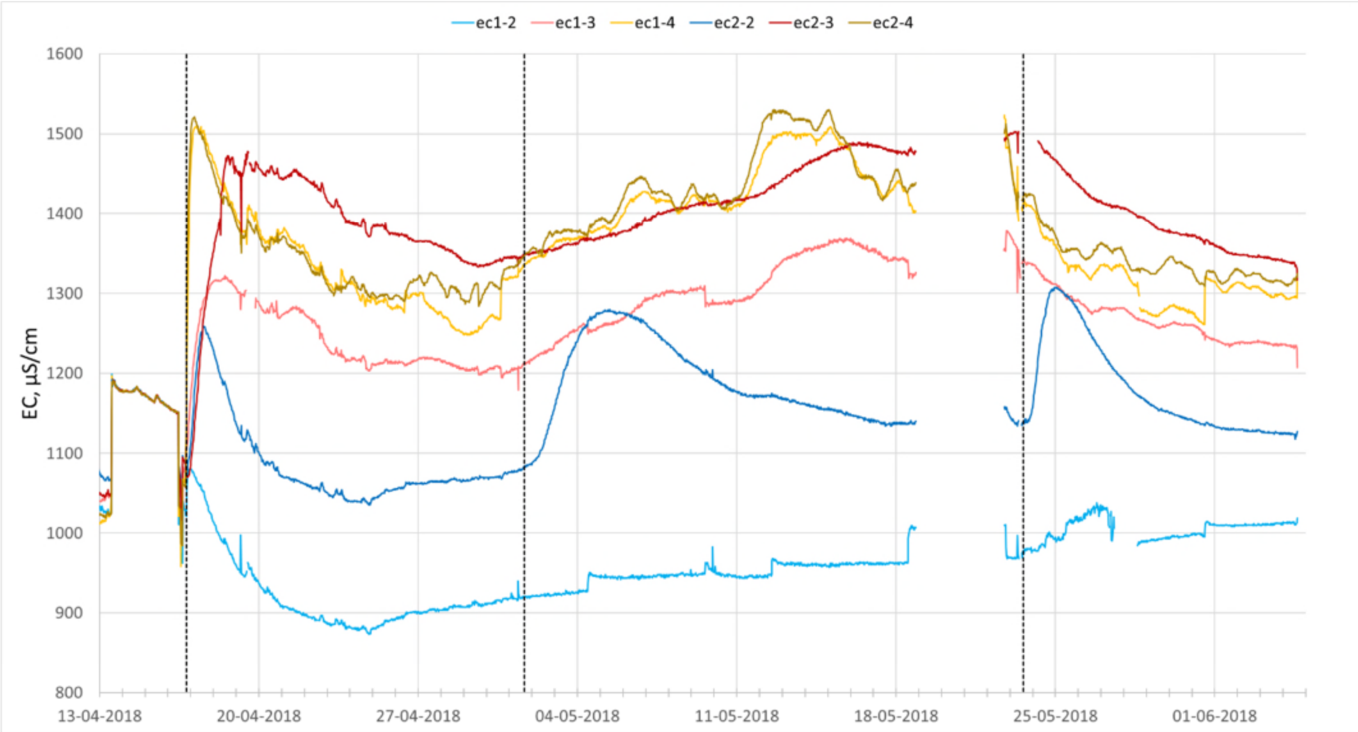
Conducted tests in the third tracer test program

The first test using the new tracer injection well was carried out with a high pumping rate of 13 m^3/h and a reinjection rate of 6.7 m^3/h, assuming that the high pumping rate implied the highest probability of seeing a breakthrough. After seeing that a breakthrough occurred, a second test was carried out with pumping and injection rates set to ~40% of the pumping and reinjection rates for the first test (4.9 m^3/h pumped and 2.6 m^3/h reinjected). Finally a third test where the pumping rates were set to ~70% of the rates in the first test was made (9.1 m^3/h pumped and 5.3 m^3/h reinjected). By making the tests at different flow rates, it should be possible to better constrain parameters for the diffusive exchange of solutes (the tracer) between the fractures where the major transport is assumed to take place and the chalk matrix, where the water is presumably close to stagnant.

Breakthrough of tracers in the third tracer tests

Results from the twelve CMT screens monitored during the full test period, comprising all three tracer injection test are plotted in Figure 20. They are divided into two groups, the shallow and the deep screens.

A)



B)

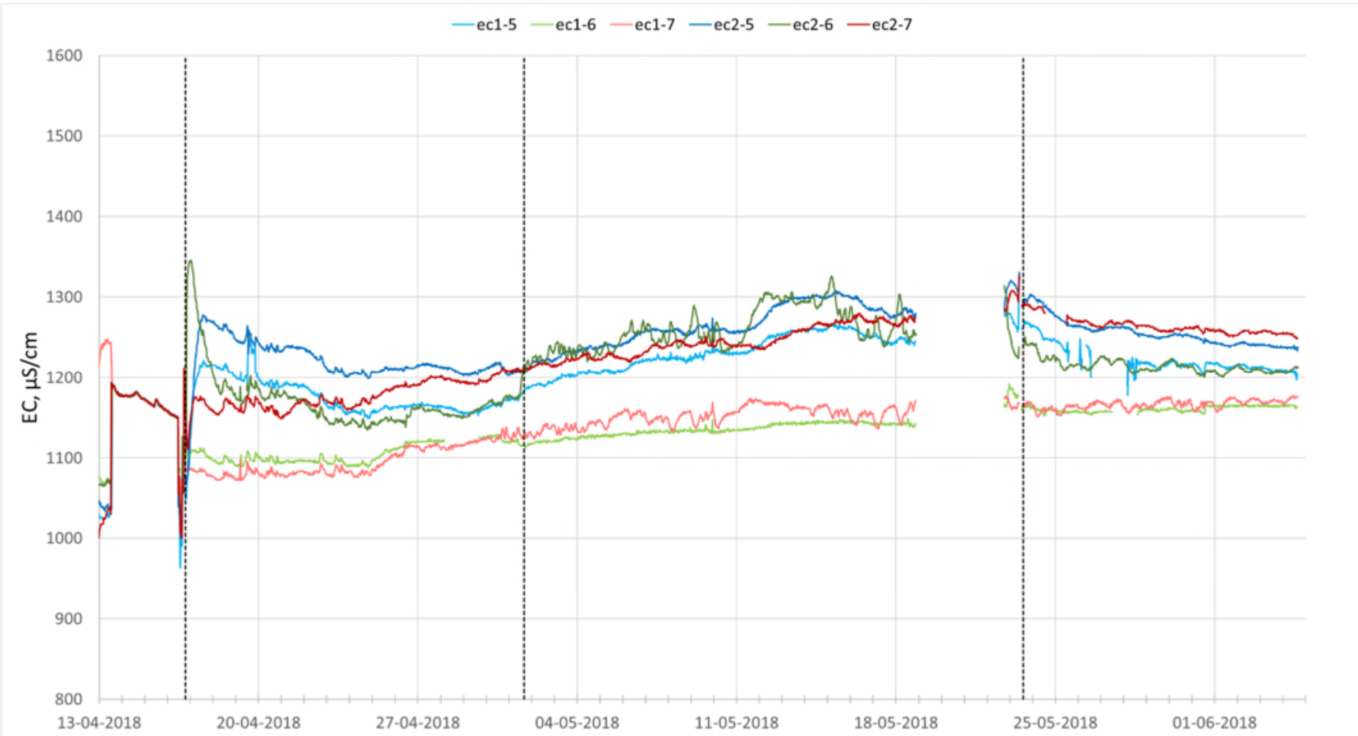


Figure 20. A) Plot of the measured EC in the upper 6 screens of CMT1+2. B) Plot of the measured EC in the lower 6 screens of CMT1+2. Vertical lines indicate the time of tracer injection for the three test. The screens

are numbered 1-7 from top to bottom in both CMT1 and CMT2 (Figure 17) i.e. screen ec1-7 and ec2-7 are the deepest screen in CMT1 and CMT2, respectively.

The upper screens in Figure 20A show very clear and for some of the screens, very fast breakthroughs for the first tracer injection with the high pumping and injection rate, but it is worth noting that the shape of the breakthrough curves varies considerably. There is no obvious relation between screen depths or distance to the tracer injection well in terms of what peaks are sharp and which are more flat. For the lower screens, Figure 20B, three screens show clear fast breakthroughs, the other screens indicate that there may be a delayed breakthrough on the 26th of April approximately 7 days after the injection. It appears that a similar bump is seen on several other curves, also for the upper screens. This could indicate that part of the tracer has taken a different, less direct route to reach the pumping well.

The breakthrough curves for the second injection with the lowest pumping rates shows a very different pattern. Only the CMT2-2 screen shows an obvious breakthrough. The peak is much broader but the peak height is similar. The broader peak is what would be expected at a lower flow rate, allowing more time for diffusion of tracer into the matrix. This on the other hand should lead to a lower peak height, but this is not the case. There is a bump approximately 9 days after the second tracer injection, both in some of the shallow and the deep screens. This is perhaps comparable to the bump after approximately 7 days after the first injection. Considering that it is more pronounced it could indicate that a larger part of the tracer has traveled along an alternative route at the low flow rate.

For the third and last test, it is again CMT2-2 that shows the most pronounced breakthrough. The peak shape is, as expected, an in-between of the first and the second peak slightly delayed compared to the first peak and more narrow compared to the second peak.

Further analysis of the breakthrough curves are made in connection with the numerical modelling.

Results of the hydrochemical analyses

During the final tracer tests water samples were collected with the following purposes

1. To confirm and supplement the breakthrough curves observed in the electrical conductivity (EC) measurements.
2. To determine whether the increase in electrical conduktivity in the deepest screen is due to the tracer test or due to up-coning from deeper parts for the chalk aquifer.
3. To determine whether trace metals are mobilized during the tracer tests.
4. To indicate whether the increase in salinity in the abstraction wells under normal operation is due to intruding saltwater from the Baltic Sea during Holocene age or due to incomplete leaching of residual saltwater in the chalk aquifer.

In total, 97 water samples were collected, primarily from the two CMT wells, but also samples from the Baltic Sea, from well 242.375 40 m b.g.s. (100 m from the Baltic Sea) and from well 242.344 85 m b.g.s. (in the middle of Falster Island 2.8 km from the Baltic Sea). The samples selected for additional analysis are chosen such that development over time is monitored in three screens (Fig.21) and depth profiles are monitored before, during and after the third tracer injection, with three additional samples representing the conditions before the final tracer tests (Fig.22).

Electrical conductivity and major ions

On an overall level there is correspondence between the variations in the measured chloride concentration and the measured electrical conductivity confirming the breakthrough curves from the tracer tests observed with the electrical conductivity measurements (Fig. 21).

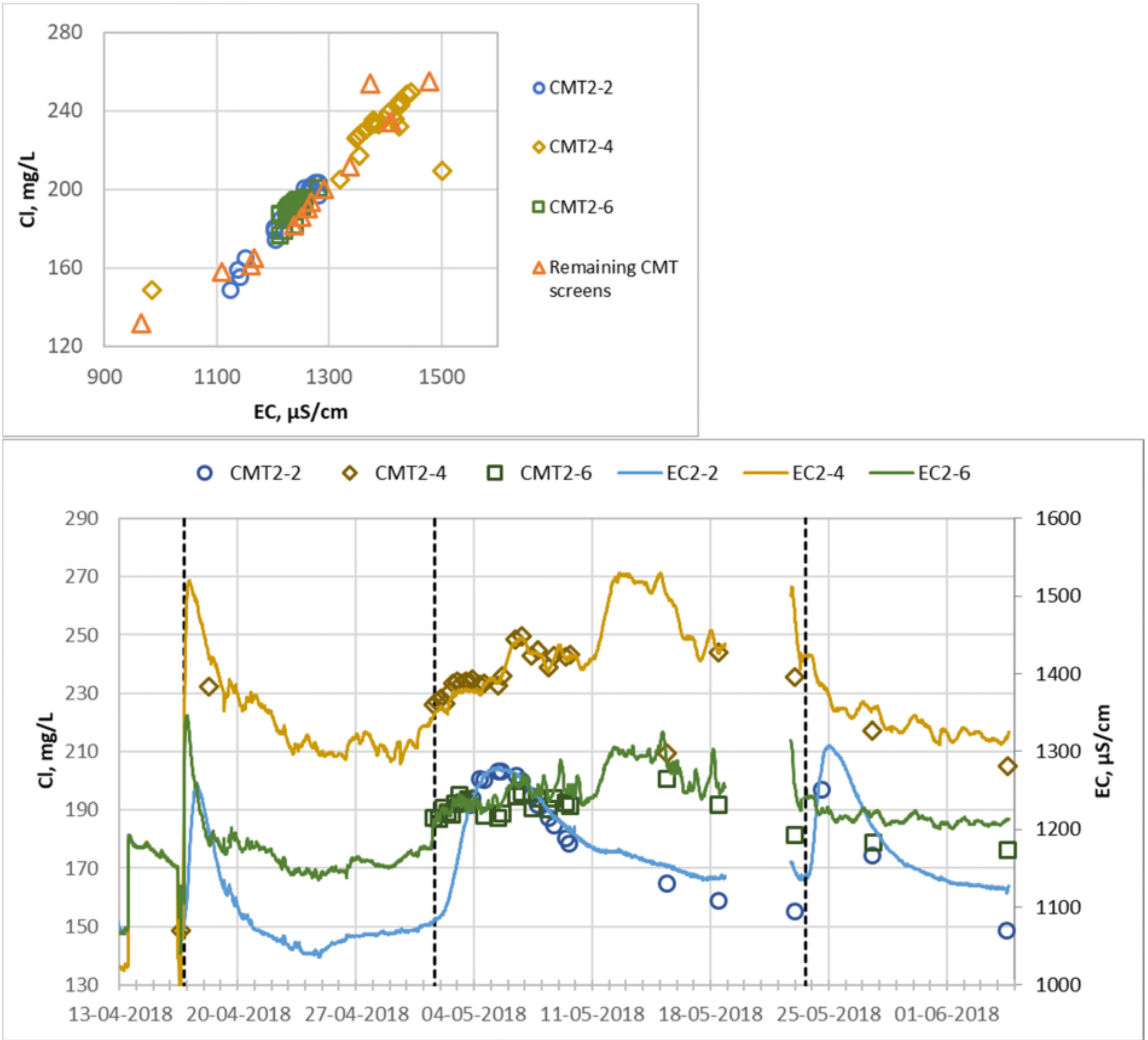


Figure 21. Top panel: Correlation between electrical conductivity (EC) and chloride. Bottom panel: EC and chloride concentration during the final tracer tests. Vertical lines indicate the time of tracer injection for the three tests.

