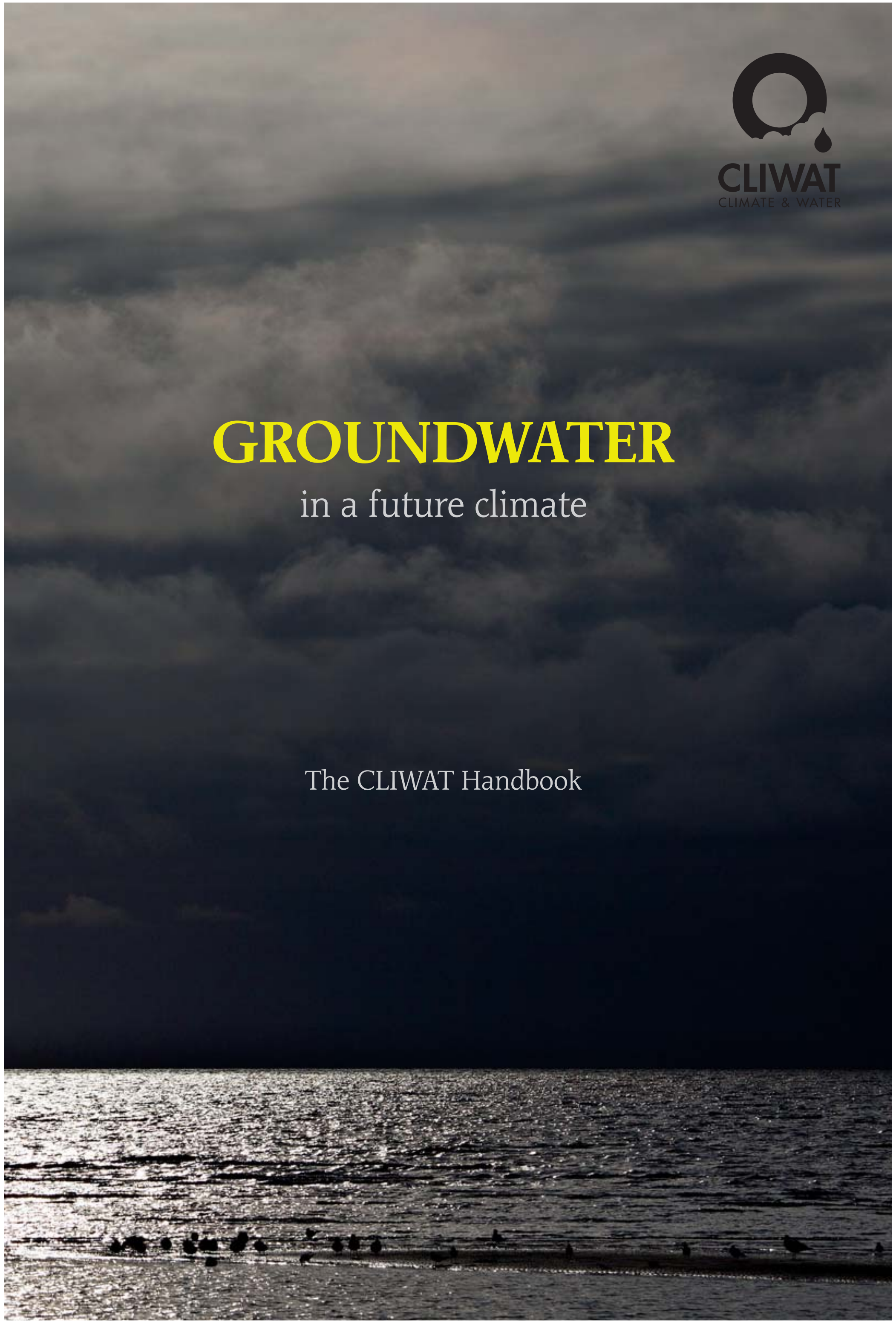

GROUNDWATER

in a future climate

The CLIWAT Handbook

Groundwater in a Future Climate
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The Cliwat Project Group
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Groundwater in a future climate

This handbook is a product of the CLIWAT project (CLImate change and groundWATer) highlighting the main results and recommendations of the project for planners and practitioners at local, regional and national levels. CLIWAT is a transnational project in the North Sea region dealing with groundwater mapping and adaptive planning and solutions for the coming challenges caused by climate change. The project aims at bridging EU-science and policy on climate change impact and adaptation in the North Sea Region at a practical level. The research and analysis covers a broad spectrum of geoscience and focuses on gaining a better understanding of the effects of climate change on the quantity and quality of groundwater. The project started in September 2008 and ends in March 2012. The project involves sixteen partners from Germany, The Netherlands, Belgium and Denmark. The handbook is complimented by a number of scientific papers from all pilot areas in a special issue of the on-line journal "Hydrology and Earth System Sciences" with the title "Assessing the impact of climate change for adaptive water management in coastal regions".

1 Introduction

The CLIWAT project is especially concerned with the effects of climate change on groundwater systems. Most of its investigations have been performed in coastal areas. Within the project, we have identified present and future challenges caused by the changed groundwater levels and developed climate scenarios focusing on shallow groundwater and deep groundwater, as well as the impact on water management.

The quality changes of the groundwater resource caused by salt water intrusion, outwash from point and diffuse sources to groundwater, surface water and ecosystems, and new demands for water use are some of the issues which have been investigated. This enables the North Sea Region to react and adapt more efficiently to the consequences of climate change.

A wide range of stakeholders, such as water management companies, the construction industry, authorities and the agricultural sector have been involved in the project, all putting forward recommendations on where the work should focus. This cooperation has been on-going during the project, where invited sectors were able to offer good ideas and evaluate the research process with the investigating scientific parties.

If any of the scenarios forecast by the IPCC become reality, this handbook can point the way forward as to what will happen to groundwater systems and the subsequent consequences for society. Furthermore, it can be used as input for development of climate proof regional river basin management plans according to EU directives and guidelines.

The handbook contains special themes related to groundwater management and the appendix contains results and experiences gained in the pilot areas.

We hope that this handbook will provide inspiration to authorities' and planners in local, regional and national offices, civil engineers, water management companies and other professionals dealing with climate change and groundwater.

Visit www.cliwat.eu and explore the CLIWAT interactive results map and much more.

We would like to express our gratitude to the individuals and public,private organisations and companies who contributed to the project and to the EU Interreg IVB North Sea Region Programme for making it possible.

Sincerely,
The CLIWAT partners

The Netherlands
Deltares
Wetterskip Fryslân
Provincie Fryslân
Vitens

Belgium
Ghent University

Germany
LIAG (Leibniz Institute for Applied Geophysics)
BGR (Federal Institute for Geosciences and Natural Resources)
LLUR (State Agency for Agriculture, Environment and Rual Areas)
SeeConsult GmbH

Denmark
Aarhus University
GEUS (Geological Survey of Denmark and Greenland)
Danish Ministry of the Environment Nature Agency
Municipality of Horsens
Region of Southern Denmark
Central Denmark Region

December 2011

2 Summary

Chapter three provides an overview of the most widelyknown challenges related to water in a future climate in the CLIWAT projectarea. The challenges vary between sectors due to different planning schedules.

Chapter four describes eight themes related to groundwater and climate change. The themes highlight areas of special focus when dealing with groundwater and climate change.

From a groundwater perspective, rising sea level has special significance in low lying coastal areas and on islands. The amount of local sea level rise is dependent on the predicted worldwide sea level response on climate change and the local land subsidence/uplift (Section 4.1).

Polder areas are low-lying areas with a delicate management system in order to keep the areas dry by transporting excess water to the sea. In view of future climate this management and the amount of fresh water is under pressure in these areas (Section 4.2).

Groundwater resources on islands are often under great pressure due to the large amounts of extracted water during the summer season and special care for management of land use and abstraction strategy (Section 4.3) is needed.

During the CLIWAT project a number of geophysical, monitoring and geochemical methods to describe the subsurface were tested and developed further. Overviews of relevant methods are given in Section 4.4.

Groundwater and integrated hydrological models serve as the main predictive tools when we try to describe the effects of future climate conditions, e.g. in river basin management plans as required by the EU Water Framework and Groundwater Directives. Although models are presently used as important tools for predicting climate change impacts, significant challenges still remain with respect to accuracy and reliability of the models. Describing future shallow geological formations and groundwater reservoirs in the countryside and in the cities with many manmade installations constitutes a major challenge. Read more in Section 4.5.

Groundwater reacts differently depending on the local geology, which forms the basic settings for the hydrological systems. In clay-rich areas much of the increased precipitation will runoff rapidly into the streams, while the groundwater table in sandy areas will rise significantly due to increased precipitation. Section 4.6 elaborates this theme.

Rising groundwater in urban areas is posing a special challenge. Section 4.7 describes the quality aspect of groundwater seen from an urban perspective and illustrates the importance of including climate change in construction industry project planning.

From the many investigations predicting future conditions in the groundwater reservoirs a number of thematic maps can be outlined, which can be used in planning and management. Examples of thematic maps are given in Section 4.8.

One of the important and challenging aspects of the adaptation process when dealing with climate change and water is getting stakeholders involved.
Chapter 5 deals with the process of understanding the importance of involving stakeholders, establishing a participatory process and achieving goals.

Through a stakeholder process such as the one implemented in the CLIWAT project, it is possible to raise local, regional and national awareness of an issue. Moreover, the participatory process of this project has demonstrated that there are numerous effective solutions that can be developed and implemented when stakeholders work together to create win-win situations – both for individual sectors and society as a whole.

An overview of existing and future EU legislation and guidelines that have special relevance to groundwater is given in Chapter 6. The chapter highlights some of the CLIWAT results in an EU policy perspective. Furthermore, Chapter 7 puts the CLIWAT project into perspective.

In the future we have to be able to create cost-effective methods for describing climatic effects on groundwater on a local scale, with accuracy and detail that both planners and engineers can use in their daily planning and construction projects.

This means that we have to develop:

- Cost-effective methods (e.g. geophysical, effective drillings, geochemistry) to describe the nearsurface geology
- Easy understandable and manageable groundwater models that describe groundwater flows and solute transport in the uppermost part of the aquifer that is suitable for planning and engineering purposes on a local scale
- Well considered monitoring of the groundwater systems on a local scale
- A better understanding of future leaching from point sources and agricultural areas in order to develop new standards for best practice
- An integrated stakeholder approach
- Efficient on-line data presentation and dissemination tools which can be updated with new results and predictions

The CLIWAT project investigations have been carried out in seven pilot areas, all situated in the North Sea Region. In the appendix you will find a description of the challenges and results in each of the pilot areas.

3 Challenges in the future climate

– an overview

The challenges related to adaptation to future climate change vary widely from sector to sector. Some sectors may adapt gradually as climate changes occurs, while others such as in the area of infrastructure planning may have to make tough decisions that last for many years. Adaptation in one sector may also influence adaptation requirements in other sectors, either by presenting new opportunities or by creating new problems. Cross-organisational and sectoral cooperation is needed to produce viable solutions.

This chapter can be used as an overview and checklist when working with adaptations related to climate-change impact on water and water resources. The themes are grouped as follows:

- Surface water, sewage and drainage systems, and wastewater treatment plants
- Groundwater, water supplies and groundwater protection
- Open countryside
- Protecting houses, roads, railway lines and other technical installations
- Physical planning
- Multifunctional solutions

Climate change adaptation is in its infancy but it is an area of growing focus.

The changes are forecasted to take place into the future, so it's natural to ask why should we work on the problem now? A short answer to that question is: Prudent planning and adaptation saves a great deal of money (EEA report no.4, 2008). An example from Denmark shows that climate change adaptation costs approx. 20% of the costs of repairing damage in a situation where there has been no adaptation (Central Denmark Region, 2010; Danish Ministry of Environment, 2007).

3.1 The climate change scenario

CLIWAT has taken its point of departure from the Intergovernmental Panel on Climate Change (IPCC) Assessment Reports and its respective A2 climate scenario. The A2 scenario is a moderate scenario based on a moderate growth in the global economy and slow reductions in the emission of greenhouse gasses.

Based on key climatic parameters in the A2 scenario, we can expect in 2100:

- Temperature Higher Greater variation
- Windspeed Higher Greater variation
- Precipitation More Greater variation
- Extreme events More Greater variation
- Sea level Higher Continuously increasing

There are 20 climate models set up worldwide, and there are 11 climate models for Europe. The climate scenarios are predominantly unequivocal for the period 2010–2050. After 2050, model forecasts diverge and thus post-2050 scenarios are subject to a great deal of uncertainty.