Depth profiles for chloride, bromide and sulfate are shown in Fig. 22 before the final tracer tests, before the third tracer injection, four days and twelve days after the third tracer injection. Before the final tracer tests chloride and bromide increases with depth. As a result of the tracer tests a bell shaped concentration profile is created for both chloride, bromide and sulfate indicating that the zone from 15 to 20 m b.g.s. is more hydraulically active.

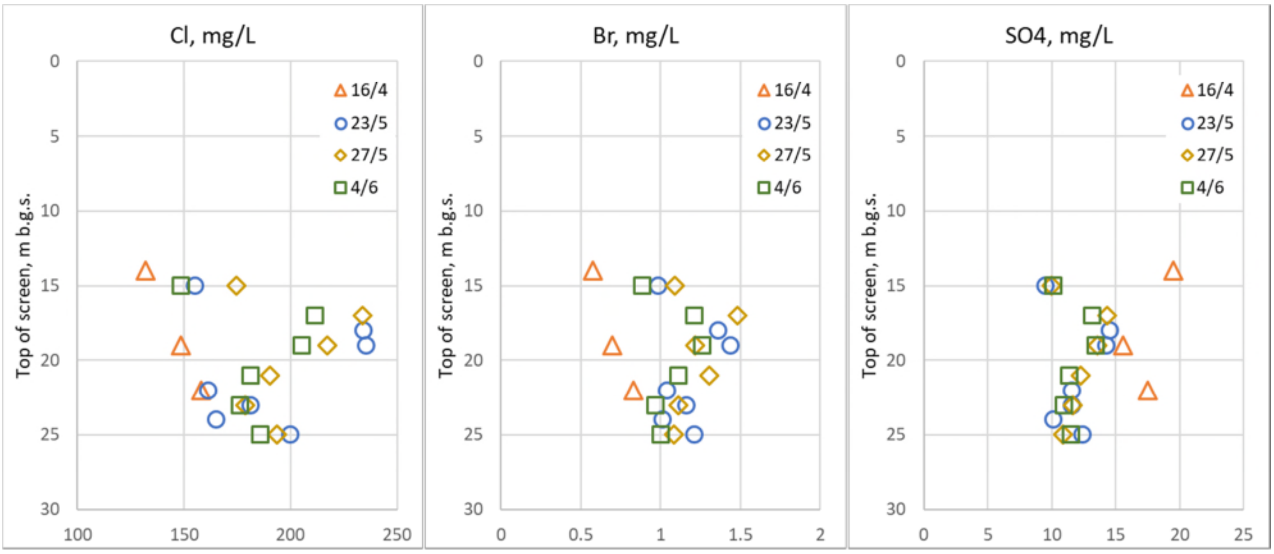


Figure 22. Concentration of chloride, bromide and sulfate over depth before the final tracer tests (16/4), before the third tracer injection (23/5), four days (27/5) and twelve days (4/6) after the third tracer injection.

The injected water for the tracer tests was abstracted from a nearby well with similar water chemistry and the geochemical changes as a result of the tracer test was expected to be minor and mainly related to ion exchange. There are no signs of pyrite oxidation as a result of the tracer test as the sulfate concentration decreases during the test compared to concentrations before the test started (Fig.22). This is also confirmed by the relatively stable concentration of sulfate observed throughout the tests (Fig. 23). The increase in iron concentration in the water from CMT2-2 (Fig. 23) observed after the second tracer injection is therefore not related to incomplete pyrite oxidation, but might be due to ion exchange. Considering the low background concentration of iron, the iron concentration could be very sensitive to ion exchange.

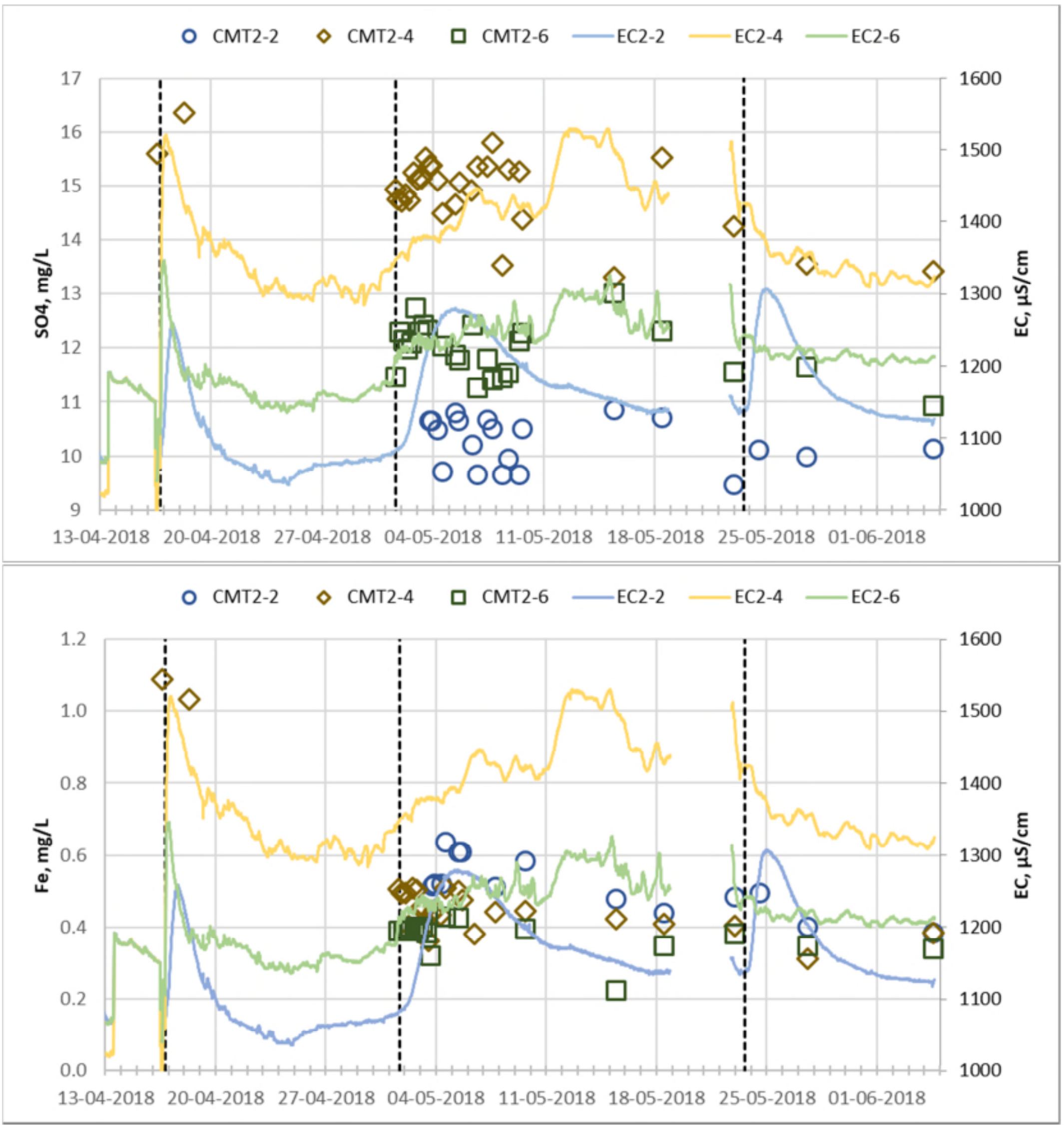


Figure 23. Sulfate concentration and electrical conductivity (EC) (top panel) and iron concentration and EC (lower panel) during the final tracer tests. Vertical lines indicate the time of tracer injection for the three tests.

Increase in electrical conductivity in the deeper screens

The electrical conductivity (EC) showed a continuous increase in the deeper screens throughout the final tracer tests (Fig 20B). As this can be a sign of up-coning of salt water from the deeper part of the Chalk aquifer, it is relevant to look further into this. Based on the water chemistry there is no indication of up-coning. The chloride concentration in the water from screen CMT1-6 does not change from before the first tracer injection (158 mg/L) to just before the third tracer injection (161 mg/L) despite an increase in electrical conductivity from 1108 µS/cm to 1160 µS/cm (Fig 24). Generally, in all screens an increasing difference between the electrical conductivity and chloride concentrations is observed just before and throughout the third tracer injection (Fig 21 and 24). The continuous increase in EC in the deeper screens as well as a continuous increase in the baseline EC of the upper screens might be due to wear on the EC electrodes or perhaps the forming of Fe-oxide coatings on the electrodes.

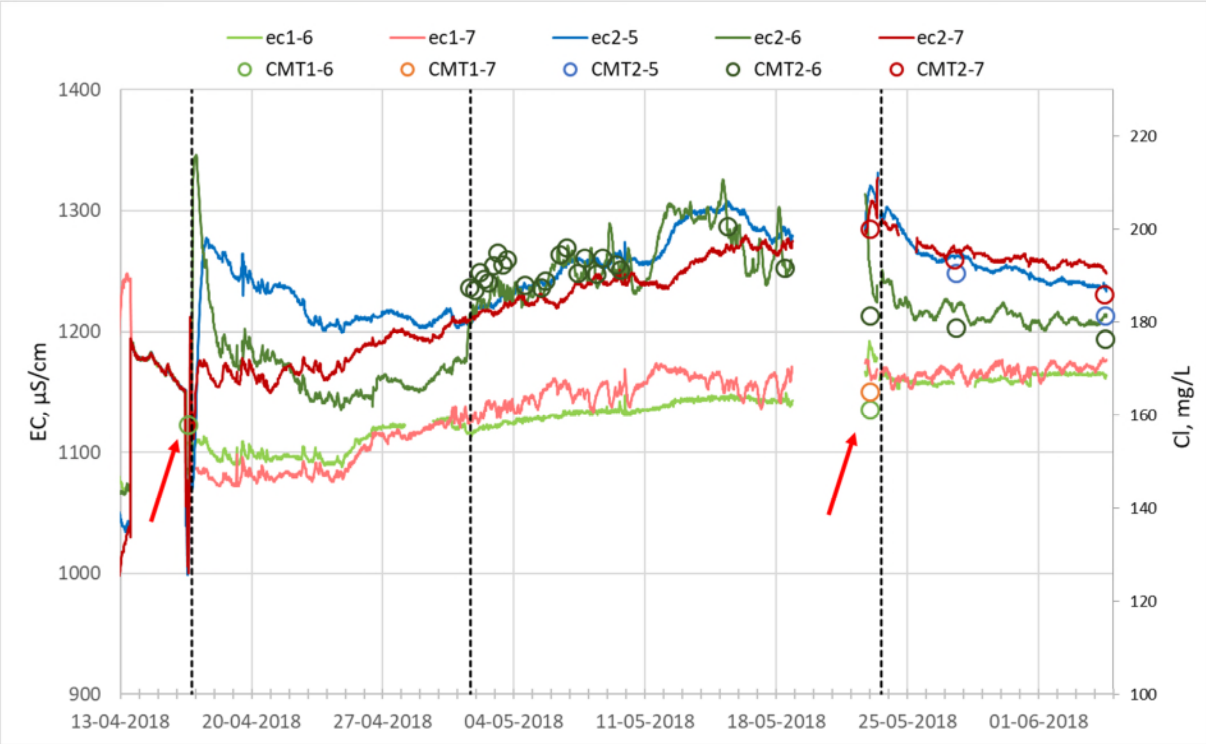


Figure 24. Electrical conductivity (EC) and chloride concentration during the final tracer tests in the five deepest screens. Vertical lines indicate the time of tracer injection for the three tests. The red arrows highlight the chloride concentration in the water from CMT1-6.

Mobilization of trace elements

Release of trace elements is mainly expected to be related to pyrite oxidation, as shown in studies of the Chalk from the Falster site (Figure 12). There are no indications of pyrite oxidation during the tracer tests (Fig 22 and 23) and release of trace elements is therefore not expected. Samples for trace element analysis were collected before and after the three tracer injections. Generally trace element concentrations are low (As < 5 µg/L, Cd < 1 µg/L, Co < 2 µg/L, Cu < 5 µg/L, Pb < 1 µg/L). The nickel concentrations before the final tracer tests are 5-13 µg/L and decrease to <5 µg/L during the tracer tests. Thus, there are no signs of rapid mobilization of trace metals during the tracer tests.

Dissolved trace elements and strontium isotopes as possible indicator of salinity sources

In the following we discuss and assess the source of the increasing salinity, whether it is due to intruding saltwater from the Baltic Sea during Holocene or due to incomplete leaching of residual saltwater in the chalk aquifer based on trace element contents and stable isotopes.

71 ground water samples were taken at different depths between 14 and 26 m in selected screens of the monitoring wells CMT1 and CMT2, which both have seven screens. The samples were collected in the period from May 1st to June 4th 2018 during the third tracer test. Further, 4 samples representing marine water from the Baltic Sea (at Marielyst) were analyzed for comparison together with two samples representing deeper groundwater (40 and 85 m in two other wells within a distance of 1 km from the test site (DGU nr. 242.375 and DGU nr. 242.344, respectively).

The samples were analyzed at GEUS using ICP-MS with the “total quant” method and the “trace element” method respectively to obtain the optimal analytical resolution. Analyzed elements were: Al, As, B, Ba, Ca, Cd, Ce, Co, Cr, Cs, Cu, Dy, Er, Eu, Fe, Gd, Ho, K, La, Li, Lu, Mg, Mn, Mo, Na, Nb, Nd, Ni, P, Pr, Rb, Sb, Sc, Se, Si, Sm, Sr, Tb, Th, Ti, Tm, U, V, W, Y, Yb, Zn & Zr.

The content of elements like Sr, Zn, Mn and Co varies among the different depth levels in the wells, and water from each level has its own characteristic levels. It is possible to clarify the differences by combining these with Mg producing distinct “geochemical fingerprints” or clustering for the different levels (Figure 25).

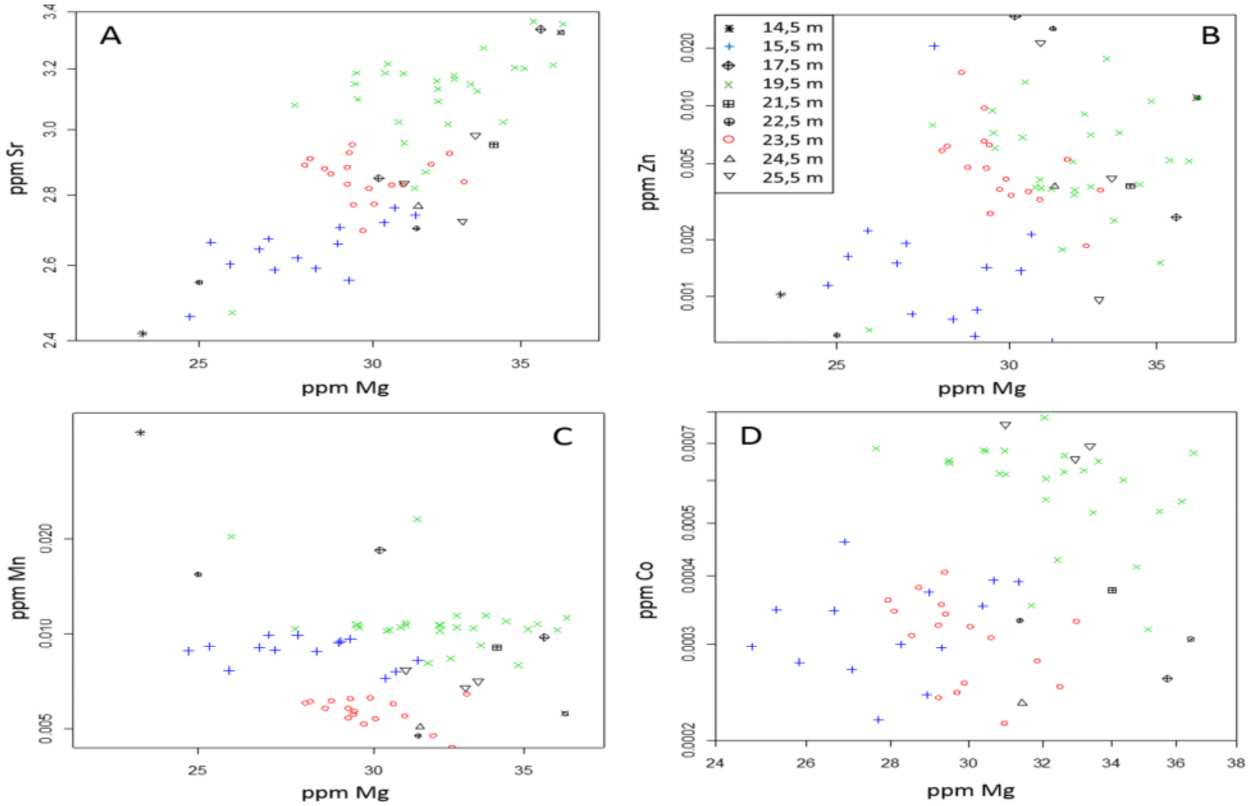


Figure 25. Sr, Zn, Mn and Co versus Mg concentrations (ppm). Depths of sampling points are shown in the legend (B).

For some parameters and some levels there is a development over time. The content of Co and Mn in e.g. the filter between 19 and 20 m (green) is more or less constant for a the first weeks, but then starts to decline (Figure 26).

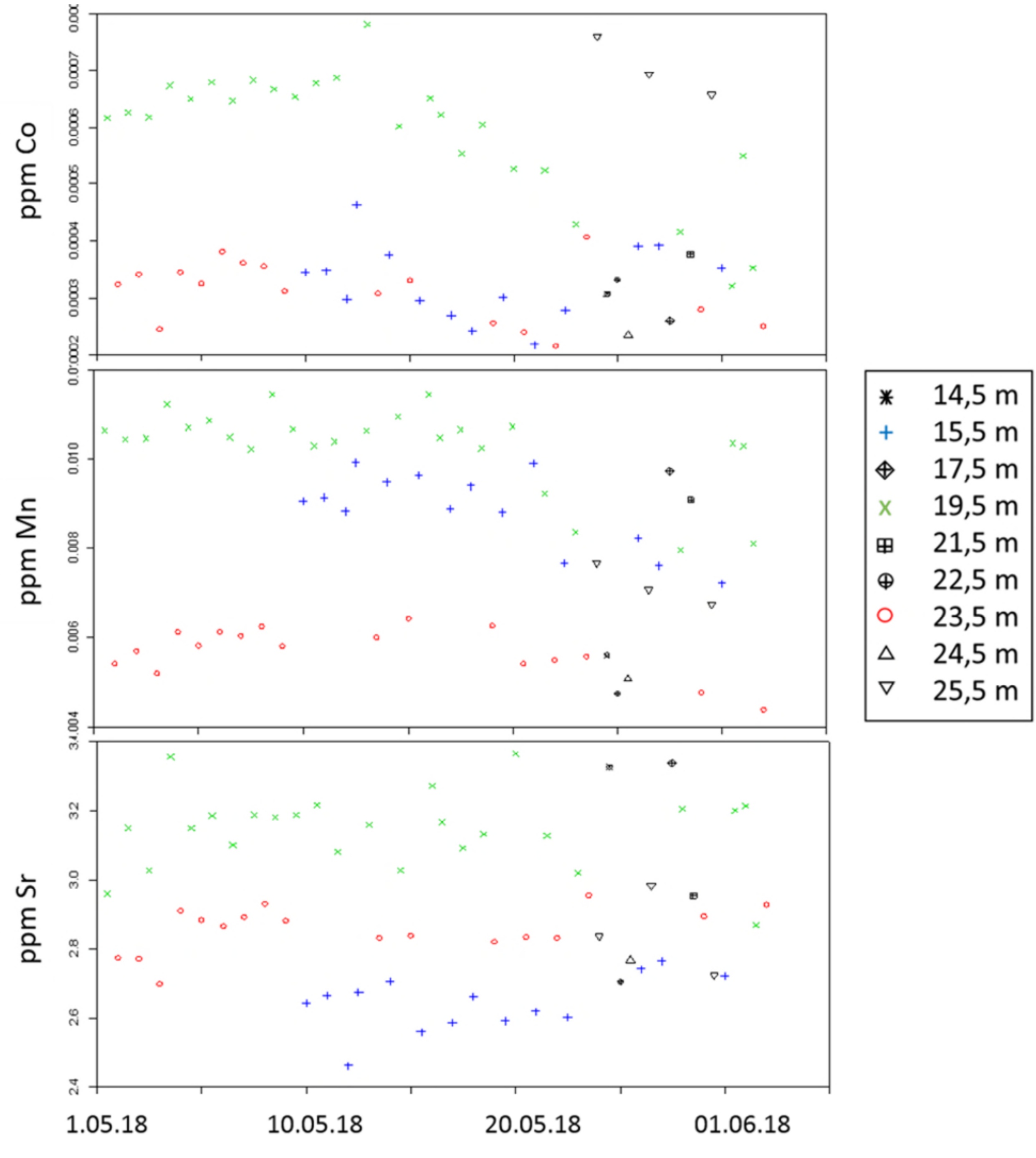


Figure 26. Co, Mn ad Sr concentrations (ppm) in the extracted water as a function of time from May 1st to June 4th 2018.

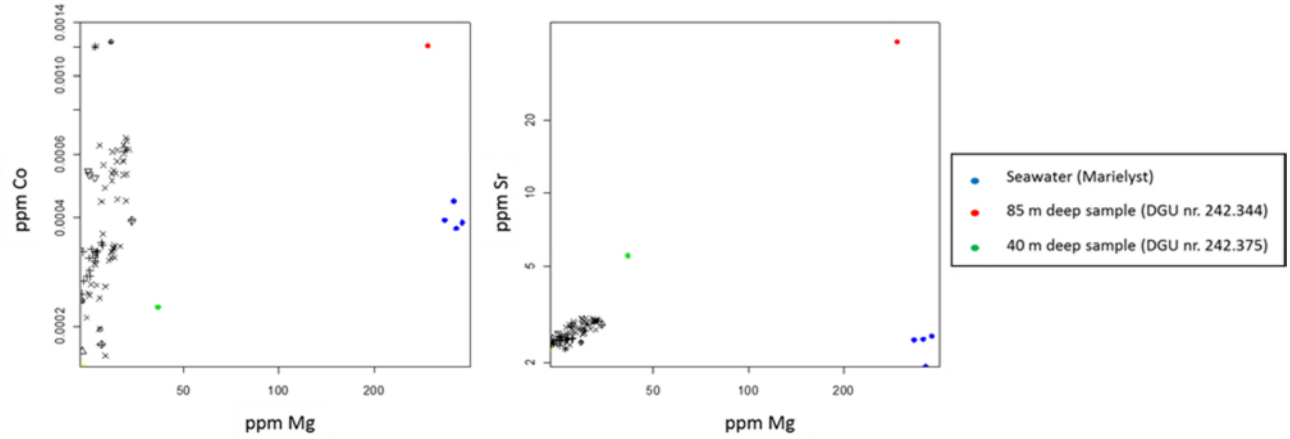


Figure 27 Sr and Co versus Mg concentrations in samples from the experiment compared to seawater (Marielyst) and two deeper wells on Falster to 85 and 40 m respectively.

The content of trace elements in seawater is very different compared to the content in the wells sampled as part of the present experiment. An example is the content of Mg, Co and Sr (Figure 27). The deep well (DGU 242.344) has a high chloride content, and this is associated with a high content of most trace elements. In this context, it can be noted, that the Sr/Mg ratio in the two deeper wells is similar to the samples taken during the tracer test but different from the seawater (Figure 27).

The distinctly different composition of the groundwater at the sampled levels (Figure 25) combined with the constant composition of the water during the first weeks of extraction (Figure 26) suggests that the composition of the water has evolved by water-rock interactions with the chalk at the various stratigraphic levels. This implies that the groundwater is undisturbed by major fluxes of water from other sources than precipitation slowly infiltrating into the reservoir.

The groundwater is slightly saline here and it is considered likely that this is due to a small amount of salt remaining from the saline “brine” present in deeper parts of the of the chalk as seen e.g. in DGU 242.344 (Figure 27).

The water from the Baltic Sea has a composition that is distinctly different (Figure 27) and it is not considered likely that the salinity in the area is caused by influx of seawater. This conclusion supports conclusions from a previous study including Sr isotopes (Figure 28, Hinsby et al., 2012).