Scenario A2				
Country	DK	DE	NL	BE
LAND				
Annual mean temperature	+3.1 °C	+2.9 °C	+2.0 °C - +4.0 °C	+3.6 ºC
Winter temperature	+3.1 °C	+3.6 °C	+1.8°C - +4.6 °C	+1.5 °C - +4 ºC
Summer temperature	+2.8 °C	+2.7 °C	+1.7°C - +5.6 °C	+2.4 °C - +7.2 ºC
Annual precipitation				
Winter precipitation	+43%	+25%	+7% - +28%	0 - +64%
Summer precipitation	-15%	-5%	-38% - +6%	-76% - 0%
Maximum daily precipitation	+21%		+8% - +54%	+20%
SEA				
Average wind	+4%	+5%	-2% - +8%	+15%
Max. water level at coast	+0.45 - +1.05 m (excl. land subsidence)	+0.94 m (including land subsidence)	+0.35 - +0.85 m (excl. land subsidence)	+ 0.7 m
LAND AND SEA				
Max. storm strength	+10%	+6%		+10 %

Table 3.1.1 IPCC's Climate scenario A2 (year 2100) is used in the pilot studies as a common frame. In the table each country specific figure is listed. It should be stressed that in all countries there are a number of scenarios which give rise to different intervals for future climate conditions. The figures given above were supplied either by Torben Sonnenborg, GEUS (DK), Hans Sultzbacher, LIAG (DE), Gualbert Oude Essink, Deltares (NL) or from reference (BE) Willems, P et al, 2009.

The maximum water level at the coast predominantly depends on whether the land is rising or subsiding in the areas. Read more details about this issue in the section "Relative sea level rise in future" in section 4.1.

3.2 Many sectors are affected

Many sectors are affected by climate change. The urgency or demand for adaptation depends on the decision times and lifetime of the installations, crops, etc., in the individual sectors. Therefore, some of the sectors will need to adapt before others.

Sector	Years
Insurance-related aspects	0–1
Farming	1–5
Fisheries	2–10
Health	1–20
Emergency readiness	1–20
Water supplies	5–60
Energy supply	5–60
Countryside and countryside protection	2–100
Forestry	40–120
Land use planning	4–500
Buildings and facilities	10–500
Coasts & dikes	10–>1,000

Table 3.2.1 Some individual sectors and an assessment of their planning schedules (Central Denmark Region, 2010)

3.3 Surface water, sewage and drainage systems, and wastewater treatment plants

We can distinguish between different types of water: waste water, lightly-polluted water from overgrown areas and water drained from town areas affected by rising groundwater, and pure water that overflows from watercourses and groundwater.

Sewage systems are dimensioned to be able to deal with water from ordinary daily use, so the challenge is to keep the other types of water out of the sewage system. Thus the motto: "Keep water locally and use it in new ways in production, urban spaces and in the countryside".

Points for reviewing:

- How do we lower water flow generated by heavy downpours to a level that our systems can manage?
- How do we handle floods from the sea or larger watercourses?
- Should sensitive buildings or installations be pulled back from flood-threatened areas (planning) or be made safe (adaptation)?
- How do we create simple waste water plants to deal with lightly-polluted runoff from roads and drained groundwater?
- How can we work with green solutions in construction (e.g. eco roofs and walls) and parks and countryside management (e.g. local lakes or moors) to strengthen evaporation and cooling and minimise runoff?
- Where and how can we use infiltration to move excess water to the groundwater?

Figure 3.3.1 In the open countryside. The image shows there was space here which could take flood water from the river, which diminished the risk of flooding further downstream in the town. Gesager Å, West of Horsens. Photo Tony Bygballe, Horsens Municipality.

3.4 Groundwater, water supplies and groundwater protection

Depending on the geographical location, the changed precipitation patterns, generally with more rainfall in winter and less in summer, are expected to result in diverse effects on groundwater. In many areas (e.g. Denmark, and border areas between Germany and Denmark) groundwater levels are expected to rise. The impact of climate change is also expected to be a function of catchment characteristics, where sandy areas will experience higher groundwater recharge than clayey areas. Higher winter precipitation is fundamentally positive with respect to groundwater resources but it can also create problems in the form of increased runoff in rivers and flooded fields and cellars in areas where extra water is being added to the local groundwater reservoirs. Dryer summers may result in higher demands for irrigation, which will increase pressure on the water resources. We can see what the future means for deeper groundwater reservoirs with a fair degree of confidence. When we examine potential local problems that will arise from shallow groundwater reservoirs, the future is far more difficult to predict.

It is unclear if the quality of the formed groundwater will remain the same. Increased leaching of pesticides and nutrients from agricultural areas may be a problem, which may only be remedied by using other kinds of crops or agricultural management systems. The increased CO_2 levels in the atmosphere will cause root systems to become stronger and this will result in better uptake of nutrients. Contaminant leaching from polluted areas may increase in total but it is unclear if concentration levels in the filtered water will change. In coastal areas increasing sea water levels are expected to result in problems with salinisation. This will adversely affect many good groundwater reservoirs, leaving useless groundwater behind.

Points for reviewing:

- Waterworks – examine facilities and wells to find out if they are at risk from flooding
- Assess if the catchment area of waterworks will change as a consequence of changing groundwater levels

- Identify potential waterlogged areas in the future
- Consider a strategy to manage field irrigation in dry summers and investigate if water reservoirs collecting winter precipitation can be installed to irrigate fields
- Consider the possibility of strengthening the capacity of the soil to retain water by using a higher quantity of organic material
- Consider the possibility of using targeted afforestation to reduce the formation of groundwater in key areas
- Ascertain if there are polluted sites that are especially exposed to runoff, flooding or increased leaching
- Carry out a study to identify where it is possible to infiltrate roof water and street water
- Outline groundwater bodies in risk of salinisation and consider new extraction strategies in the well sites to minimise the problems

3.5 Open countryside

The altered precipitation pattern means that more areas in the open country will be waterlogged for most of the year due to rising groundwater. The watercourses must be able to handle more powerful downpours and dry summers must be dealt with.

The open countryside is characterised by the fact that there is more space to accommodate large climate adaptation solutions, but the many small solutions that can be found in the countryside ("hydro brakes") could provide a high degree of multi-functionality (more attractive countryside, less erosion, reduced nitrogen and pesticides, and function as reservoirs that can be used in the dry summers) and be a valuable part of the solution.

Points for reviewing:

- Analyse catchment watercourses and identify storage points and watercourse constriction areas with the potential for retaining water in extreme situations

- Consider where waterlogged land in catchment areas will be, by using groundwater models and interviews with local landowners
- Consider catchment areas where wetlands can be established permanently and area for temporary flooding in shorter periods
- Consider which functions can be placed in any new wetlands (e.g. countryside close to the city, new biotopes, nitrogen removal, sedimentation areas, etc.)
- Ascertain if infrastructure, such as road embankments can interact with wetlands
- Plan how and where protected areas for cultivation can exist
- Examine the catchment area widely and find small areas that can be used as hydro brakes and local reservoirs that perhaps have several functions
- Consider how to establish cooperation with landowners regarding projects

Figure 3.5.1 Nature finds its own solutions. This corner of a wheat-field acted as a temporary water storage area after heavy rainfalls saturated the soil and the local groundwater reservoir. The farmer found that it was a problem. We should cooperate with local farmers and other interested stakeholders to look for new multifunctional solutions for small areas, like the one pictured above. A local water reservoir that handles extreme weather events may also operate as a recreational area, for growing willow as a biofuel resource or perhaps just a natural waterhole for local wildlife. Hovedgaard, North of Horsens. Photo Jes Pedersen, Central Denmark Region.

3.6 Protecting infrastructure and technical installations

The most significant effects will come from rising sea levels and respective increased storm floods, from rising groundwater and from increased precipitation, both from long-term winter precipitation and from more extreme and intensive downpours in the summer and autumn months.

The essential problem is that many of our towns and transport routes, forms of transport, manufacturing, residences and ways of living are placed in locations that are appropriate for historic water levels and climate. These relationships have now changed so much that we must consider if some of our towns, infrastructure, etc., are correctly located and the technologies we are using are sustainable and future-proof.

On the positive side, climate change means greater utilisation of increased solar energy, wind energy, temperature, and increased volumes of rainwater and groundwater.

Points for reviewing:

- Map where there is a risk of damage from rising groundwater, storm floods or watercourses
- Carry out an analysis to ascertain if there are any facilities in risk areas
- Consider if individual buildings/installations should be protected from climate change or if there should be centralised solutions (like dykes) for large areas, e.g. towns and cities
- Consider if the establishment of climate change protection can provide several functions and interplay with other functions in the area
- Compile a catalogue of simple technical solutions that can be continually and successively implemented, e.g. in the case of maintenance
- Establish a demonstration area, where specialists and the general public can see examples of climate solutions

Roads and railways

The impact of raised groundwater level will affect existing roads and railways. In low-lying areas, groundwater will flow into underground road and rail infrastructure, which will cause a change in structural stability. This may lead to cavities, penetration damage or even a collapse of the structure.

For existing roads and railways, damage prevention measures can be introduced during planned restoration or maintenance while new roads will have to be built with a draining system adapted to the changed conditions. In larger structures, the local hydrological system has to be understood and local groundwater models are a useful tool for establishing a basis for designing an appropriate draining system. For example, the Danish road directorate is modelling the effects of changed groundwater conditions to foresee the hydrological changes on the drainage of the road network. This work is done in collaboration with partners in the CLIWAT project and has been included in the Danish national board established in the CLIWAT project.

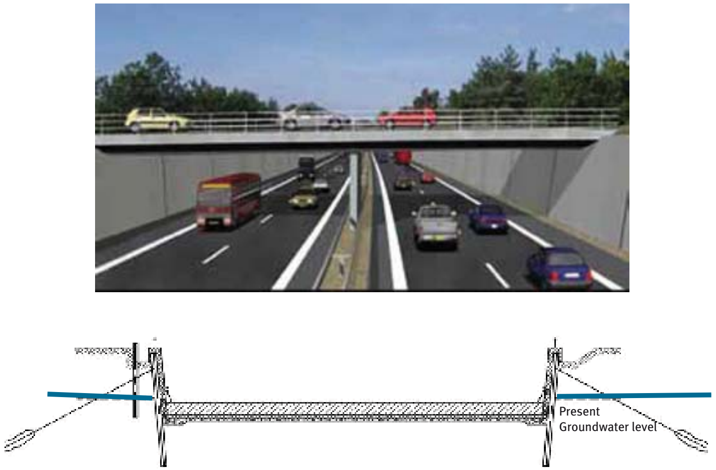


Figure 3.6.1 A motorway in central Jutland where the bottom is situated 7 m beneath terrain and below the present groundwater level. After Danish Road Directorate.

3.7 Physical planning

Climate change adaptation planning is not yet an area incorporated into planning in many areas.

Planning for climate change adaptation requires a high degree of cross-organisation work and total solutions. Everyone contributes and owns the solutions. The optimum solution is one that integrates reductions in CO_2 emissions and climate change adaptation in a concerted plan. The publication of climate change adaptation planning requires care, so that no single landowner is unnecessarily disadvantaged when pointed out.

Points for reviewing:

- If possible, make a factual theme map that shows flood-threatened areas (from rising groundwater, watercourses, lakes and sea) and flood-proof areas
- If possible, make a map showing risks, where Risk = damage extent x probability
- Using the above-named maps, a long-term plan should be devised at a regional and municipal level. In connection with this, consider how interested parties can be involved in a debate about visions
- Prepare a climate change adaptation plan with maps that show:
  - Dry areas
  - Flood-threatened areas with shared protection (dykes, etc.)
  - Flood-threatened areas with individual flood-proof buildings
  - Areas exempted from future construction
  - Areas where water can be stored
  - Areas laid out as future storage basins
  - Areas where local filtration of rainwater can take place

- Consider whether contingency plans should be prepared for specially threatened local areas.
- Consider establishing beacon projects with examples of exciting integrated planning.

3.8 Multifunctional solutions

Climate change adaptation is not necessarily rocket science. Solutions for many of the described problems already exist today.

What is crucial is the ability to combine individual solutions from different sectors and think about the positive aspects of climate change. A good combination can actually create new values for society and make the coming work considerably less expensive.

The key concept is good processes between different players involved in climate change adaptation. With an open mind, participants can discover together and search for the win-win situation; where individual sectors use each other in useful ways.

All of the elements should provide multifunction in the future, in such a way that they contribute to good climate change adaptation.

4 Climate and groundwater

In this chapter a number of themes of special interest to future challenges in respect of groundwater are described.

From a groundwater perspective, rising sea level has special significance in low lying coastal areas and on islands. The amount of local sea level rise is dependent on the overall sea level rise and the local land subsidence/uplift (Section 4.1).

Polder areas are areas with a delicate management system in order to keep the areas dry by transporting excess water to the sea. In view of future climate the amount of fresh water is under pressure in these areas (Section 4.2).

Groundwater resources on islands are often under great pressure due to the large amounts of extracted water during the summer season (section 4.3).

During the CLIWAT project a number of methods to describe the subsurface were tested and developed further. Overviews of relevant methods are given in Section 4.4.

Groundwater and integrated hydrological models serve as the main predictive tools when we try to describe the effects of future climate conditions, e.g. in river basin management plans as required by the EU Water Framework and Groundwater Directives. Although models are presently used as important tools for predicting climate change impacts, significant challenges still remain with respect to accuracy and reliability of the models. Describing future shallow formations and groundwater reservoirs in the countryside and in the cities with many man-made installations is a major future challenge. Read more in Section 4.5.