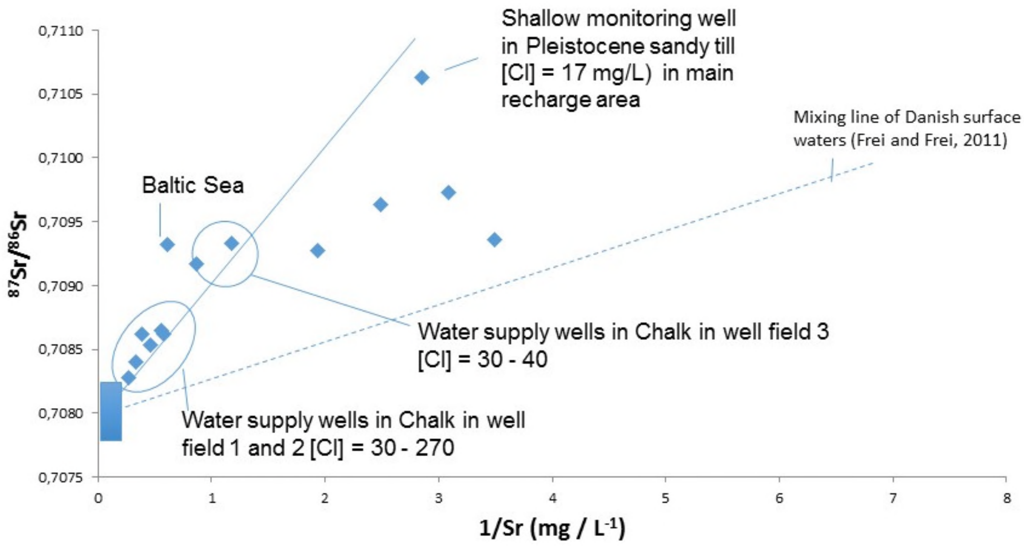


Figure 28. Sr isotope ratio in selected groundwater samples on Marielyst, Falster compared to the Baltic Sea and Danish surface waters (Frei and Frei, 2011)

Figure 28 indicate that groundwater in the three well fields are on a mixing line between connate waters in the deeper part of the Chalk (blue rectangle) and freshwater in the shallow monitoring well in a Pleistocene sandy till at well field 3 rather than with seawater from the Baltic Sea. This is just an indication as it is based on only one measurement of the strontium ratio in the Baltic Sea and one in measurement of freshwater in the main groundwater recharge zone. Data from Andersson et al (1992), however, plots slightly lower and more towards the y-axis (at 0.42-0.5, 0,70925) and further away from the mixing line of the groundwater samples. This supports the conclusion that deeper connate saline waters from the Chalk affects the salinity in the most shallow part of the aquifer either through up-coning or through insufficient freshening of the Chalk glacitectonite, rather than from intrusion of saline waters from the Baltic Sea.

Assessment of ion-exchange effects during tracer tests by PhreeqC modelling

To analyze ion-exchange effects during the tracer experiment a 1D reactive transport model was set up in PHREEQC. The model used one cell with stagnant water next to each cell of mobile water. The tracer test is set up so that the flow rate of the water going straight from the injection to sampling wells is close to linear, meaning that the flow can be approximated by a 1D PHREEQC model with cells of equal length. 24 cells of 0.5 m were used, thereby including 1,5 m upstream of the injection The tracer injections were made by changing the composition of the water in 4 cells upstream and downstream of the injection point and then let the transport continue by putting background water into the upstream of the column (SOLUTION 0 in PHREEQC). This was done to approximate that during injection the tracer water presumably spreads in all directions from the injection well, producing a zone of tracer water in a relatively short time (30 min) compared to the travel time to the sampling wells. Breakthroughs were observed in several of the sampled intervals, however the breakthroughs from the screen named CMT2-2 were the most distinct, so these are the only breakthroughs included in the modelling. The background water used was a modified water composition based on the first samples taken from CMT1-2, with some adjustments made to make e.g. Cl fit better. The tracer solution was made from an average of samples from different depths assuming this was the composition of the pumped water used for the tracer, then 2.5 kg of NaCl was added

The slow breakthrough indicated that a comparatively large part of the porosity, the mobile part, was involved in transporting the tracer advectively. A mobile porosity of 5% was chosen together with an immobile porosity of 35%.The modelling showed that there is a close coupling of the exchange rate between the mobile and immobile water and the dispersivity. With a low dispersivity less water moves faster than average, giving more time for exchange by diffusion between the mobile and immobile water, leading to a lower breakthrough peak. After some trial and error a dispersivity of 3 m and an exchange rate of 4E-6 s^{-1} was chosen. The cation exchange capacity has been set to 200 mmol/L corresponding to ~5 mmol pr. 100 g assuming a porosity of 40%.

The actual measured data are somewhat sparse, most af the samples taken are from the second breakthrough, where the flow rate was slowest. Figure 29 shows the results from PHREEQC using the standard exchange coefficients in the database. It is clear the only the model response for Na is similar to the observed. Considering that the exchange coefficients in the PHREEQC-database are based on soils – it is not that surprising that the relative cation exchange behavior is different in the glaciotectonite that the transport takes place in. The response in K and Fe(2) (not shown) is much higher than predicted, while the response for Ca and Mg is much lower than predicted. The observable effect on Ca and Mg appears to be below the limit of detection.

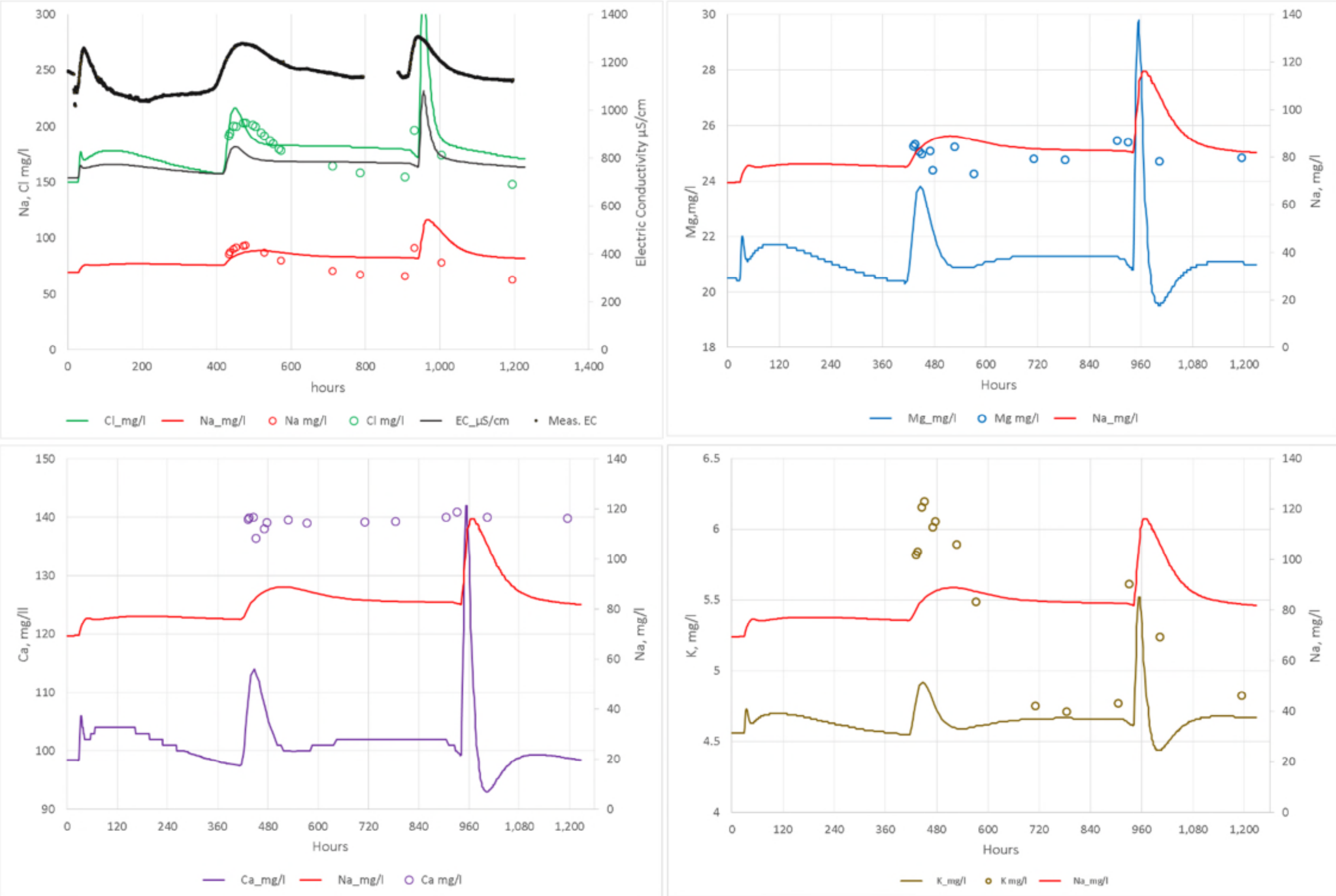


Figure 29: Measured cations, chloride (circles), EC(dots) and PHREEQC model results (lines) using the standard PHREEQC exchange coefficients

Some attempts were made to change the logK exchange coefficients for Ca, Mg, K and Fe. This improved the model response, but only very slightly. An example is shown in Figure 30 , where the logK exchange coefficients for K, Ca, Mg and Fe(2) were simply doubled. Based on the attempts made it appears that more values need to be measured to constrain the problem. At least the total exchange capacity, but also the actual distribution of cations on the exchanger with the composition of the associated pore water could be used to derive cation exchange coefficients – with the current limited datasets it is difficult to proceed.

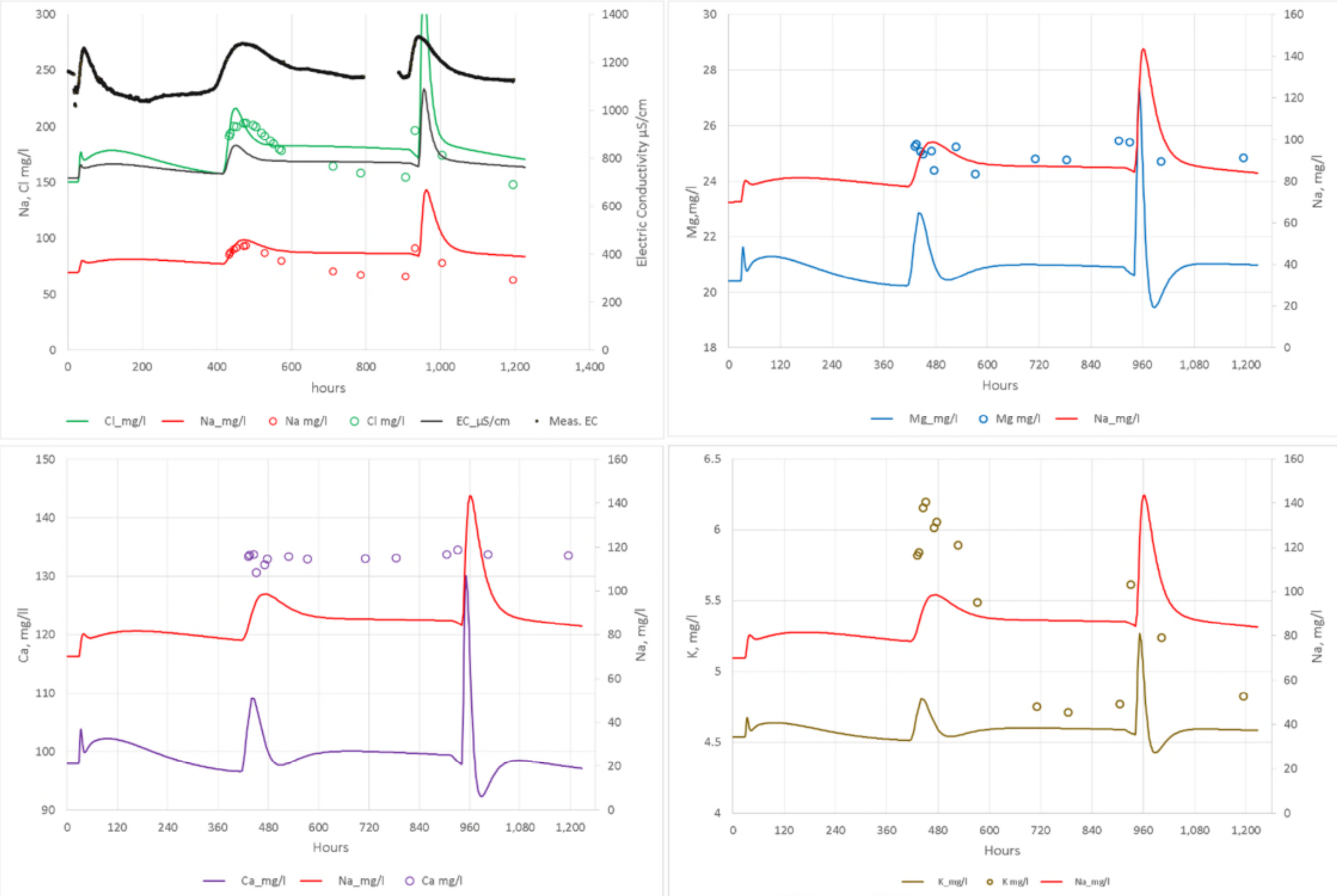


Figure 30: Measured cations, chloride (circles), EC(dots) and PHREEQC model results (lines) where the standard logK values for the PHREEQC exchange coefficients have been doubled.

Both Figure 29 and 30 show that the modelling does predicts the somewhat contraintuitive peakheights/areas that were observed in the EC. The second breakthrough curve has a quite high but also quite broad peak with an area that appears much larger than the area of the first peak. The model curves show the same pattern, indicating that it is a result of the exchange between the mobile and immobile phase and not a result of a completely different flow patterns for the different flow rates.

Model simulations of tracer breakthrough and SWS system design

Simulation of tracer breakthroughs and determination of hydraulic parameters of the glacitectonite

Groundwater flow in a fractured coastal chalk aquifer is characterized as a dual domain (dual porosity) when it comes to transport of saltwater. Dual domain transport is where there are two distinct domains that affect the transport processes, a mobile domain, the fractures where the majority of advective flow occurs, and the immobile domain, the matrix (unfractured single porosity part) of the aquifer where the primary transport mechanism is diffusion and dispersion.