Groundwater reacts differently depending on the local geology which forms the basic settings for the hydrological systems. In clay-rich areas much of the increased precipitation will runoff rapidly in the streams, while the groundwater table in sandy areas will rise significantly due to increased precipitation. Section 4.6 elaborates this theme.

Rising groundwater in urban areas is posing a special challenge. In section 4.7 describes the quality aspect of groundwater seen from an urban perspective and illustrates the importance of including climate change in construction industry project planning.

From the many investigations predicting future conditions in the groundwater reservoirs a number of thematic maps can be outlined, which can be used in planning and management. Examples of thematic maps are given in Section 4.8.

4.1 Sea level changes with special focus on land subsidence

Sea level rise is caused by several interacting factors, some may result in a rise and others may result in fall. When we are dealing with the sea level rise related to global warming, we can identify two main components: Sea level rise is caused essentially by the expansion of sea water due to temperature increase and the melting of glacier ice in the Arctic and Antarctic regions. However, there are other factors which contribute to the relative movement of sea level at a local level. In the following section land subsidence at the "CLIWAT" North Sea Coast is evaluated.

Land subsidence varies in magnitude and form in a complex pattern along the North Sea coast. This can be seen in Fig. 4.1.1, where the expected land subsidence for the Netherlands after the first half of the current century is displayed. The main consequence of land subsidence at the North Sea Coast in combination with global warming is a significant rising sea level.

The reasons of this subsidence are different. Land subsidence is caused by crustal movements which cannot be solely attributed to tectonic activities. It clearly contains a non-linear, glacial- and/or hydro-isostatic component, which is only small on the Belgian coastal plain but increases significantly along the Dutch and the northwest German coast. The subsidence is at least in part related to the post-glacial collapse of the so-called peripheral fore bulge which developed around the Fennoscandian centre of ice loading during the Last Glacial Maximum (a. Vink, et al,) (A. Daschkeit and H. Sterr 2003).

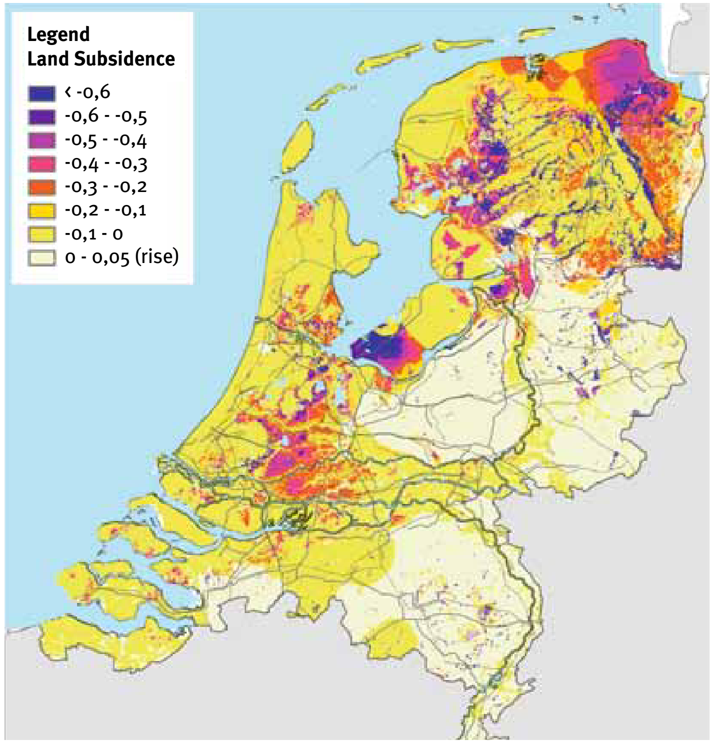


Fig. 4.1.1 Expected land subsidence for the Netherlands in meters after the first half of the current century. The overall subsidence is 10–40 cm, locally up to 80 cm.

A further relevant process for land subsidence is caused by the compaction of peat which occurs in wide areas of the North Sea coast. The peat is compacted due to the pressure of the overlying sedimentary layers (H. Streif, 2004), dewatering and oxidation. Clay shrinkage, peat oxidation, deep salt mining and/or oil and gas extraction can also contribute to land subsidence.

Land subsidence plays a subordinate role on the Belgium coast and on the Dutch North Sea island but its impact on the German East Frisian islands should be considered. For the pilot area of Borkum, a subsidence figure of 15 cm was used as a best estimate extrapolation from regional values described in the literature.

The amount of sea level rise for the German North Sea using the IPCC emission scenarios (IPCC 2007) has been computed by S. Rahmstorf (2007). Fig 4.1.2 illustrates the predicted sea level change for different IPCC emission scenarios. Using the IPCC-A2 scenario from 1995 until 2100, including land subsidence, the sea will have changed its elevation by 1 m or 0.94 m from 2010 to the year 2100. This value will be used for the simulations with the numerical model in Pilot Area D Borkum. Rahmstorf also estimates the possible error in the computations for the sea level (marked grey in Fig. 4.1.2).

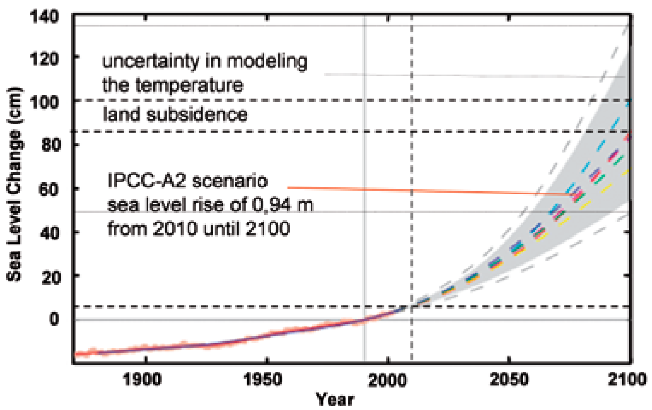


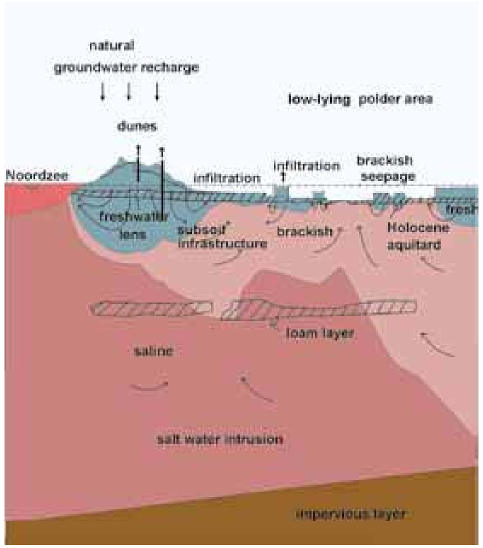
Fig.4.1.2 Predicted sea level rise (without accounting for the subsidence) of the German North Sea until 2100 using the IPCC-A2 scenario (after Rahmstorf 2007)

4.2 Polder areas

Polders are low-lying areas enclosed by dunes, dikes or more elevated surrounding areas (fig 4.2.1). They are frequently found in The Netherlands, Belgium and parts of Denmark and Germany. They have their own network of artificial drainage channels, which are used to manually control the water level. Good management of the water level is imperative for those areas that are used for agriculture.

Coastal aquifers will become more saline due to salt water intrusion and this could lead to a loss in fresh groundwater resources. In addition, low-lying delta areas have another process called seepage, i.e. upward flow of groundwater because a higher hydraulic head in the first aquifer, which is situated just below the Holocene confining layer, exceeds the phreatic and surface water levels. Seepage will lead to more saline groundwater and surface water systems, mainly because the seepage will come from brackish to saline groundwater from old marine deposits.
Sea level rise and climate change will have a measurable impact on groundwater and surface water management in the polder areas. With long term sea level rise:

- The discharge opportunities into the sea will decrease. A possible consequence of this is that water will have to be stored longer in the polder areas; so the storage capacity of the polder areas will have to increase. Another possibility, already used in the polders below sea level in The Netherlands, is to use pumps to discharge the water at a higher sea level.
- Seepage and seepage salinity will increase in the polder areas. In many areas this will lead to an increase in the salt load of the surface water system which will adversely affect fresh water resources and crop yield when the saline water is used for irrigation.
- The small fresh water lenses on top of the saline groundwater are at risk of getting brackish when the seepage increases. Those small fresh water lenses in saline seepage areas make agriculture possible.
- Fresh water lenses that are situated in the areas with a small dune belt are at a much greater risk of diminishing. Dunes acting as important reservoirs for freshwater are threatened by saltwater intrusion. In Belgium, the dimensions of the dunes differ from location to location.



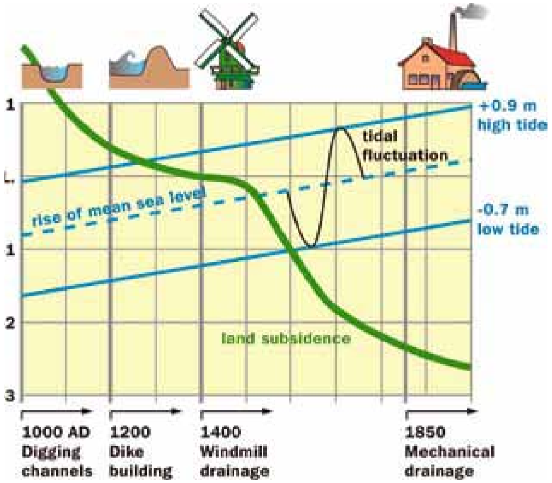


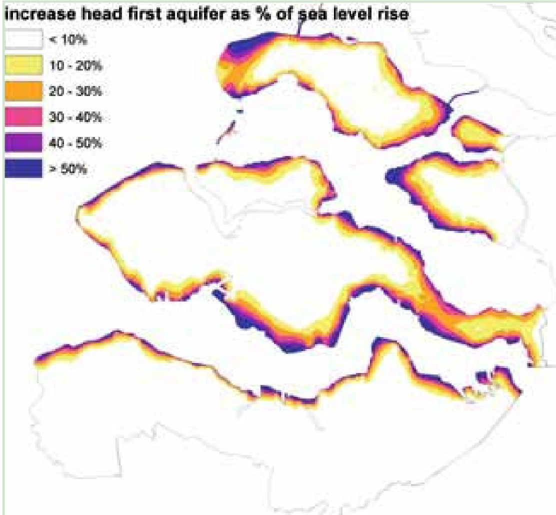
Figure 4.2.1.a Conceptualisation of the Dutch and Belgium coastal groundwater system. Figure 4.2.1.b Land subsidence in the Netherlands during the past 1,000 years [van de Ven, 1993]

It's expected that periods of heavy rainfall and severe storms will occur more frequently in the future. Due to inadequate drainage, flooding may arise during such periods of heavy rainfall. Inundation of agricultural and urban areas causes economical damage. In the polder area these periods of heavy rainfall could result in infiltration of important amounts of fresh water in the aquifer, whereas at the present moment this fresh water is drained away as quickly as possible. Additionally, severe storms may result in flooding whereby sea water inundates parts of nature reserves. In this case, salt water will enter the aquifer. Consequently, these floods will significantly alter the groundwater flow and the freshwater – saltwater distribution.

The impact on recharge patterns and polder drainage will also affect agriculture. The predicted increase of periods of drought will cause a reduction of the small fresh water resources. The coastal plain groundwater resources need to be monitored and protected to meet current and future demands for water. Smart new methods for drainage can help to protect polder area agricultural land from salinisation, drought and inundation.

Focus should be placed on the following:

- Optimisation of drainage of the polder areas for drought, salinisation and inundation
- Maintaining or increasing the fresh water lenses in the dune areas
- Maintaining or increasing the small fresh water lenses in seepage areas
- Monitoring the groundwater resources
- Determining effects of climate changes compared to other effects on groundwater resources in polder areas



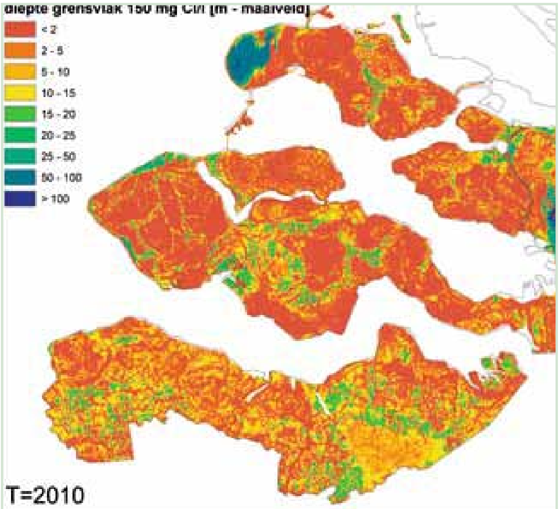
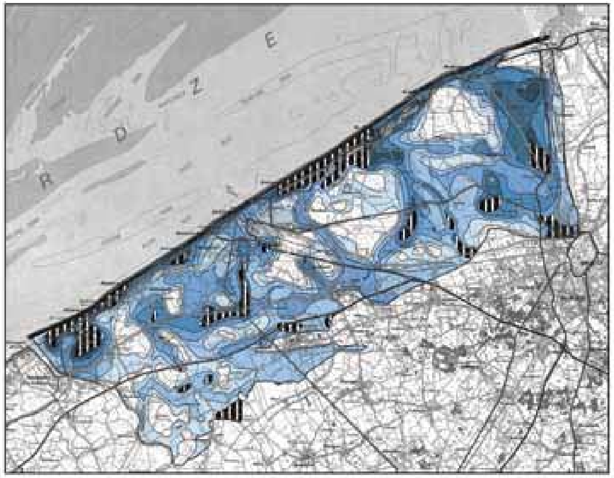


Figure 4.2.2.a The influence of see level rise on the groundwater head in the first aquifer in the Netherlands. Figure 4.2.2.b The depth of the fresh-brackish interface of the groundwater in the Netherlands.



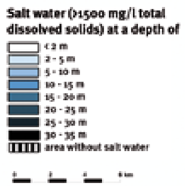


Figure 4.2.3 Depth to the 1,500 mg/l isosurface in the central Belgian coastal plain (Vandenbohede et al,2010).

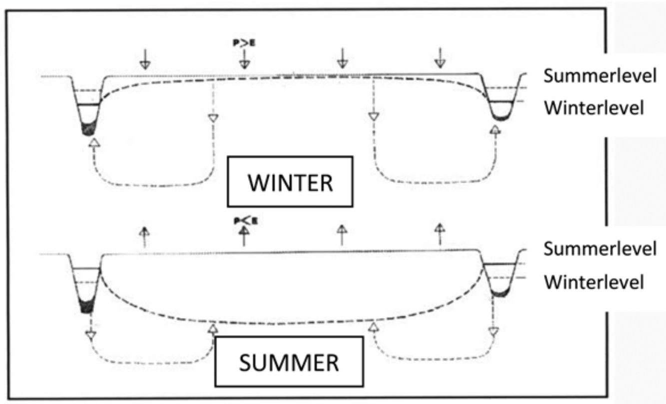


Figure 4.2.4 Management and related groundwater level and surface water level in polder areas during winter and summer (WES, 2005).

4.3 Groundwater resources on islands

Several sandy islands are situated in front of the Dutch, German, and Danish coasts. They are called the Wadden islands. Based on the Ghyben-Herzberg principle, a fresh groundwater lens has been established under these islands. The dunes are rising several meters above sea level. As a consequence of the increasing rainfall, the groundwater in the dunes subsurface rises (swell) to above sea level. The resulting formed isostatic pressure pushes the interface of salt/fresh water downwards.

On a small area of the islands we can find a complete water cycle with all of the associated components. The water lenses are the "beating heart" of the water system of the island and make them unique. Humans (inhabitants and tourists), plants and animals depend on this fresh water. The CLIWAT project selected the islands Terschelling and Borkum as pilot areas, with the aim of investigating the impact of increasing salt water intrusion and shrinkage of the fresh water lens (caused by sea level rise) on barrier island fresh water resources.

Groundwater & coastal defence

The dunes of the islands form a natural barrier against flooding and protect the people who live there. Structural erosion and loss of sediment will have an effect on the equilibrium based on the Ghyben-Herzberg principle. In this case, with smaller dunes the coastal defence function will decrease, the groundwater table will become lower and the fresh water lens smaller. The total effect will be that the risk of salinisation will increase.

Groundwater & ecology

We can find dry and wet environments close to each other among the dunes, each with a huge variation of, mostly rare, plant species. The plants in these dune slacks are strongly related to the site-specific quantity and quality of groundwater. Disturbance of this eco-system caused by groundwater abstraction, coastal erosion or climate change can have an adverse effect on these fragile ecological systems in the dunes.

Groundwater & drinking water

For the drinking-water facilities, a greater part of these islands are dependent on the fresh groundwater that can be found in the freshwater lens under these islands. Water supply companies placed the screens of pumping wells in this lens. Several factors can affect the sustainability of the drinking water supply in the future. Naturally, the level of domestic water consumption is one factor – will there be enough fresh water in this water lens to produce the domestic water without risks for saline up-coning? Another important factor will be the effect of sea level rise and climate change on the distribution of the salt/fresh interface and the 'shape' of the fresh water lens.

Hydrological water circle Wadden islands

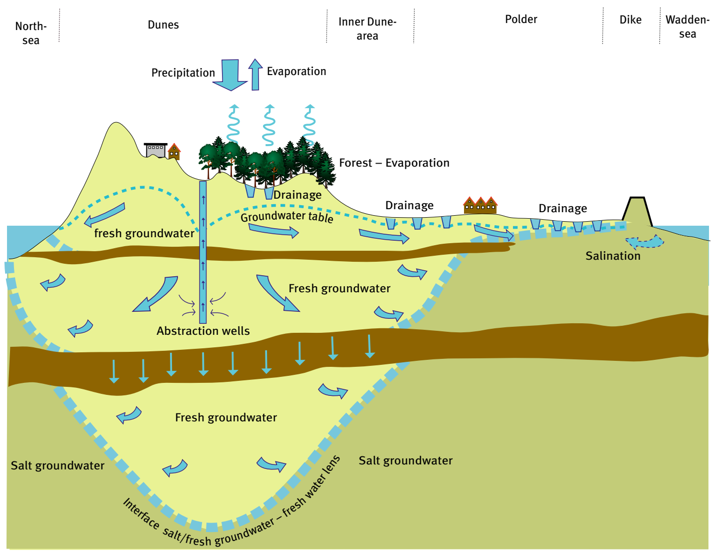


Figure 4.3.1 Cross-section hydrological water cycle

Groundwater & agriculture

On the south sides of the islands there is (reclaimed) marshland and agricultural land, used by farmers to graze their cattle. Until now the fresh water supply of these areas has been based on a very shallow fresh water lens. Sea level rise and an increase of salt seepage may change fertile and healthy grassland into less valuable grassland. Will 'traditional' farming on the islands remain possible when the climate changes?

The effect of climate change on groundwater on the islands

The 'quality of life' on the islands is strongly related to fresh groundwater, based on a small-scale water cycle. Tiny changes in this cycle can have effect for this quality of life for humans, animals and plants. The equilibrium between fresh groundwater and salt groundwater is the driving force behind the hydrological system. For the near future, the major question is how to manage the groundwater resources on these islands. Any effective utilisation of the groundwater resources means there has to be enhanced knowledge of the island subsurface. This information is essential to counteract the hazards of the increased salt water intrusion and it is far more effcient if we find out at an early stage.. It is important that we understand how the water cycle and the hydrological system, works.

By carrying out examinations using bore holes and by systematically using hydrogeological and geophysical methods (such as those utilised at Borkum and Terchelling), the fresh water lens can be analysed becoming polluted by the surface. Using numerical models and monitoring systems, the configuration of the water supply well fields can be optimised in order to prevent excessive salinisation caused by up-coning or saltwater intrusion from the sea due to sea level rise.

That is why investing in research into the effects of climate change is necessary and useful. It ensures we can manage our groundwater recourses on the islands in a sustainable way!

Figure 4.3.2 Borkum North East coast 29 January 2007. Ten days after hurricane »Kyrill«. Seawater is covering a large part of the land behind the dunes.

4.4 Investigation methods

Hydrogeological modelling is »the engine« to produce valid climate predictions in the groundwater systems. In order to set up the groundwater models it is essential to have a comprehensive understanding of the geological subsurface of the earth in the areas being investigated. Geophysical methods greatly contribute to the geological understanding of the subsurface area and can be obtained without using the direct method such as boreholes or coastal profiles. The CLIWAT project focused on the development of these geophysical methods (new as older) so that basic climate modeling could be refined.

Actual situation					
Geophysical surveys	**Property / parameter**	**contribution to model**	**1-D**	**2-D**	**3-D**
Seismic methods	Seismic velocity, elastic properties	Layer boundaries and porosity indicator			
- P-wave				X	(x)
- S-wave				X	(x)
- VSP (vertical seismic profile)			X		
Resistivity methods	Resistivity or conductivity	Layer boundaries Salinity / clay content Porosity / permeability indicator			
- EM (electromagnetic)			X	X	X
- TEM (EM in time domain)			X	X	X
- IP and DC (induced polarisation and direct current)			X	X	(x)
GPR (ground penetrating radar)	Permittivity / dielectric constant	Near surface structure and water content --> mapping water table		X	(x)
MRS (magnetic resonance sounding)	NMR-Amplitude and relaxation time	Water content, effective porosity, hydraulic conductivity	X	X	
Gravity	Density	Structural features, modelling		X	(x)
Borehole and well logging	Diverse	Layer boundaries, salinity, clay content, water content, lithology	X		
Direct push, CPT (cone penetration test) + additional tools	Sleeve friction and tip resistance additionally, e.g. resistivity, water sampling	Lithology discrimination (clay, sand)	X		
Pump tests		Hydraulic conductivity	X		
Dating age of groundwater		Residence time	X		
Change in time					
Monitoring	Resistivity via vertical electrode chain, etc.		X	X	
Change in time and space					
Modelling	Variable density groundwater flow and coupled solute transport Hydraulic conductivity, transmissivity, heads, storage coefficient	Changes in groundwater flow			X

Table 4.4.1 Geophysical methods relevant for groundwater research (see also Kirsch 2009).

Essential data for the database for hydrogeological modelling in the CLIWAT project were thus obtained from geophysical measurements (e.g., Kok et al. 2010, Burschil et al. 2011, Sulzbacher et al. 2011). In Table 4.4.1 the main characteristics of the geophysical methods used in the project are listed.

In several pilot areas, airborne electromagnetic (SkyTEM or HEM) and reflection seismic surveys were carried out. The electrical resistivity measurements obtained from SkyTEM surveys (Fig. 4.4.1) were used to delineate freshwater bodies, saltwater intrusions, groundwater protective clay layers and contaminant plumes. It was found that the problems of interpreting resistivity data (saline groundwater versus clay) could be solved by including MRS data in the interpretation (Günther et al. 2011). A correlation between hydraulic conductivity and electrical resistivity was found from borehole data. This could be used for an interpretation of the resistivity distribution inside the aquifer in terms of the distribution of hydraulic conductivities (Kirsch et al. 2011).

Reflection seismic surveys, backed by vertical seismic profiles, illustrate the layer sequence in the groundwater, relevant to the range of depth. The “classical” application was the detection of buried valleys (e.g. BURVAL Working Group 2009) which were also found in the CLIWAT pilot areas. On the island of Föhr (Pilot Area E), intense glacial thrust faulting was detected (Fig. 4.4.1). This could lead to pathways for infiltration of rainwater as well as contaminants into the groundwater body.

High resolution reflection seismic data were used as a constraint for the interpretation of SkyTEM results. Taking the depth to seismic reflectors as depth of resistivity changes, a more reliable resistivity cross section is obtained, which enables a better interpretation of the layer sequence in terms of water bearing sands, clayey protecting layers and saltwater intrusions (Fig. 4.4.1).

Also of special interest from a climate perspective, is an automated electrical resistivity tomography system that monitors changes in the transition zone between the freshwater lenses and the underlying saltwater on the North Sea island of Borkum (Grinat et al. 2010). The system will help the waterworks in understanding the effects of pumping and warn them in case of up coning of saline groundwater.

The CLIWAT project shows that in the future we have to have a stronger focus on how to describe the uppermost layers of the earth in order to predict where groundwater flooding can pose a risk to infrastructure, etc.

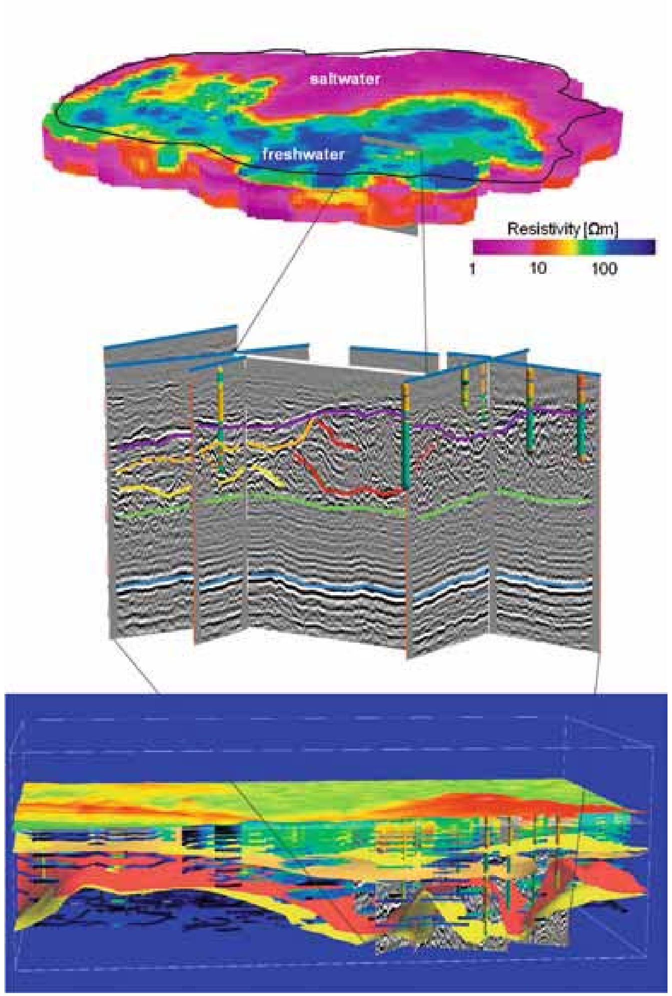


Figure 4.4.1 Examples from the North Sea island of Föhr (after Burschil et al. 2011): (top image) 3-D data volume of resistivity from the SkyTEM survey displaying saltwater bearing areas (very low resistivity); (middle image) seismic depth sections revealing buried valley (purple horizon) and thrust faults or push moraines (red and yellow horizons) above detachment plane (green horizon); (bottom image) view into 3-D geological model of the Island of Föhr based on drillings, SkyTEM and reflection seismic sections, exposing a very detailed layer structure.