In numerical models including dual domain options, it is possible to specify separate transport parameters for each of these domains. The mass transfer coefficient approach is used in the groundwater models for calculating the transport of saltwater between the two domains. Numerous case studies have shown that a dual domain simulation may improve calibration and better represent field conditions. It is characteristic for dual-continuum or highly heterogeneous aquifers that the breakthrough curve in tracer tests shows a long tailing. Dual-domain transport is also referred to as dual-porosity, or two-region transport.

One of the main purposes of the field activities, pumping tests and tracer tests, were to obtain characteristic parameter values for chalk aquifers, e.g. hydraulic conductivities, storage coefficients and mass transfer coefficients. The conducted pumping and tracer tests have provided parameters for the local dual domain variable density model for the Falster replication site.

The geological and geophysical field investigations was intended to provide data for the interpretation and conceptualisation of the hydrogeological model to be implemented in the groundwater models. Pumping tests provide information on hydraulic conductivities and storage parameters. The field tracer tests provide parameter values for modelling the effect of dual domain geological regimes on the salt water.

The CXTFIT analytic code, included in the STANMOD software, is used for estimating mass transfer coefficients and dispersivity coefficients based on the tracer test experiments. CXTFIT is a 1D model. In addition, the groundwater model userinterface GMS is used for comparetive 1D simulation.

The dual domain groundwater models are established using the GMS software, which include the groundwater flow, transport and variable density codes MODFLOW, MT3DMS, and SEAWAT. GMS is used for simulating different SWS test designs applied to the fractured chalk aquifer. GMS are used for 3D model simulations.

As the tracer tests turned out with a very diverse picture of the flow and transport regime in the very complex glaciotectonically affected chalk aquifer, it was decided to use generic groundwater models for evaluating different SWS test designs. A generic groundwater model is a simplified generalized model setup of the actual hydrogeological setting at the replication site. For the generic models various boundary conditions, sinks and sources, and hydraulic parameters from previous model studies in the area are combined with results from field activities described earlier in this report.

The first step is to evaluate the effect of the dual domain system by comparing the same generic model with and without applying the dual domain concept (Figure x: Single Domain model, Dual Domain model-1). The effect of model simulations with and without implementing the domain option is illustrated for one of the SWS designs, the Freshkeeper.

A generic model is established for analysing the effect of the complexity of the glaciotectonically affected chalk aquifer for fresh and saltwater flow (Figure x: Dual Domain model-1, -2, -3). The effect of the heterogeneities of the chalk aquifer, as experienced from the tracer tests and the geological fieldwork, is evaluated by using different mass transfer coefficients estimated in different depths from the tracer tests.

One generic model is selected for evaluation three SWS Test Designs at the Falster replication site (Figure 31: SWS Test Design-1, -2, -3). For each test design different pumping schemes is tested with focus on long-term effects of the SWS technologies. The SWS test designs and pumping schemes are described in further detail in the following chapter.

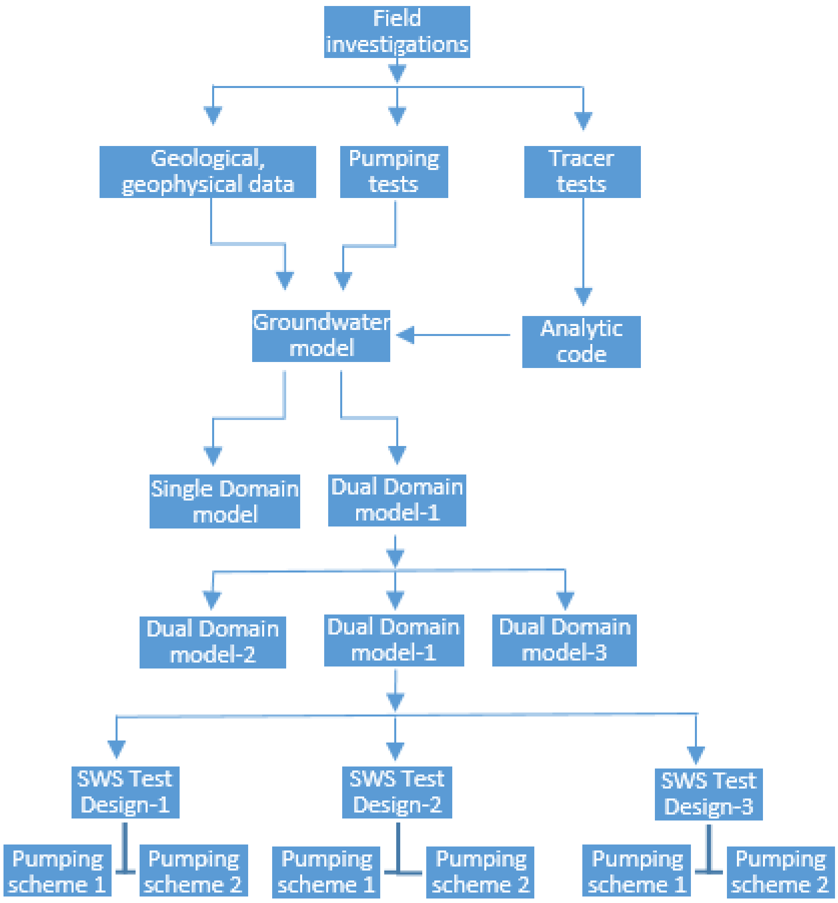


Figure 31. Flow diagram showing the steps from field investigations to groundwater model simulations local SWS designs

Based on measured data from the tracer tests the CXTFIT analytic code is used for estimating the saltwater transport parameters, the mass transfer coefficients and the dispersivity coefficient (Figure 32, Table 1).

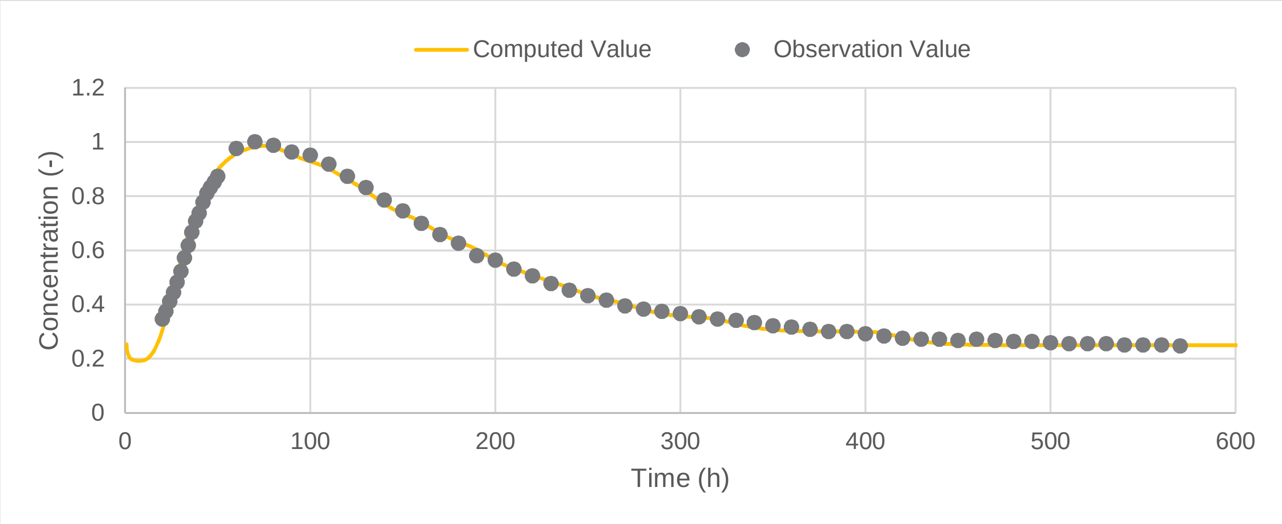


Figure 32. Example of estimation of the mass transfer coefficients by the CXTFIT analytic code, observed data from monitoring screen CMT2-2, the first tracer test

Table 1. Mass transfer coefficients and dispersivity coefficient estimated with CXTFIT code

Depth (m)	Monitoring point	Tracer test no.	β (mass transfer coefficient) (h^{-1})	Longitudinal dispersivity (m)
15	CMT 2-2	1	0.9	24
19	CMT 2-4	1	1.0	3.6
23	CMT 2-6	1	0.8	4.9

Table 2. Mass transfer coefficients and dispersivity coefficient estimated with GMS groundwater model

Depth (m)	Monitoring point	Tracer test no.	β (mass transfer coefficient) (h^{-1})	Longitudinal dispersivity (m)
15	CMT 2-2	1	5.0e-6	0.95

Although the fit in Figure 32 looks very accurate, the estimated mass transfer coefficient seems quite high compared to literature values. More analyses of the specification of the input parameteres as well as the parameter estimation setup are needed in order to better understand the complex 3D hydrogeological system and the model results. A comparison with the mass mass transfer coefficient estimated by the 3D GMS model shows a significant difference (Table 2).

Figure 33 shows the principles of the three SWS system designs, the 'Freshmaker', the 'ASR Costal', and the 'Freshkeeper'. The 'ASR Costal' and the 'Freshkeeper' system designs are found the most relevant at the Falster replication site, and these two SWS system designs are implemented and tested in the generic groundwater models.

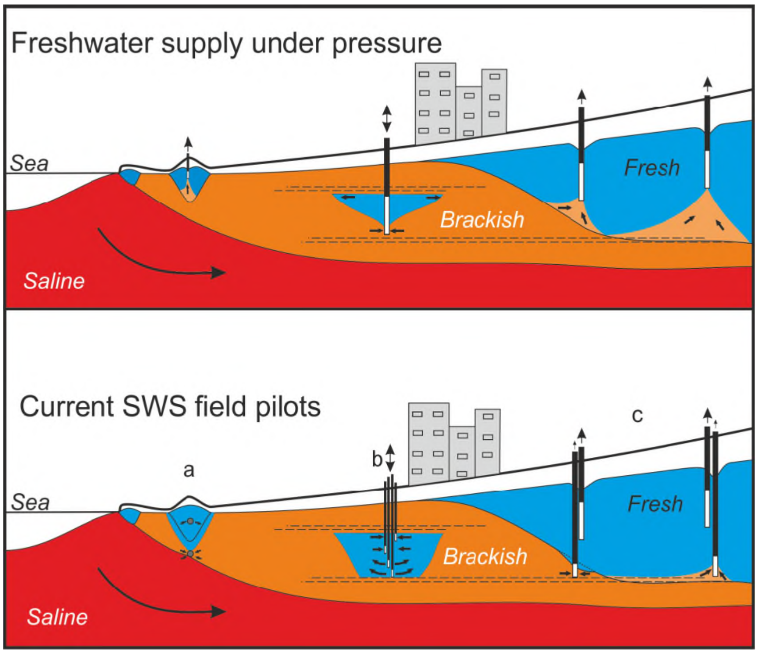


Figure 33. SWS system designs: a) Freshmaker, b) ASR Coastal, c) Freshkeeper

Model scenarios with the SWS concepts 'Freshkeeper' and 'ASR Coastal' applied in the local chalk aquifer at the Falster replication site is used for the assessments of the most efficient schemes for securing future freshwater abstraction at the well field. Figure 17 shows the location of the water supply well, the potential 'Freshkeeper' wells UB1 and T1, and the other wells at the Falster test and replication site.

Test design 1:

'Freshkeeper': Brackish water is pumped from the deeper part of UB1, desalinised and re-injected at different pumping rates near the water supply well.

Test design 2:

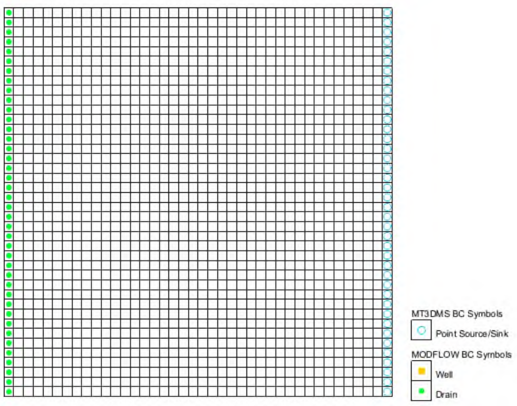
'ASR Coastal': Injecting and storing freshwater during the winter period with excess precipitation, and abstracting groundwater during the summer period with high water demand.

Test design 3:

Combined 'Freshkeeper' and 'AS(T)R Coastal': Brackish water is pumped from the deeper part of UB1, desalinised and re-injected at different pumping rates in wells at different distances and depths upstream the water supply well.

Each of the three SWS test designs are tested with one generic dual domain groundwater model (Figure x: Dual Domain model-1). Depending on the test design different pumping schemes are applied to evaluate the most efficient pumping scheme.

The generic dual domain groundwater flow and transport model has been setup using the GMS modeling software. The model has a horizontal size of 2000 m x 2000 m and a vertical extension from 2 m to -70 m above mean sea level (AMSL). The horizontal grid zise is 50 m x 50 m, and the model has 14 horizontal layers with a thickness of 5 m. The chalk aquifer extends from -10 m to -70 m AMSL. There is groundwater recharge to the top layer and a drain chanal actc as boundary condition to the west (Figure 34). The source of saltwater is diffusion from the deepest layer with a fixed concentration of 10500 mg TDS/l. The model setup is based on privious model studies (Rasmussen et al. 2013 and 2015).