Future development of geophysical methods should therefore also focus on this aspect.

Geophysics offers a wide range of methods for understanding subsurface geology and hydrogeology. The data coverage of a pilot area compared to classic geodata (e.g. boreholes) is often very limited. By introducing the entire range of geophysical methods for subsurface exploration, we can develop much better geological models and thereby enhance the basic set-up for climate modeling and for forecasting. Geophysical methods are widely used and have been specially developed to study the deeper subsurface. In the CLIWAT project some of these methods were tailored to studying near-surface geology and hydrogeology.

4.5 Hydrological models as predictive tool

Future changes in climate, e.g. precipitation, temperature and sea level, are expected to affect the quantity and quality of the water resources. However, the impact of climate change on hydrological systems can be hard to predict. Often, a hydrological system is too complex to be able to make intuitive evaluations of the effects. Therefore, hydrological models are nor-

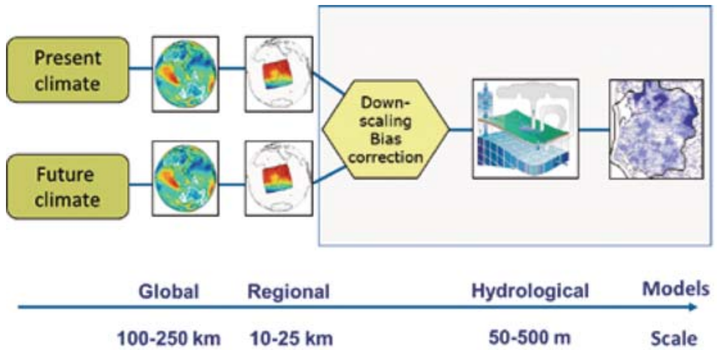


Figure 4.5.1 Illustration of the climate change impact modeling process, from definition of climate scenarios, outputs from global climate models, downscaling through regional climate models, bias-correction, and hydrological model to the final results. Each step of the process is associated with uncertainties.

mally used to evaluate the consequences of climate changes. Based on projections of the future climate and sea level, hydrological models are able to quantify the temporal and spatial distribution of the consequences on water resources and associated or dependent ecosystems. Hence, hydrological models are important tools for adapting to future, e.g., river basin management plans as required by the EU Water Framework and Groundwater Directives. Although the models are currently used as important tools for predicting climate change impacts, significant challenges still remain with respect to their accuracy and reliability.

Types of hydrological models applied in CLIWAT

Different types of modelling tools have been used in the CLIWAT project, including integrated hydrological models, Density dependent groundwater models and solute transport models. Integrated hydrological models are typically used for problems that include the integrated assessment of the evolution of both groundwater and surface water quantity and quality such as the impact of groundwater abstraction on low flow in streams; the effect of increasing precipitation and/or sea levels on flooding of coastal areas and stream valleys, and discharge and nutrient loadings of associated or dependent ecosystems. In CLIWAT, these types of models have been used in Aarhus River (DK), Horsens (DK), and the trans-boundary Schleswig area (DK/DE). Groundwater models are normally used for groundwater protection and contamination problems, e.g., to delineate capture zones to well fields or to predict the fate of contaminant leaching from deposits or landfills. Groundwater models have been applied at Egebjerg (DK), Hoerlykke (DK) and Föhr (DE). Density-dependent flow and solute transport models have the ability to include the effects of density contrasts between seawater and freshwater, and are used to quantify the intrusion of saltwater into coastal aquifers. Sea level rise will increase the risk of saltwater contamination of the coastal aquifers that are presently used to supply domestic and agricultural needs. In CLIWAT, such models have been applied at the Belgische Middenkust (BE), the trans-boundary area of Zeeland (BE/NL), and at the islands of Terschelling (NL) and Borkum (DE).

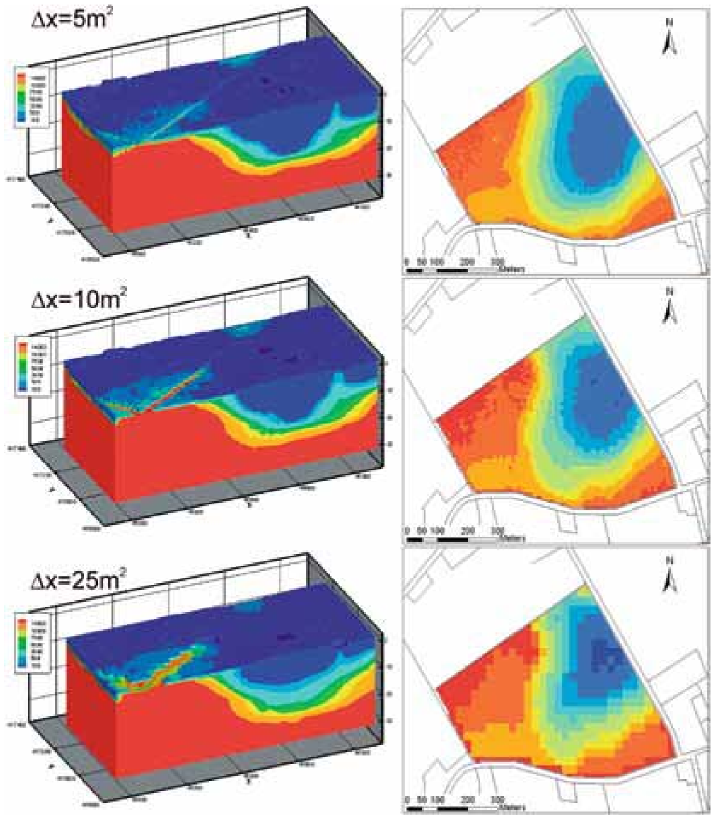


Figure 4.5.2: The effect of different grid sizes on the shape and volume of shallow rainwater lenses, as well as the salt load to the surface water system.

Challenges

Although numerical models have been successfully applied in CLIWAT, the work carried out during the project has also pinpointed several deficiencies. Quantification of the impact of climate change on the hydrological system is still facing several challenges. Below, the most important shortcomings are briefly described.

Description of shallow formations

The CLIWAT project has demonstrated that in many places within the North Sea Region, the description of the hydrological processes close to the surface is challenging. First, the knowledge of the shallow geology is restricted to information from boreholes. Geophysical methods such as airborne electromagnetic methods are presently not able to map the shallow geology with sufficient accuracy and the construction of geological models for this region is therefore exclusively based on sparse borehole information. In addition, the amount of hydrogeological data describing shallow formations is often relatively low since these aquifers are normally not used as groundwater reservoirs and therefore not intensively monitored. Hence, measurements of the groundwater levels, hydraulic parameters, etc., are often sparse, which limits the reliability of the resulting model.

The description of the groundwater flow in near surface aquifers is also complicated by the presence of artificial drains. Many areas in the North Sea Region are characterised as lowlands. Both agricultural and urban areas have been drained extensively during the last centuries to prevent the soil surface from becoming inundated or saturated with water. However, the location and efficiency of the drainage systems are normally not known. Additionally, the model description of the interaction between groundwater flow and flow through drain pipes is not well established when large scale models are considered. This lack of knowledge may result in large uncertainties with respect to quantification of the risk of inundation in a future climate.

Urban areas

The study of the impact of climate change in urban areas has traditionally focused solely on the risk of flooding due to the limited capacity of sewage systems. Climate change will however put additionally pressure on many cities which require that an integrated assessment of groundwater, surface waters and the sewage system. These systems are expected to interact more often in future situations, in response to extreme precipitation events or in periods where large volumes of precipitation are expected, particularly during winter. In such periods, the initial wetness of the urban area is important and the interaction between the different zones is important. Software that describes the entire hydrological system, including the sewage system, is not included in standard packages. Additionally, the knowledge of and experience with working with such an application of integrated model systems is required.

Describing groundwater flow in an urban area is complicated because the shallow aquifers and soil are often highly disturbed due to various construction activities, including the installation of sewage and water supply systems, roads, buildings, etc. Hence, if accurate predictions of the flow through shallow groundwater and the interaction with surface waters are to be produced, knowledge of the "anthropogenic" geology has to be provided. Methods for investigating and interpreting the geology of these anthropogenic settings are required.

Scale and resolution of model and data

Computer technology and modelling have developed fast during the last decade and it is now possible to describe large areas with a relatively high resolution (small grid elements). In Table 1 a list of recommended resolutions for different phenomena is provided. Modelling transient large-scale flow and transport in 3D groundwater systems is technical possible, but techniques to properly solve the advection-dispersion equation are often very time consuming. Using the wrong scheme may result in many months of calculation time and/or unacceptable mixing of fresh-brackish-saline groundwater systems due to large numerical dispersion. For instance, the grid Peclet number condition imposes that the dimension of the element should be not greater than a few times the magnitude of the longitudinal dispersivity that represents hydrodynamic dispersion. Some computer codes base the solution of the advection-dispersion equation on standard finite element or finite difference techniques and must satisfy this (Peclet) condition of spatial discretisation. In practice, this means that many hundreds of millions of elements are required to correctly model large-scale coastal hydrogeologic systems, which is a time consuming task. However, compared to the 1990s, memory capacity is no longer a problem.

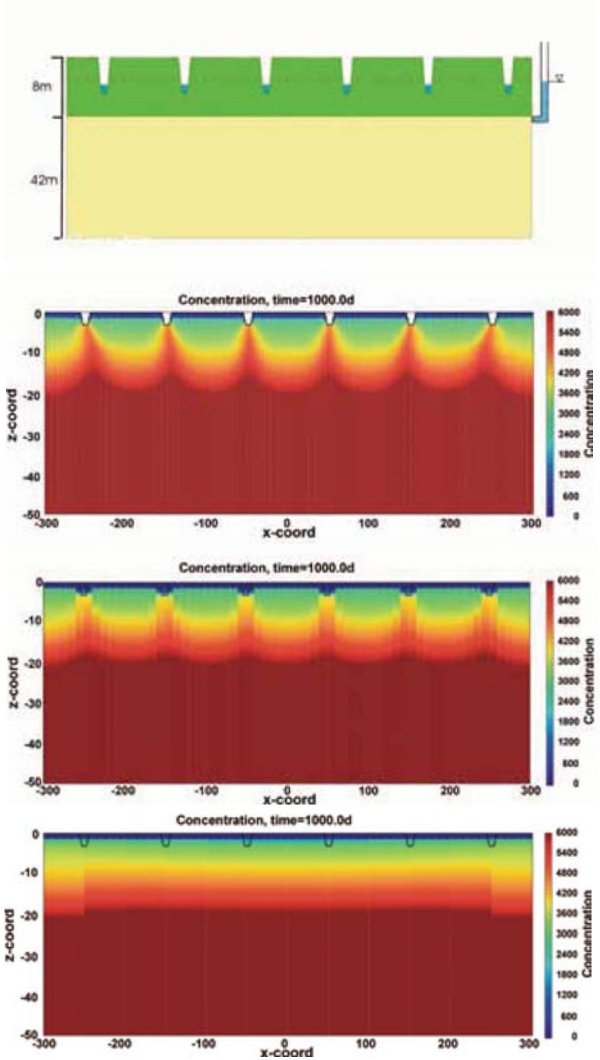


Figure 4.5.3 Three 2D profiles of chloride concentration in the subsurface and flow toward ditches. Cell-size is increasing downward. It shows that the horizontal cell size determines whether the up-coning occurs or not, effecting the salt load estimation towards the surface water system.

However, in order to obtain accurate predictions of the hydrological variables (groundwater level, salinity, etc.), fine discretisation of the numerical model is not a sufficient requirement. High resolution data on the formation properties and the state of the present system, e.g. hydraulic head, are also needed as input to the models. High resolution data on hydraulic properties are often missing, which ultimately limits the potential accuracy of the model results. Basically, frequently there is not enough hydrogeological data available to carry out calibration and verification. Data collection should be intensified, which is time and budget consuming, though new innovative monitoring techniques are currently available (e.g., airborne geophysics, online via satellite). However, we have to accept that the collection of data will always lag behind the developments in computer modelling, especially in data-poor areas.