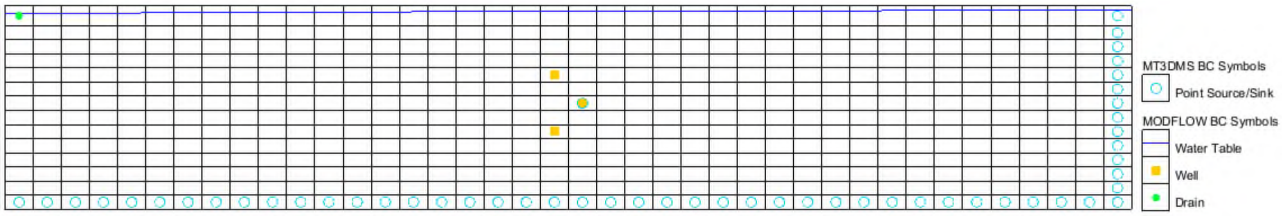


Figure 34. Location of wells in the model for Test design 1. Pumping well, P1 (uppe left well), Freshkeeper well, FK1 (lower left well), injection well, INJ1 (the well to the right)

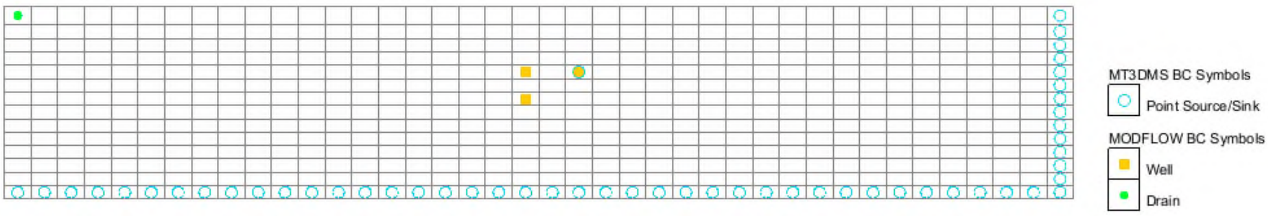


Figure 35. Groundwater model setup. Location of wells for Test design 2 and 3. Pumping well, P1 (uppe left well), Freshkeeper well, FK1 (lower left well), injection well, INJ1 (the well to the upper right)

The groundwater model includes threes wells, one pumping well (P1), one Freshkeeper well (FK1), and one injection well (INJ1) (Figure 34 and 35).

An initial model run for 1000 years with only diffusion, drainage by the canal, and groundwater recharge was completed and used as initial conditions, starting concentrations, for following model analyses.

The groundwater model first simulate 60 years of pumping from P1 corresponding to the actual pumping history at the Marielyst waterworks. This period is followed by a period of 20 years with implementation of the different SWS test designs using the wells FK1 and INJ1.

A sensivity analysis of porosity (immobile, mobile) and mass transfer ceofficient has been conducted (Table 3 and Figure 36). A continous pumping scheme has been applied for the addditional 20 years modeling including SWS (P1: 68 m^3/d abstraction, FK1: 34 m^3/d abstraction, INJ1: 34 m^3/d injection).

Table 3. Sensivity analysis of porosity (ϴ) and mass transfer ceofficient (β)

Sens. No.	θim	θm	θtotal	β (1/d)	Comments
0	0.399	0.001	0.4	0.0001	Dual domain, basis model

1	0.35	0.05	0.4	0.0001	Dual domain model
2	0.3	0.1	0.4	0.0001	Dual domain model
3	0.399	0.001	0.4	0.01	Dual domain model
4	-	-	0.4	-	EPM model

θ: porosity = immobile (im), mobile (m), total

β: mass transfer coefficient

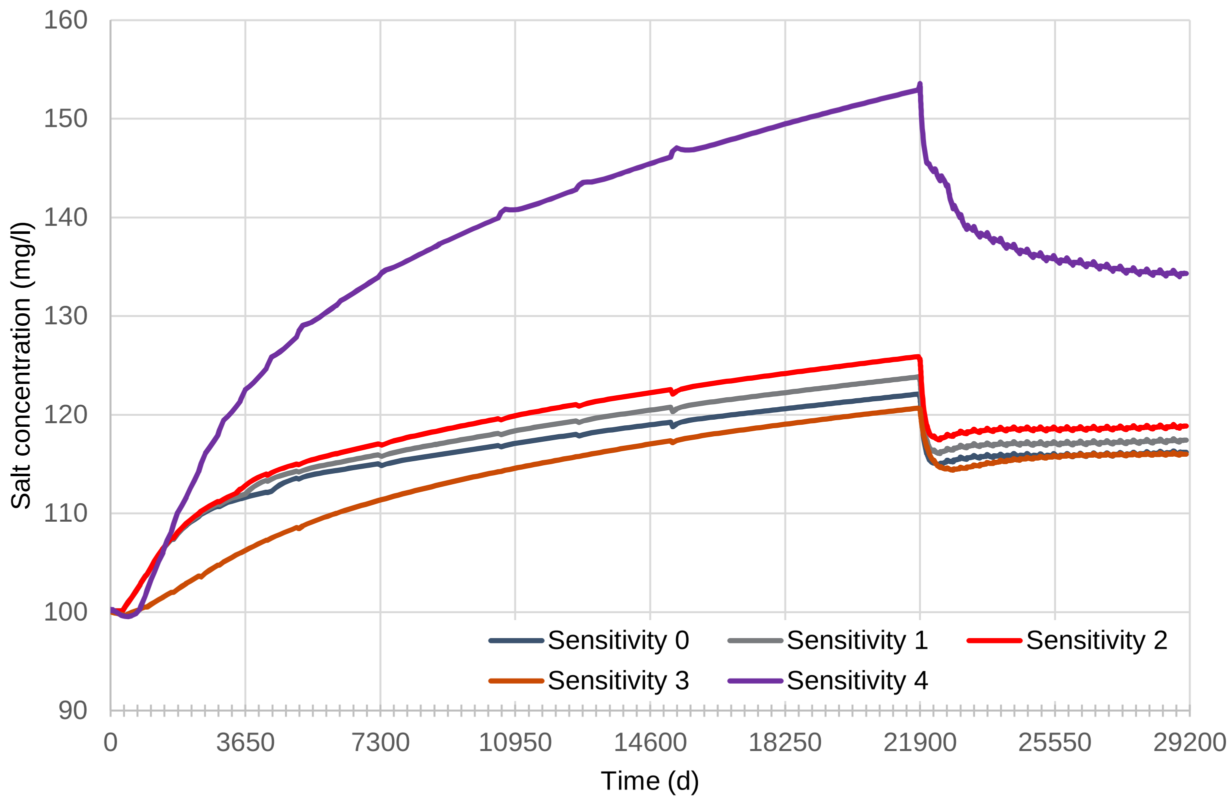


Figure 36. Sensivity analysis of porosity (Ө) and mass transfer ceofficient (β). For explanation of Sensitivity analyses 0-4 see Table 3.

The sensivity analysis shows a significant higher salt concentration for the EPM-model (Equivalent Porous Media) compared to the dual domain model (Sensivity 4 and 0 in Figure 36). With a higher mobile porosity the model simualtions shows a slightly higher salt concentration (Sensivity 0 compared to Sensivity 1 and 2 in Figure 36). With a higher mass transfer coefficient the model simualtions shows a slightly lower salt concentration (Sensivity 0 compared to Sensivity 3 in Figure 36).

Simulations of SWS system design and efficiency

Test design 1:

'Freshkeeper': Brackish water is pumped from FK1 in the deeper part of the aquifer below P1, desalinised and re-injected at different pumping rates in INJ1 near the water supply well P1 (Table 4 Scenario 2 and 3).

Test design 2:

'ASR Coastal': Injecting and storing freshwater during the winter period with excess precipitation, and abstracting groundwater during the summer period with high water demand (Table 4 Scenario 4).

Table 4. Scenarios for Test design 1 and 2

Scenario no.	P1 Q (m3/d)	FK1 Q (m3/d)	INJ1 Q* (m3/d)	FK1 depth below P1 (m)	INJ1 depth below P1 (m)	Comments
0	-68	0	0	20	10	Dual domain, basis model
1	-68	-10	0	20	10	
2	-68	-10	+9	20	10	
3	-68	-34	+30	20	10	
4	-85	-10	+9/+33	20	10	
5	-85	-10	+9/+33	20	10	EPM model

* cycle of half year pumping with different rates Sc. 4 and 5

Q pumping rate : abstraction (-), injection (+)

P1: Pumping well. FK1: FreshKeeper well. INJ1: Injection well

The installation of a 'Freshkeeper' well, FK1, below the pumping well P1 shows a decrease in the salt concentration in the pumping well P1. It also shows a minor increase over time in the salt concentration in the pumping well P1 (Scenario 1 compared to Scenario 0 in Figure 8x).

In Scenario 2 90% of the groundwater abstracted with FK1 is re-injected in well INJ1 with a constant concentration of 100 mg/l. Compared to Scenario 1 the salt concentration is lower in P1 and it reaches a constant level over the 20 years simulation period.

A further increase in both the abstraction from FK1 and the re-injection in INJ1 in Scenario 3 (Table 4) reduces the salt concentration P1 significant, and a decreasing concentration over time is seen in P1 (Scenario 3 compared to Scenario 2 in Figure 8x)

In Scenario 4 the abstraction from P1 is increased by 25% and the surplus groundwater is injected in the winter half-year in INJ1. The Freshkeeper well FK1 and re-injection well INJ1 are operated as in Scenario 2 (Table 4x). The changes in the salt concentration in the pumping well P1 in Scenario 4 is very similar to what was seen in Scenario 2.

Scenario 5 shows a significant higher salt concentration in P1 for the EPM-model compared to the dual domain model (Scenario 5 and 4 in Figure 37).

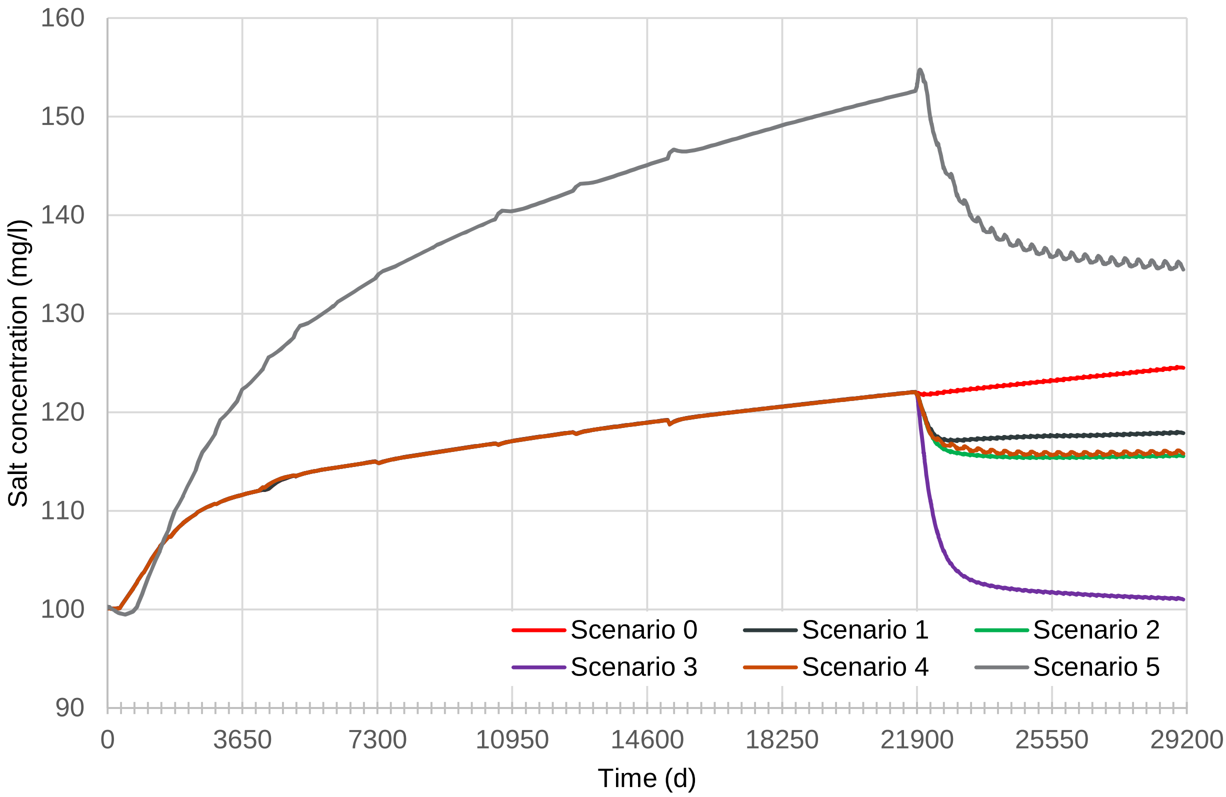


Figure 37. Scenarios for Test design 1 and 2. For explanation of scenario 0-5 see Table 4

Test design 3:

Combined 'Freshkeeper' and 'ASR Coastal': Brackish water is pumped from the deeper part of the aquifer for FK1, desalinised and re-injected at different pumping rates in the well INJ1 at different distances from the water supply well P1 (Table 5).