Sufficient amounts of data are obviously important: for instance, without knowing the initial salinity distribution, it would be unwise to take expensive measures. In a variable-density flow system, the initial density that should be implemented in the numerical model can highly determine the velocities and thus the transport of fresh, brackish and saline groundwater. An accurate 3D density matrix can be critical for the accuracy of the model. Under certain hydrogeological conditions, the initial density distribution for a numerical model can be derived by just simulating the groundwater flow system under consideration for many (tens of) years until a steady-state situation from a density point of view is achieved. For instance, the initial (undisturbed) density distribution of a freshwater lens in a dune area can be derived by implementing natural fresh groundwater recharge in a completely saline aquifer system and simulate the system long enough, e.g. 100 years. The obtained steady-state density distribution will probably be the original distribution without human activities as groundwater extractions. Unfortunately, many coastal aquifer systems are at present not in dynamic equilibrium, for instance due to long-term sea level fluctuations or large-scale human activities with long-term effects on the groundwater system (e.g. the reclamation of low-lying areas in the Dutch coastal zone during the seventeenth century). For these specific cases, the best estimate of the 'initial' density distribution is probably the present measured one. In general, data of the density distribution is often scarce, and 3D modelling of variable-density groundwater flow in coastal aquifers is often based on insufficient amounts of good quality data.

At a very large scale (national scale), the resolution of the hydrological models are typically in the order of hundreds of metres (e.g., 250 m or 500 m). Models at this scale are useful for obtaining an overall assessment of the water resources. However, they may be too coarse to accurately describe local phenomena such as capture zones or solute transport locally. A solution to this problem may be to use nested models; a methodology that combines global and regional climate models and which is routinely used within the climate research community. Hydrology may to a large extent take advantage of this methodology by developing standardised methodologies for the coupling of e.g. national or regional models to local models.

Quantification of modelling uncertainty

It is important to emphasise that the predictions generated by hydrological models exhibit a wide degree of uncertainty. First, the climatic input to the hydrological models is not known precisely. The emission of greenhouse gasses, which is the driving force of climate changes, is based on scenarios for the future which by definition are associated with significant uncertainty. The projections of future climate are quantified using climate models and comparison of the results from different climate models reveals that an additional and significant source of uncertainty is found here. Secondly, the hydrological models represent simplifications of the natural systems and can therefore not be expected to provide an exact representation of the reality. Different types of hydrological models or different setups of the same modelling system will produce different results. Hence, an additional degree of uncertainty can be related to the hydrological model itself.

Hence, the predictions of future impacts on the hydrological systems are associated with significant uncertainties which should be kept in mind when used for water management decisions. However, it should not prevent the use of model results when making plans for the future be-

Phenomena	Domain	Resolution (m)				
		5	25	100	250	1000
Water resources assessment						
Impact on drawdown and discharge	Saturated groundwater flow/Unsat.			√	√	√
	Surface waters			√	√	√
Groundwater protection						
Groundwater recharge	Saturated groundwater flow		√	√	√	
Capture zones	Saturated groundwater/ particle trac.		√	√		
Saltwater: Surface Water-Groundwater						
Salt load to surface water systems	Saturated groundwater flow	√	√			
	Special interest to initial salinity distribution	√	√			
	Special interest to interaction GW-SW (resistance)		√	√		
Saltwater: Coastal zone						
Deep freshwater lenses (dune area)	Regional – saturated groundwater flow	√	√	√	√	
	National/Continental (total freshwater volume)				√	√
Creeks			√	√		
Shallow rain water lenses (agricultural parcels)	Saturated groundwater flow	√	√			
Salt damage to crops	Saturated groundwater flow	√				
	Unsaturated zone					
Transport: Nutrient and pesticide						
Pollution freshwater resources	Saturated groundwater flow		√	√		

Table 4.5.1 Model resolution (grid size) required for different problems.

cause the models provide a unique possibility and the best possible way to quantify the effects of climate change. Instead, the uncertainty should be included in the decision-making process and used to make sustainable solutions to future challenges. However, this requires that operational methods for quantifying the many uncertainties are developed, which is a significant challenge.

4.6 Geology and climate response

This chapter illustrates the importance of geological settings in relation to climate changes, with the exception of low lying delta areas. The projected change in precipitation varies regionally, and different hydrological systems can react in various ways to the same introduced changes. Local effects from climate changes vary, depending on the local geology which forms the basic settings for the hydrological systems.

Groundwater resources located in areas at some distance from the sea are almost unaffected by sea level rise. The magnitude of the hydrological response to the simulated climate change is highly dependent on the geological setting of the investigated model area (Roosmalen et al 2007). To illustrate the matter, two overall geological settings are presented: Clayeyareas and Sandy areas.

Clayeyareas

In clayey areas the topsoil is dominated by low-permeability soils and the aquifers are protected by thick clay layers of regional extent. Only minor changes in groundwater levels are predicted. The groundwater models setup in the CLIWAT project shows a slight increase in groundwater head in the clayey areas. However an increase in runoff is expected.

As the groundwater table will rise slightly, the amount of groundwater available for extraction for domestic water supplies will likewise increase slightly. As the soil cannot absorb water from heavy rainfalls fast enough, the peak flow in the rivers will increase dramatically, new wetlands will

arise and many new areas will need drainage in order to continue to be used for arable farming and forestry. In "normal years" irrigation will not be needed in clay-dominated soils due to the high water storage capacity of the soil. In very dry summers, many watercourses will dry out in longer dry spells.

Groundwater systems in clayeyareas do however respond to climate changes with a certain time delay. This means, for example, that the deeper aquifers are likely to respond in a matter of years-decades, whereas shallow aquifers have a response time within weeks-months.

In particular there should be focus on:

- Management of the runoff from the river systems must be carefully planned in order to create an environment where the runoff is slowed (and thereby more will infiltrate instead of flooding). This can lead to areas that have to be reserved for temporary flooding, dams, and wetlands
- Identification of comming wet areas and planning of drainage where required (blue spot maps)
- Evaluation of suitability of capture and protection zones for abstraction wells used for drinking and agricultural purposes in respect to periods with extreme conditions (dry or wet)
- Prevention of flooding of abstraction wells and technical installations

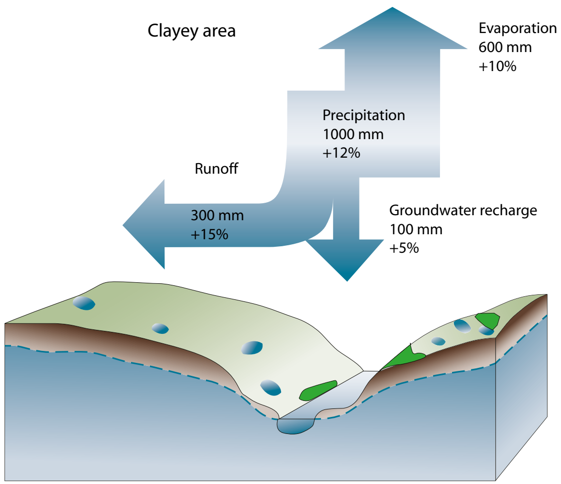


Figure 4.6.1. In clay-rich areas, runoff in watercourses during heavy rainfalls will increase dramatically where the topography typically has steeper slopes and because the soil is not able to absorb the excess water. The formation of groundwater will only increase slightly. Numbers indicates future water balances as modelled by GEUS, The water balance is simplified from modelling the A2 scenario.

Sandy areas

The sandy areas are characterized by sandy top soils and large interconnected aquifers. Groundwater recharge will increase significantly, resulting in higher groundwater levels and increasing groundwater–river interaction. Further an increase in run-off is to be expected.

In sandy areas the soil will to a higher extent be able to absorb the increasing amount of precipitation and the groundwater table will rise significantly. The soil will also to some extent be able to absorb water from heavy rainfalls although temporary wet areas will form in areas where the groundwater table is close to the surface. Increased runoff in rivers will occur but in a more smooth manner than in clay areas with higher topography differences. During coming dry summers there will be an enhanced

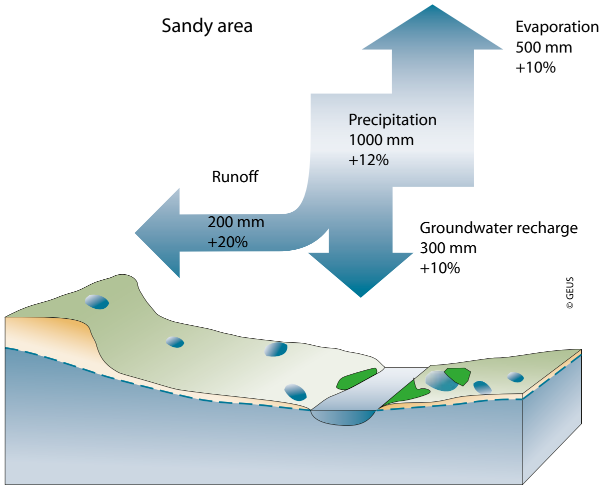


Figure 4.6.2 In (flat) sandy areas the increasing precipitation will result in increasing amounts of water infiltrating to the groundwater, causing groundwater levels to rise and groundwater flooding. Numbers indicate future water balances as modelled by GEUS, The water balance is simplified from modelling the A2 scenario..

need for irrigation, but with the right management of the extraction the surplus groundwaterinfiltration during winter can be used for irrigation. Outwash of nutrients may rise in these areas and needs further investigation.

Ground water systems in sandy areas respond to climate changes with a minor time delay. This means for example, that the deeper aquifers (without a thick clay cover) likely respond in a matter of months- few years, whereas the near surface aquifers has a response time within days-weeks.

In particular there should be focus on:

- Sustainable management of the increased demand for irrigation must be develloped
- Surface flooding of installations, cellars, roads etc caused by groundwater
- Management of increased runoff in rivers
- Living with the regularly flooded areas or drainage of groundwater-flooded areas

4.7 Pollution in urban areas

Figure 4.7.1: Aerial photo of the coastal city of Aarhus.

Cities and towns located in low-lying coastal areas are facing the challenges of rising groundwater caused by changed precipitation patterns and rising sea levels.

This will affect the water quantity and quality in these towns and cities. Low-lying cities have often been built on locations that were formerly wetlands or near rivers/estuaries and they face challenges of rising waters today and in the future. Their urban infrastructures have been designed to deal with former and present climate standards but the impact of "new" climate changes may be significant and thereby introduce the need of adapting to "new" climate standards, by raising dikes or building ports with higher piers.

Surplus groundwater and excess rainwater must be drained to revent groundwater flooding,; especially in areas where the terrain lies below the groundwater level.

In the low-lying cities and towns, the rising groundwater will increase the risk of flooding in cellars, underground parking areas and lowered roads. It may also lead to more water entering the sewage system and thus increasing the load on wastewater treatment plants. In addition, the impact of changed climate includes increasing the contamination flux of the water in and close to the city.

Groundwater quality

Xenobiotics (contaminants) are increasingly being considered as ecotoxicologically relevant for the aquatic environment and human health (Mussolf et al, 2007).

The quality of groundwater located in aquifers below the cities and towns is strongly variable. In some areas the groundwater is highly polluted, while in others it is uncontaminated (Region Midtjylland, 2011, Ellis P.A. and Rivett M.O. 2006 and Shepherd, K.A et al. 2006).). The source of pollution is typically caused by former or present surface or sub surface activities, e.g. contaminants from cars or sewage systems. Further contamination is caused by present day or former industrial or landfill sites that are located in the proximity of groundwater. The widely varying water quality means there is a need for a strategy where water is purified before it is discharged into any nearby river, lake or sea. Figure 4.7.2 illustrates a simplified version of water flow in a town. The quality of the water is illustrated by four different colours and illustrates the need for water purification. There is a large degree of interference between surface water and groundwater. The quality of the water in the city is generally unknown. But the studies in CLIWAT have showed that the groundwater in the towns is affected by sewage, former and present industry and other surface activities. To prevent contamination of the surrounding environment, the contaminated water should be treated before being discharged into the environment.

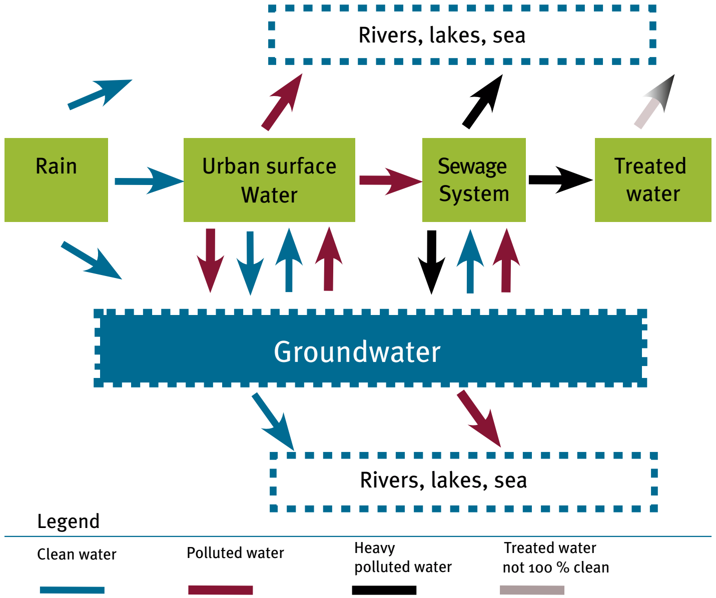


Figure 4.7.2 The flow of water in a city today

Effects on landfills

In contaminated areas like landfill sites, the changed climate can have several effects. The models in CLIWAT studies have shown that the direction of flow of the contaminated plume can change. In some cases, this can cause contamination of groundwater that was formerly considered to be without any risk. The studies also show that the extension of the groundwater plume is not significantly increased. This means that the changes in precipitation do not cause an increase in the spread of the contamination from landfill sites in these two examples.