Table 5 Scenarios for Test design 3

Scenario no.	P1 Q (m3/d)	FK1 Q (m3/d)	INJ1 Q* (m3/d)	FK1 depth below P1 (m)	INJ1 distance to P1 (m)	Comments
0	-68	0	0	10	100	Dual domain, basis model
1	-68	-34	0	10	100	
2	-68	-34	+34	10	100	
3	-68	-34	+34	5	100	
4	-68	-34	+34	15	100	
5	-68	-34	+34	10	150	
6	-68	-17	+17	10	100	

* cycle of half year pumping and half year without no pumping

Q pumping rate: abstraction (-), injection (+)

P1: Pumping well. FK1: FreshKeeper well. INJ1: Injection well

The most efficient scenario for Test design 3 is Scenario 4 where the FK1 abstraction is moved to a deeper position in the aquifer. In Scenario 4 a significant decrease in the salt concentration is seen in P1 (Figure 38).

If FK1 is moved to a higher position in the aquifer closer to P1 (Scenario 3) or if the pumping rates are reduced for both FK1 and INJ1 (Scenario 6) only a small positive effect is seen on the saltwater concentration in P1. In addition, the concentration in P1 will continue to increase because water is only re-injected in the winter half-year, compared to scenarios with Test design 1 and 2 (Table 4 and Figure 37).

In Scenario 5 the injection well is moved further away from the pumping well and a minor increase in the salewater concentration is seen in P1 compared to Scenario 2 (Table 5 and Figure 38).

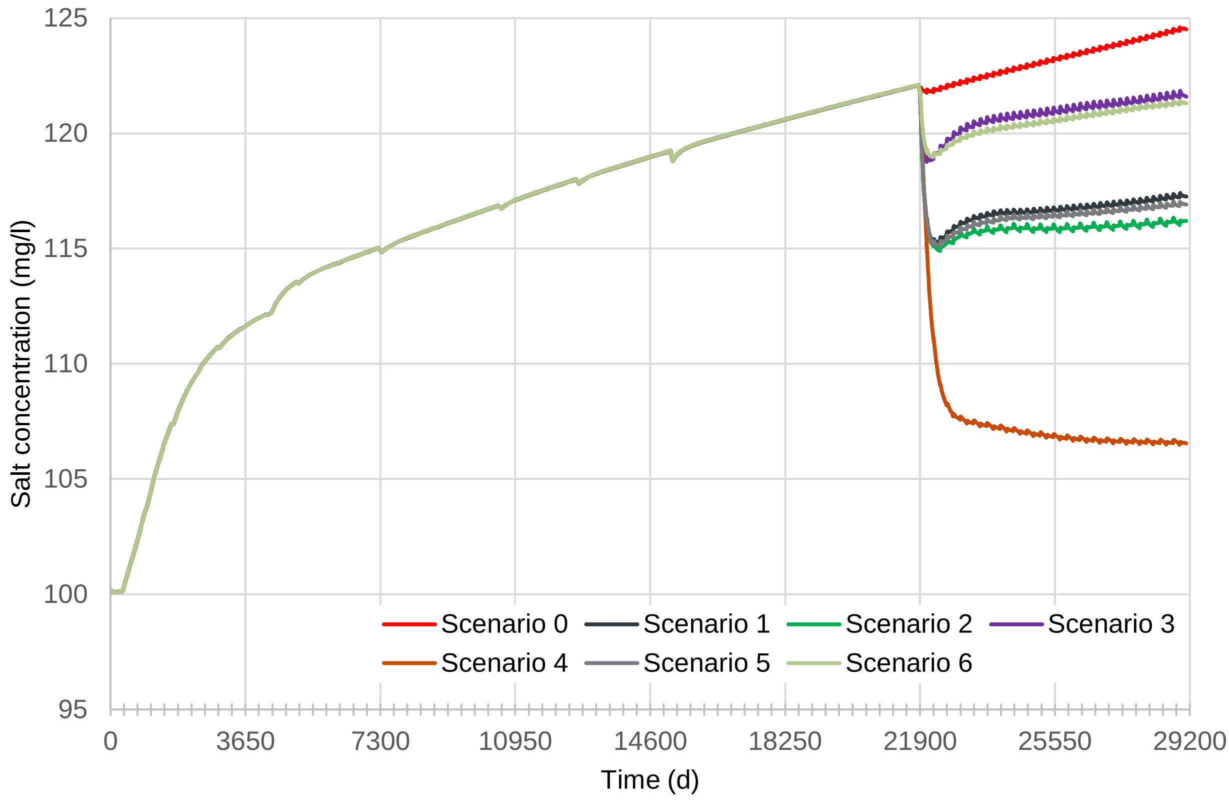


Figure 38. Scenarios for Test design 3. For explanation of scenarios 0-6 see Table 5

A generic groundwater model has been used because no hydrostratigrafic model based on the field studies and hydrogeological tests has been made due to the complexity of the local geology.

A more precise site specific model would require a detailed conceptual understanding and model of the fractured and glacial disturbed chalk aquifer system, and a more thorough analysis of the saltwater distribution in the aquifer. The initial saltwater concentrations for model simulations are important. Also a more thorough analysis of the saltwater origin in the aquifer is important for deciding if only diffusion or also seawater intrusion processes should to be included in the modeling. A site specific model should also include a finer discretization of the model domain both horizontally and vertically, include variable density effects, and be calibrated using site specific data of e.g. mobile porosity and mass transfer coefficients

The modeled scenarios with the simplified generic model representing the complex hydrological conditions of the Falster replication site should be intrepreted with causion due to the risk of over-simplification.

The model results with the generic groundwater models show a significant lower salt concentration in the water supply well when using dual domain model compared to the an EPM-model (Equivalent Porous Media).

The most significant effect of the SWS designs is the position of the 'Freshkeeper' well and the re-injection well in relation to the water supply well, and the volumes of 'Freshkeeper' abstraction and the volumes of re-injected groundwater.

A cyclic injection e.g. only injection during the winter half-year shows only minor cyclic variations in the salt concentration in the water supply well compared to more longterm trends in concentrations.

The completed groundwater modeling for the Falster test and replication site indicate a potential for a successful use of the SWS concepts 'Freshkeeper' and 'ASR Coastal' in glacial disturbed fractured chalk aquifers.

Cost-efficiency of relevant water purification methods

Methods and costs of desalinisation of slightly brackish groundwater in chalk aquifer with elevated hardness

There are currently no waterworks in Denmark using desalination as part of the water treatment or production. Therefore, methods and the adjacent costs in Denmark primarily uses the knowledge from production facilities for industrial purposes.

The two types of methods available and used are the osmotic (RO) and the Nano filter. Costs of standard solutions for both methods based on flow demand of 10-15 m3/h lies in the range of 60-100.000 €.

The hardness of groundwater in chalk aquifer requires further water treatment with softening before desalination otherwise the desalination installation will most likely suffer severely damage after only short time due to incrustation of chalk. Cost of softener solution for the involved flow is somewhat dependent of the method used. In this case 50.000 € is probably covering.

The cost for a permanent installation (wiring, re-piping etc.) of the desalination and softening equipment in existing housing assuming sufficient space is available can roughly be estimated to 30-50.000 €.

Total cost in range of 140-200.000 € for the installation of a production line using a part of the normal water treatment facility (i.e. sand filter) at the waterwork before softening and desalination (assumed no cost for this).

There are no available experiences in the use of installations like this in Denmark and expected lifetime for the combined installation is hard to predict. Expected lifetime for a pump is 20 years as this type of installation is much more complex lifetime thus assumed less.

The combined process uses water for backwash and processing. A total loss of 25-30% is expected. Costs for energy to high-pressure pumping and additives to the softening process are primarily dependent of the actual water quality. Cost for maintenance and use of spare parts are unknown.

In total the processing cost of the of up to 75.000 m3/y of desalinated water on a single production line using part of the waterwork for housing and the existing sand filter as pretreatment is estimated to be in the range of 0.4-0.6 € per m3.

For comparison between small scale treatment costs for hard but pure brackish water and soft but polluted drainage water see section after the following section on drainage water purification.

Purification methods for drainage water containing pathogens, pesticides and pharmaceuticals

The ASR-Coastal of the SWS techniques uses managed aquifer recharge (MAR) for the storage of treated water types in the subsurface. The treated water is infiltrated into aquifers either via injection wells or infiltration basins (Dillon, 2010). As it is not possible to use infiltration basins on Falster only an ASR-Coastal solution or modification of this method can be applied on the site. A range of different water types may be used for MAR in wells including treated and purified storm water, rainwater, desalinized brackish water and even wastewater. However, if water of lower quality is used the infiltrated water has to be carefully purified to meet health and environmental standards for its later use for e.g. drinking or irrigation.

At the Falster pilot site, it has been suggested to use purified drainage water for injection directly into the aquifer ASR-coastal to prevent saltwater intrusion (Hinsby et al., 2015). Though, there are concerns related to the presence of pathogens, organic pollutants and inorganic nutrients in this types of water, and therefore it has to be carefully purified before a potential injection. Agricultural pesticides are typically present in drainage water and have been detected at the Falster site, although mostly below the EU threshold level of 0.1 µg/l (Hinsby et al., 2015). Furthermore, analysis of treated wastewater from a nearby WWTP revealed a number of emerging pollutants including pharmaceuticals such as painkillers and antibiotics; some in very high concentrations (> 1000 µg/l). These compounds may eventually enter drainage waters were they have to be removed before used in an ASR coastal scheme developed for the Falster site.

Many organic pollutants can be removed by activated carbon filtration being most effective against hydrophobic compounds. Activated carbon is most often used for treatment of polluted groundwater to be used for drinking where the amount of particulate and dissolved organic matter is low. Drainage water contains higher amounts of organic matter, which may cause rapid saturation of the sorption sites on the activated carbon and block the filter pore space.

Membrane filtration is another technology that may be used for removal of organic pollutants in drainage water. Advanced membrane processes such as reverse osmosis or nano-filtration has been shown to remove efficiently a broad spectrum of pesticides, pharmaceuticals and personal care products from contaminated water (Yoon et al., 200&; Lipp et al., 2010; Bodzek et al., 2011). Membrane filtration is very effective and can remove > 99 % of most organic pollutants. Along with the pollutants, other water constituents will also be removed including organic matter, ions such as nitrate and nutrients. The filtration process, however, produce a rejected water stream with the pollutants being concentrated. In practise 10% or even more of the water being purified will be rejected and has to be treated e.g. by activated carbon filtration as previously suggested (Hinsby et al., 2015)

Recently, ordinary sand filters used at waterworks, but added specific contaminant degrading bacteria was suggested as a technology to remediate pesticide-polluted drinking water (Brenner et al., 2013). As an example, it was shown possible to remediate drinking water polluted by the pesticide residue 2,6-dichlorobenzamide (BAM) by adding the BAM-degrading bacterium Aminobacter MSH1 to a waterworks sand filter. BAM was removed to below the threshold limit, but it was difficult to maintain degradation activity for longer time periods (> 1 month) probably due to the very low pesticide concentrations in groundwater, being too low to sustain degradation activity (Albers et al., 2015). This bioremediation technology may well be combined with the membrane technology thereby benefiting from the higher pollutant concentrations in the rejected water (Ellegaard-Jensen 2017). Following the bioremediation process, the water may still contain essential nutrients and ions and depending on present legislation, it may be reinjected into the pure water stream (figure 39).

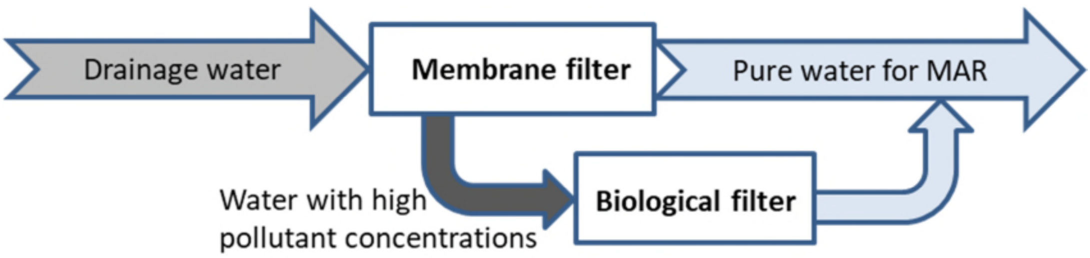


Figure 39. Combined membrane filtration and biological filter technology for remediation of drainage water to be used for managed aquifer recharge (MAR). Drainage water is membrane filtered producing pure water to be used for MAR. The pollutants are concentrated in rejected water, which are treated in a biological filter allowing it to enter the pure water stream.

At present, such combined technology is only at the trial stage and it is difficult to determine whether it could be used for remediation of drainage water at the Falster pilot site. The technology is being developed as a mobile device, but it will still require a high degree of maintenance making it less cost effective for treatment of smaller water volumes. Furthermore, drainage water may contain high concentrations of nitrate that will be concentrated in the rejected water, but not removed during the biological treatment. Whether it will be allowed to reinject nitrate-containing water may depend on the aquifer type, as nitrate probably will be removed by denitrification if the aquifer is anaerobic. For both active carbon filtration, membrane filtration, and the combined technology, a pre-treatment will be required to precipitate particulate organic matter otherwise clogging the filters. Potential, pathogenic bacteria may as well be present in the effluent water and it may be required that these are removed before the water is used for MAR e.g. by UV-irradiation.

In conclusion, there are technologies to be used to treat drainage water to a quality standard that will allow its use for an ASR-coastal. The treatment, however, may be too costly due to the relative small volumes of water to be treated and the strong purification requirements (see next section).

Comparison of installation and operation costs of small-scale water treatment and purification systems

The costs involved in the advanced treatment of either drainage water or abstracted brackish water are estimated with assistance from the water treatment company Silhorko-Eurowater A/S. They are not sale offers and to be considered as rough estimates where many uncertainties are involved.