In areas where groundwater in the present climate is not in hydraulic contact with the nearby rivers or lakes, the rising groundwater may have an impact on surface ecosystems. This is the case of the landfill site in Pilot Area E (Hørlykke), where the rising groundwater leads to a changed drainage pattern in the local creek, which affects the water quality. In the Eskelund landfill site in Pilot Area G, the nearby creek is affected by the landfill site and the climate change will lead to an increase in the amount of contamination /pollutants which enters the creek.

In the Eskelund case, it was evident that the local waterworks could stay clear of contamination by maintaining the current abstraction level. This

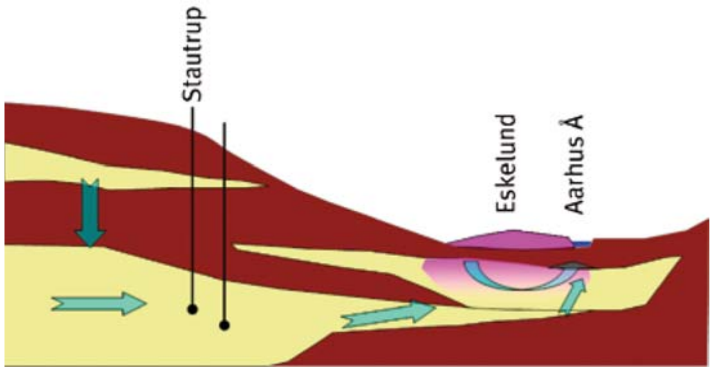


Figure 4.7.3 Groundwater flow in aquifers near the Eskelund landfill site, Pilot Area G

was evident because the dominant flow direction is from west to east, towards the landfill site. In addition, it was outlined that the contamination could be drawn towards the waterworks if the abstraction was increased. Figure 4.7.3 indicates the hydrological system of the Eskelund landfill site.

For both systems, it is clear that the hydraulic system has to be evaluated prior to any decisions being made. If remediation is planned, it is important to design a facility that can deal with greater volumes of water in the future. In many cases, groundwater models based on consistent geological and hydrological data are powerful and useful tools that help to increase our understanding of the hydrological system.

4.8 Thematic maps

The impact of climate change on the environment and society will have different dimensions. The impact will reach from global processes down to small-scale events in a very local setting. Research projects like CLIWAT must effectively communicate the results of the investigations and their recommendations for future adaptations. This means that technical subjects with often very complex context have to be described and illustrated in a form that is understandable to the general public. Text and thematic maps offers the possibilities to do this. Whereas printed analogue maps were used predominantly in the past, today digital maps combined with GIS systems are the preferred choice. In particular, interactive maps give the user the opportunity to display exactly the details and data he is interested in. Hardcopies of digital maps and printed analogue maps are still of importance in situations where there is no digital media available, e.g. at fieldworks.

The kind of subjects visualised in a map, as well as the scale of it, can vary strongly, depending on the purpose it was made for. The appearance of a map is determined by the specifications of topic, objects, size, date and chosen layout.

The topics of thematic maps in the CLIWAT project are sea level rise, changes in groundwater recharge, changes in groundwater tables, changing catchment areas of waterworks, changes in groundwater quality (salt water intrusion, nutrients and pesticides), changes in need for irrigation, etc. The objects shown in the maps can be spatial (e.g. areas with risk of flooding), linear (e.g. risk for roads or railway tracks) or punctual (e.g. wells with polluted groundwater). Depending on the spatial distribution of the objects shown, the size of a map can vary from large scale (e.g. land use map) to small scale (e.g. single buildings).

The CLIWAT project used various geological and hydrological models of the pilot areas to predict regional and local developments. To illustrate the potential climate change impacts, maps can show the development of the groundwater systems in the future and highlight where adaptations are needed.

Some examples of the numerous thematic maps that have been provided in the CLIWAT project are shown here.

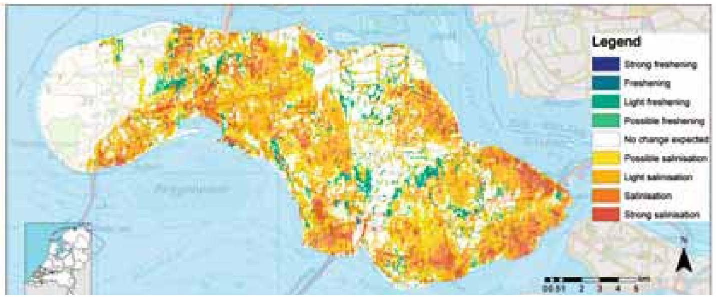


Fig: 4.8.1: The map shows the anticipated status of the phreatic groundwater in 2050 on the island Schouwqen-Duiveland in the Province Zeeland, in the south-western part of The Netherlands. The map combines the effects of the currently occurring salinisation processes, projected to continue until 2050 with the effects of climate change.

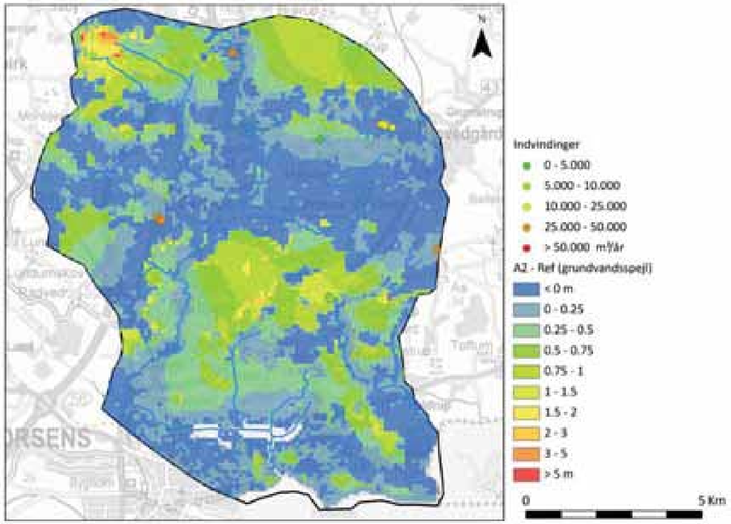


Fig 4.8.2: Egebjerg Pilot Area F (DK) – The map is showing changes in the water table as predicted in the IPCC`s A2 scenario for the surface near layers.

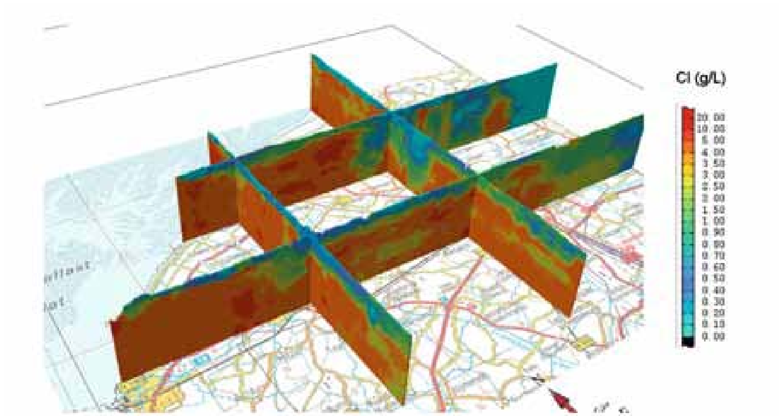


Fig 4.8.3: Cl-distribution for the upper 40 meters in the Fryslan pilot area. The map shows the Cl- concentration (g/L) in the current situation, based on all datasets available to us, including the HEM, skyTEM, ECPT's and water samples collected in the CLIWAT project.

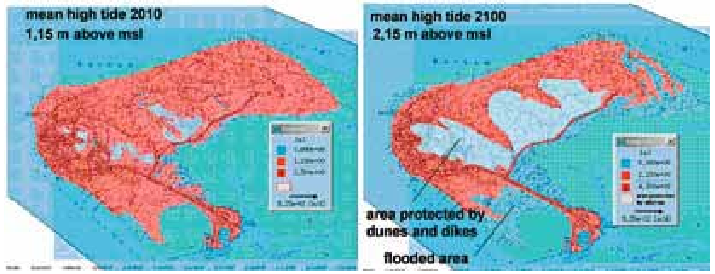


Fig 4.8.4: Borkum Pilot Area D (D) – The map is showing the island (mean sea level) at present time compared with the simulated A2 scenario for year 2100. The results is that the sea level is 0,94 m higher and thereby flooding about 25 % of the island.

This table gives a few examples of useful maps and helps the planner or water manager e.g. to understand the magnitude and geographically distribution of climate change impact.

Thematic map	Map is used to indicate	Pilot Area
Sea-level change	areas with increasing risk of flooding	A, B, C, D, F
Salt water intrusion	areas where groundwater quality is threatened by salt water intrusion	A, B, C, D,
Groundwater recharge	regional change in groundwater abstraction possibilities	E, F
Groundwater table changes	areas with increasing risk of flooding / demand for extension of drainage	E, F
Precipitation / evapo-transpiration	areas with increasing need for irrigation	E
Infrastructure	areas threatened by damage to houses, roads and crucial infra-structure (dikes, etc.)	D, E, F
Groundwater pollution	extent of change of groundwater pollution	F, G, E

5 Involving stakeholders

Figure 5.1 Stakeholder involvement

The active participation of different interest groups in the development and implementation of CLIWAT has been a cornerstone of the project. The involvement of key stakeholders has played a central role in the evaluation of the effects of various climate scenarios, cooperation across regional and national boundaries, and ultimately, the development of adaptive approaches to water management.

This chapter describes the value of stakeholder involvement in relation to resource management, the various levels of stakeholder involvement and the establishment of a participatory process. Examples from the CLIWAT project are given in in the text boxes and serve to highlight the benefits, challenges and solutions that have arisen out of the participatory process. Additionally, a bibliography of handbooks on participatory processes is provided.

5.1 Why participation?

Stakeholder and public participation is now widely used for supporting any planning, policy or decision-making process. Stakeholders are those who are considered to be directly or indirectly affecting or affected by a management decision (Glicken, 2000), and their participation often allows them to influence the outcomes of a project or process. Participation is widely accepted as playing a key role in many environmental and resources management processes and policy developments. Specifically, the active involvement and contribution of stakeholders can have the following beneficial effects for a given project or planning process:

- incorporate local and practitioners' knowledge into the project development and research activities
- support capacity building and improved understanding of the research approach and results
- improve quality of project outcomes,
- ensure broader acceptance of project outcomes
- contribute to broader dissemination and uptake of the results

In the case of CLIWAT, the implementation of the project and its results have benefited from including stakeholders at all stages of the project, from inception to dissemination of results. Box 5.1 provides some specific examples, which are also presented in sections 5.4 and 5.5 of this chapter.

Box 5.1. Examples of stakeholder involvment processes from 3 countries The value of the stakeholder process: Perspectives of CLIWAT partners and stakeholders

Germany: The German project team used special events to raise awareness among the general public of the vulnerability of the freshwater lens on the coastal islands in the North Sea. This has provided a foundation for later communication to the public of the specific effects of climate change, and demonstrated through the CLIWAT groundwater models and scenarios.

Belgium: "CLIWAT provides an excellent opportunity to gather everyone involved in the coastal area. It is for us as stakeholders, an interesting platform to exchange ideas and a vision for the future of coastal groundwater management together with researchers and other stakeholders alike." (comment by a representative of the Flemish Environmental Agency).

Denmark: The awareness CLIWAT has brought to the regional and national debate regarding climate change and groundwater is valuable. A major part of the concern in Denmark at the moment is focused on sudden heavy rainfall and the resulting collapse of sewage systems in urbanised areas. The CLIWAT project and the meeting of the Danish stakeholder board has secured that future challenges regarding change in groundwater levels and quality is taken into account.

5.2 Establishing a Participatory Process

Once the decision has been taken that a participatory process is necessary or desirable, consideration needs to be given to the nature of this involvement both in form and level. Should it involve the general public and stakeholders or just one of these groups? When this is determined, the extent of their involvement needs to be established, ranging from more passive one-way information provision to collaborative designing/decision making. Finally, the process requires a detailed plan at the start of a project.