The estimates uses relatively small designs making it possible to install at the wellsite or near to the wellsite in order to minimize costs to transport pipes in the urbanized area. Installations uses a container as housing for equipment and filters in order to minimize costs of permanent housing. Furthermore, the estimates assume the costs of establishing power supply and costs of removal of process wastewater equals zero.

The types of treatment and steps involved in overall treatment of the two resources considered are as follows:

	Pretreatment	Softening	RO/nanofilter	Biological filter
Drainage water	+		+	+

Brackish groundwater	+	+	+	

The cost of a compact container fitted installation is 250.000 € for either types of treatment for production capacities of 10-15m^3/h.

Process costs

The energy used in the abstraction and combined treatment of the two types of water is equal. So is the installation and energy used to infiltrate in the subsurface.

The variables include mainly the need for backwashing filters for the different types of water and the difference in cost of installation of the softening process for the brackish groundwater compared to the final biological filter for the drainage water. The need for backwash depends mainly on the actual water quality and the process. It is very hard to estimate lower costs for one process than another before actual testing. Another variable though is the abundance of the two types of water. The brackish groundwater is available in all seasons and weather situations. Meanwhile the drainage water is at least less accessible in spring/summer during draughts and in winter when temperatures are below zero.

The process of the brackish groundwater can be more constant during the year and subsequent easier to perform. The inconstant process of drainage water will demand further cost to more startups during the year. The table below lists energy consumption in the various steps in the process for both water types. Power estimates based on ideal or near ideal situations.

kW/m^3	Abstraction	Pretreatment	RO/nanofilter	Softening or biological filter	Infiltration
Drainage water	0,1	0,3	1,0	0,3	0,1
Brackish groundwater	0,15	0,3	1,5	0,3	0,1

The energy consumed in the overall process is mainly dependent on the RO/nanofilter process and could be much higher than estimated in the table due to more difficult water quality e.g. higher salinity. In total an energy consumption of 2,0 kWh/m^3 for drainage water and 2,5 kWh/m^3 or even higher for brackish water must be expected (1 kWh = 0,08-0,09 € in Denmark).

The costs of membrane replacement maintenance and parts of pretreatment and the RO/nanofilter process and chemicals or bacteria added to the softening or biological filter are assumed equal for two types of water and in the same range as cost for power. Maintenance/m^3 = 0,2 €

Capital recovery for the installations based on interest level of 2% and expected lifetime for the installations of maximum 20 years equals 16.600 €/y.

Production rates from the different types of water will not be the same as above mentioned depending on the drainage water production. Assuming there will be downtime 4 month every year for the drainage water process due to lack of drainage water besides backwash periods and downtime due to maintenance for both types of water. Production from drainage water is 2/3 of brackish water. The capital recovery will of cause influence in 3/2 higher cost of the drainage water.

In the table below all cost are calculated in euro (€) and the production is limited as mentioned above.

	Production m3/year	**Energy cost /m3**	**Maintenance cost/m3**	**Capital recovery cost/m3**	**Total cost/m3**
Drainage Water	50000	0,2	0,2	0,33	**0,73**
Brackish Water	75000	0,25	0,2	0,22	**0,67**

Water quality issues

The risk of releasing trace elements by injecting oxidizing water in an ASR or ASTR (Aquifer Storage Transport and Recovery) water banking scheme appears to be small at the Falster site as long as the injected water has been properly purified.

Development of SCADA/PLS systems

Real-time or rather near real-time observation and application of measurements of mainly electrical conductivity and/or chloride concentrations in groundwater and water supply wells is a prerequisite for controlling saltwater intrusion into water supply wells. Preferably this should be made in groundwater at some distance as an early warning in order to change abstraction schemes in due time before the saltwater affect the supply well. The issues related to understanding of the hydraulic behavior of the glacially disturbed fractured chalk (the glacitectonite) also resulted in severe delays in developing monitoring and control systems, which would work efficiently in such a setting.

New options and possibilities for near real-time monitoring of saltwater intrusion informing the SCADA/PLS solutions

As mentioned in the previous chapter efficient control of saltwater intrusion requires efficient monitoring of groundwater salinity around the water supply wells. Monitoring systems requires electrical power both for measurements and data transfer. The power may be obtained from the water supply installations but if the monitoring systems and data transmission has to be installed away from the general power supply systems, batteries or solar power is required. Generally, solar power may not be stable enough in some regions and the life time of batteries used for monitoring devices and data transmission via mobile network is rather short.

At the Falster field site we therefore decided to test groundwater monitoring devices for measurements of groundwater head and salinity using data transmission via the low power network of the IoT service provider “Sigfox” (https://www.sigfox.com/en) and compare it to measurements via standard mobile network solutions. It was clearly demonstrated that the battery life time of the sensors and data transmission system using Sigfox was signifant longer than the sensors connected to mobile network transmission systems. This is a clear benefit of the Sigfox system, the downside is that it is able to transmit fewer data especially at short time intervals.

Stakeholders consultations

To support SWS trust building and the local decision-making process DBT together with GEUS planned and carried out stakeholder consultations at the Guldborgsund municipality about the case study area and potential SWS for controlling salt water intrusion on the Falster island. This participatory technology assessment (pTA) was performed in the very beginning of the SUBSOL project with the aim to act as a test study prior for similar stakeholder dialogues at the other three replication sites in Mexico, Holland and Greece, respectively.

The pTA at Falster

Stakeholders at the case site were identified through outreach studies in the local area. The stakeholders were informed through a brief folder about the SUBSOL project and this was followed by an interview-round among all identified stakeholder-groups to get an impression of the main issues at stake in the area regarding use of freshwater. The interviews focused on five main points among the stakeholders: their connection to the area, current/historical issues regarding water, history of controversies, mapping of informal power-structure, concerns and priorities regarding the project.

Based on this information a workshop was set up with the participation of all stakeholder groups which included homeowners' associations, the waterworks, dike associations, the local bird-watching station, Guldborgsund Municipality, the local branch of the Danish Association for Nature Conservation, the Marielyst gulf club, the Land Reclamation Society of Bøtø Nor, tourist- and business association, and the utility company of Guldborgsund Municipality.

The workshop was planned as an interaction between group discussions and plenary sessions and included presentations from SUBSOL (DBT and GEUS) and from the utility company.

On the workshop the participants were provided with additional information about the challenges of local water supply issues and the current efforts to deal with the problems as well as the SWS technology and the planned exploratory drillings. The participants discussed the future water needs and the potential of SWS to deal with the challenges. They also identified potential conflicts of interest and potential risks, barriers and uncertainties regarding SWS. Main concerns on saltwater intrusion were mapped and pros & cons of different alternatives to the present solution as well as pros & cons of SUBSOL solutions were debated.

A main point on the workshop regarding a further development of a local SWS solution was about what criteria a SUBSOL solution should meet to be a suitable alternative to current solutions. The discussion-groups were asked to agree on a ranking of the importance of five criteria: water quality, environmental consideration, security against flooding, security of supply, economy.

Input to the local SWS development

The pTA resulted in a number of specific recommendations regarding future freshwater technology for example about cooperation between neighbor waterworks, about draining of fields and summerhouse areas, use of existing drainage canals, collection of rainwater, future information to stakeholders, and much more. The stakeholders became aware that the current solution, continuing to move present drillings further away from the sea, is not feasible and sustainable in the future. On the other hand, the participants were very skeptical to the idea of pumping purified wastewater down to the groundwater. The local residents had a strong focus on changes in groundwater level that might weakening the foundation under the dike.

Regarding which criteria to be in focus and handled in a future solution, water quality and environmental consideration were the two criteria, which got the most support from the stakeholders.

The results and experience from this pTA-process gave valuable input to the design of the pTAs in the subsequent SUBSOL replication sites. Lessons learned from all four pTA sessions the results have been disseminated in the solution package (D 4.2) written by

DBT as a toolkit for stakeholders and decision-makers. The title is Participatory Technology Assessment of Subsurface Water Solutions; A Step-by-Step Guide to Stakeholder Involvement.

Roadmap for future application of SWS at the Falster site and similar hydrogeological settings.

Future perspectives

The exceptionally dry and warm summer of 2018 in Denmark has so far emphasized that the main problem for Danish waterworks isn't water scarcity nor intrusion of saline groundwater, but rather nutrient and pesticide pollution mainly from agricultural activities.

Although water scarcity and salt water intrusion is not the main concern yet many waterworks with deep chalk aquifers as primary resource are focused on lowering of the chlorine content in the produced drinking water.

Dialogs with the technical staff from three waterworks situated in different regions of Denmark all using chalk aquifers as the main resource indicates that problems with salt-water intrusion are rather low. However, problems with higher values of chloride do occur in some wells typically in relation to residual salt water as on Falster. Because freshwater scarcity is no problem, the solution is often to close the actual wells with highest chloride concentrations.

Increasing quality problems in the present resource, due to the mentioned pollution with especially pesticides from agriculture, can lead to use of deeper aquifers and then again lead to some issues with residual salt water. Increasing quality problems will for the time being rather lead to more intense treatment of water using e.g. activated carbon than to the use of sws.

Analysis and results from the final drillings and field tests carried out by GEUS form the basis for development of specific recommendations for future initiatives for fresh water management in the case area. A fruitful way to continue the process prior to the final decision-making process in the waterworks and the Falster Municipality will be to consult the Falster stakeholders again and present and discuss specific initiatives and recommendations based on the most recent results of the field studies and scenario simulations. Such stakeholder consultation would serve as a logical follow up on the previous consultation process with updated information and will be in accordance with the wishes expressed by the stakeholders at the workshop.

Such a dialogue process will contribute to the effort making the technologies more visible and better understood and to addressing requirements of the stakeholders in the local society so that the implementation enjoys local support and legitimacy.

Considering the fact that water quality and the environment were of the most concern to the stakeholders it seems that desalinization of deeper unpolluted brackish groundwater is the best and most likely source for injection of freshwater to enhance the freshwater resources in the Chalk aquifer. The costs for this is only slightly less than the costs for purification of drainage water, and the cost-efficiency of both implementation, operation and maintenance of such this solutions is, however, currently considered too high for Falster and similar Danish settings. The costs of available alternatives such as the drilling of new wells and/or supply from neighbouring water works are still much lower,.

The expected climate change in the future will most probably change the freshwater situation, but for the time being there is no real lack of freshwater in Danish waterworks, hence no real interests in the Danish drinking water market for solutions primarily focused on increasing the subsurface volume of freshwater. Currently the climate models project wetter winters and hence increasing water tables in Denmark. Still SWS techniques may be required e.g. on Falster, where very high seasonal variations in water demand during the summer combined with potential long dry periods and drougths may put the resource under pressure.

From a technical point of view the most promising sws in Denmark in general is most probably the Freshkeeper technique. Currently 2-3 waterworks could in the near future be willing to test the Freshkeeper for reducing residual saline water in the aquifer and perhaps more important to provide sufficient water to feed surface water streams if dry summers are prevailing. The saline tolerance accepted for streams lies in the range of 500-1000 mg/l of chloride i.e. 2-4 times the drinking water standard.

The use of SWS for irrigation purposes in Denmark is generally not of relevance as long as sufficient freshwater is available in secondary aquifers. Although several irrigation wells in the investigated Falster site are threatened by salt water intrusion the costs of desalinization is still too high.

The near future

GEUS will continue to investigate the saltwater intrusion issue and explore the possible use of the subsurface water solutions on Falster in a new project (TACTIC - Tools for assessment of climate change impact and adaptation strategies) of the new GeoERA programme (www.geoera.eu). The TACTIC project has two work packages closely related to SubSol one dealing with salt water intrusion issues and one dealing with groundwater adaptation strategies. The Falster site is a case study in both.

Futhermore, GEUS will add additional information about the Falster site as a special case of a dual-porosity fracture carbonate aquifer, to the SubSol Knowledge Environments (KE) on subsurface water solutions (http://www.subsol.org/home/article/subsol-knowledge-environment) and explore possibilities of creating additional links between the SubSol KE, the European Inventory of Groundwater Research (http://kindraproject.eu/eigr/) and the GeoERA Information Platform on subsurface resources (http://geoera.eu/themes/information-platform/). The latter is part of the European Geological Data Infrastructure (http://www.europe-geology.eu/).

Orbicon and GEUS will continue to explore the possibilities and needs for implementing small to medium scale SWS in Denmark in well fields in sandy as well as dual-porosity fractured chalk aquifers. The implementation of such methods are currently not critical for Denmark, but for many other coastal regions, globally. With the projected climate change we believe that SWS techniques will be of increasing importance in the future also in Denmark.

Conclusion

The conducted tests at the Falster test and replication site demonstrate that a combination of the "Freshkeeper" and "ASR-Coastal" SWS techniques has a significant potential for ensuring a future sustainable abstraction of groundwater resources of the Marielyst Water Works from a technical point of view.

Currently, the added costs for:

1) Detailed site assessment studies,

2) Treatment and purification of either freshwater from nearby drain ditches or brackish waters from deeper parts of the chalk before injection or reuse and

3) Operation and maintenance of the water treatment systems

in combination seem to be too high to be an attractive solution for Marielyst Water Works in the near future. Additional obstacles include difficulties obtaining permissions for injection of treated water types in aquifers used for drinking water supply.

However, our field investigations indicate that it may only be a matter of time before salt water intrusion issues becomes so severe that the application of SWS techniques is the only option if the local authorities and the water works want to keep the water supply within the area.

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