Various forms of stakeholder involvement

Participation can take place with four different levels of involvement: information provision, public consultation, active involvement (co-designing) and decision making (co-deciding). As a basic condition for all levels of participation, it is essential that there is access to relevant and sufficient *information* (e.g., through newsletters, websites, flyers, street stalls or conference stands).

In a stakeholder *consultation* process, the participants are normally asked to provide their opinion, and also their knowledge of the issues/circumstances surrounding draft plans, proposed measures or policies, and/or preliminary results. Consultation can take place in written or oral/active form. In the case of the *active involvement* of stakeholders, as has been undertaken in CLIWAT, the organisations represented have a share of the responsibility for, or at least the opportunity to provide input into the creation of a plan or policy, its implementation and/or the use of results. In contrast to a public consultation process, it is often impossible to actively involve all possible stakeholders in a process. Therefore, a selection of stakeholders needs to be made, and this is often done by means of a stakeholder analysis (see Section 5.2.3).

Depending on the issue being addressed and/or the goal of the participatory process, the level of success will depend upon selecting the appropriate elements including:

- level (or extent) of involvement
- range of stakeholders
- geographical scale
- participatory method

Although a project such as CLIWAT may be undertaken at the higher national or transnational scale, it may be nonetheless valuable to organise at least a part of the participatory process at the local scale, because effects of management decisions will be felt most directly at this scale (European Commission, 2003). In the CLIWAT project, a combination of national and

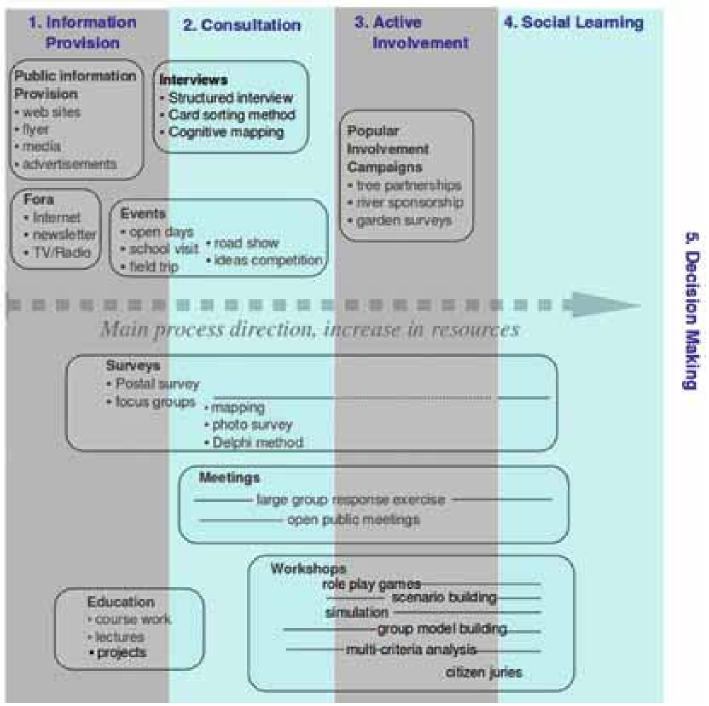


Figure 5.2.1 Levels and classes of participation (Hare and Krywkow, 2005, p. 19)

transnational boards was established to ensure that stakeholders felt directly connected to the issues discussed, but also that the results from the national boards were used in the project as a whole, which transcends national boundaries (see Section 5.2.3 for more details).

Finally, in deciding on the type of participatory process to implement, a broad range of methods exists from which a suitable method can be selected depending on the participatory goal, the level of involvement and type and number of participants (Hare and Krywkow, 2005, and Krywkow, 2009). Figure 5.2.1 provides a preliminary classification of methods according to the level of involvement.

Creating a participatory plan

A participatory plan serves as a road map for a project involving stakeholders. It describes how stakeholders will be identified, how they should be engaged and what should be discussed. The common components of a participatory process that are reflected in the plan include:

- Problem analysis. Literature study, field study, etc.
- Identification of participants through stakeholder analysis (identified through literature and media research and/or surveys/interviews)
- Defining the role of the stakeholders. Can they make recommendations or decisions?
- Setting the agenda. Detailed description of and schedule for individual meetings including objectives
- Development of a communication plan
- Allocation of resources/securing co-financing
- Process for knowledge elicitation. Interviews, surveys, workshops, focus groups
- Education activities (presentations, field trips, etc.)
- Monitoring and evaluation of the process and its outcomes (stakeholder feedback is useful)
- Recruiting volunteers
- Checklist for preparation and implementation of participatory process

The plan outlines *a stakeholder analysis* as an initial step in the process of selecting stakeholders. The participation of all relevant stakeholders is a key to a successful participatory process and their selection is therefore described in the next section. The implementation of a participatory process is outlined briefly in Section 5.4. For detailed information, several documents that provide guidance for those wishing to establish a participatory process are listed at the end of this chapter.

Selecting Stakeholders

Before initiating a participatory process, it is important to get a detailed understanding of the problem as it is perceived by the stakeholders. In addition to providing a better insight into the perception of the problem, a stakeholder analysis also serves as a basis for selecting appropriate stakeholders for the participatory process. Stakeholder analysis is a three-stage, iterative process: identify, categorise and select stakeholders (see Figure 5.2.2).

Figure 5.2.2: Stages of stakeholder analysis (Hare and Krywkow, 2005)

As a first step, a list of possible stakeholders has to be made. It should include all groups and individuals who have a possible stake or interest in the issue, preferably grouped according to areas of interest and competency. This identification process can be improved or speeded up by drawing on the advice of those stakeholders already confirmed as being necessary to the process.

Potential stakeholders are then prioritised and the extent of their involvement is determined. A possible framework for this checklist is shown in Table 5.1. It allows a listing of the interests of the stakeholders, their attitude towards the issue, the level of power/authority held (national, regional, local by type of authority: political, financial and human) and the degree of influence of each stakeholder (very strong – strong – average – weak – very weak), as well as the role and the degree of involvement the stakeholder should have in the participatory process.

Stakeholder	Type	Stake/ Interest	Attitude	Power*			Level	Role	Degree of Involvement
				P	F	H			
....	.....								

* p = political, f = financial, h = human

Table 5.1: Stakeholder Analysis Table

Selecting stakeholders depends on the purpose of the participatory process. If the aim is to involve potential objectors, these criteria may be helpful in selecting those stakeholders who hold more power and may oppose the project or aspects of it. If a diverse range of stakeholders is desired,

then one or more stakeholders from each category (e.g. local, regional, national) can be selected. While selecting stakeholders, the number of desired participants has to be taken into account. A larger group allows for more representation across sectors and scales. Involvement of a broad range of backgrounds requires more skilful facilitation of meetings, but also enhances the prospects for the success of a given plan or project on a broader level. With a smaller group, social learning is more likely to occur, active involvement is more likely to be successful and the participatory process will be less expensive to implement. The process for engaging stakeholders in the CLIWAT project is described in Box 5.2.

Box 5.2 Engaging stakeholders in the CLIWAT Project

At the outset of the CLIWAT project, a generic participatory plan was developed by a consultancy specialising in participatory processes. This document prescribed the establishment of four national boards (one in each partner country) and one transnational board comprising representatives from the national boards. The plan was then adapted to the needs of each country.

Among the CLIWAT project partners, it was agreed that the members of the national boards should represent all spatial levels and a range of sectors, and they should be "hands-on" representatives of their respective interest groups. For each national board 10 to 20 representatives were anticipated.

The main challenge in establishing a national board was securing representation from a range of sectors and at more than one scale level. This was relatively successful in Denmark. The Danish board was made up of participants from many sectors such as water, agriculture, and highway and rail authorities, and from all levels (state, regional, and municipal), as well as from consultancy companies and academic institutions. This led to many fruitful discussions about the CLIWAT results and upcoming challenges that cross-sectoral boundaries. Thus, in Denmark the stakeholder process has become a platform for future cooperation.

5.3 Implementing and Managing a Participatory Process

There are a variety of challenges and potential solutions to those challenges that those implementing a participatory process should be aware of. Stakeholder processes require careful planning if they are to meet their objectives. Some of the most important considerations are:

- ensuring that sufficient resources are allocated
- establishing realistic expectations
- ensuring that the leadership is sufficiently strong to guide and maintain control of the process
- avoiding information overload

(Hare and Krywkow, 2005)

Furthermore, it is strongly advised that:

- those facilitating a process remain open to the outcomes of that process
- responsibilities are shared, for the sake of shared ownership of the process, and for social learning
- the participatory process remains attractive to stakeholders throughout the duration of the project or planning process - not only at the beginning, but also during the process by avoiding information overload, ensuring an appropriate pace and including sufficient substance in the process

(Ridder et al., 2005)

In Box 5.3, some of the most important insights about managing a stakeholder processes that were learned in the CLIWAT project are presented. For more detailed guidance, the handbook, “Learning Together to Manage Together: Improving participation in water management”, produced by the European-funded HarmoniCOP project, describes all the elements needed for establishing and managing a participatory process, and how to assess or evaluate progress and achievements.

Box 5.3 Insights from stakeholder processes in CLIWAT

In an interim evaluation of the CLIWAT national and transnational boards, most partners viewed the work of the boards positively. In addition, several conclusions were drawn and recommendations made based on the experience with the CLIWAT participatory process:

- Getting and keeping stakeholders involved can be challenging (e.g. stakeholder fatigue). Creative solutions such as catchy kick-off events (e.g. with higher profile keynote speakers, field visits, etc) can be effective in attracting stakeholders. It should be possible for stakeholders to clearly see their role in the project. During the meetings, scientific methods and results need to be presented in a way that is understandable to the stakeholder.

- Present realistic expectations of stakeholder involvement and the project as a whole (i.e. state clearly what the project can and what it cannot achieve)

- Resources should be allocated by project partners for the national boards, primarily for planning and implementation of meetings.

- Project partners naturally place higher value on the scientific dissemination of project results than non-scientific dissemination types (such as training and project newsletters). It was valuable to bring in a project partner to support the non-scientific dissemination. In CLIWAT, a dissemination plan (Schmidt, 2009) was developed at the outset of the project to ensure that project progress and results were communicated to diverse audiences.

5.4 Assessing the Achievements of a Participatory Process

The success of the participatory process can only be measured against the goals of the project or the initiative as a whole. Some achievements or failures will be apparent depending on the project results. However, in order to have a complete picture of the effectiveness of a stakeholder process, an evaluation is needed. The HarmoniCOP handbook mentioned above includes a chapter on monitoring and evaluating a participatory process. It provides a comprehensive checklist of questions that supports this evaluation process.

A central challenge when addressing the impacts of climate on groundwater is developing approaches and solutions that draw on multiple disciplines and involve multiple scales. Engaging researchers, practitioners and stakeholders from these various scales, sectors and disciplines is thus vital to an interdisciplinary project of this nature. Several of the achievements of the CLIWAT stakeholder process that reflect the importance of this approach are presented in Box 5.4.

Through a stakeholder process such as that implemented in the CLIWAT project, it is possible to raise local, regional and national awareness of an issue. Moreover, the participatory process of this project has demonstrated that there are numerous effective solutions that can be developed and implemented when stakeholders work together to create win-win situations both for individual sectors and society as a whole.

Box 5.4: Achievements of the CLIWAT Stakeholder Process

In the CLIWAT project, it is possible to distinguish short and long term impacts of stakeholder involvement. In the short term, awareness of the effects of climate change on the groundwater was raised among stakeholders involved in the project and represented on the boards. It was raised to the extent that practices have changed. For example, the Danish Road Directorate has made the stability of new highways a higher priority, and the Dutch water distribution company, Vitens, is now mapping saline and fresh water lenses in coastal areas of the Netherlands.

In German pilot areas, fieldwork presentations as well as presentations at special events helped to attract stakeholders. In the two pilot areas (Borkum and Schleswig/Föhr) stakeholders were able to try out the methods for examining groundwater. These events supported the building up of local and regional knowledge. Stakeholders and the public were informed of new techniques and technical developments through presentations on fieldwork. The project team took advantage of World Water Day and Energy Day on the island of Borkum in order to also reach out to the general public.

In the longer term, new methods for mapping of saline freshwater are being linked between countries (e.g. Denmark and the Netherlands), which permits more accurate predictions of climate change and freshwater availability. Furthermore, CLIWAT has contributed to a wider acceptance of groundwater as a parameter in the water cycle that has to be taken into account when dealing with climate change adaptation. A further tangible spin-off of the stakeholder board meetings was agreement on a ten-year collaboration project between the Danish Roads Directorate and the Geological Survey of Denmark and Greenland to include the effects of changing groundwater levels when building highways in Denmark.

Further Guidance on setting up participatory processes

Ridder, D., E. Mostert, and H. A. Wolters. 2005. *Learning Together to Manage Together – Improving participation in water management.* Publisher: University of Osnabrück, Institute of Environmental Systems Research. Osnabrück.

The HarmoniCOP Handbook provides practical and easy-to-follow advice on all aspects of setting up and running a participatory process. It is available in English, German, Dutch and French and can be downloaded for free from http://www.harmonicop.uos.de/handbook.php

Krywkow, J. 2009. *A Methodological Framework for Participatory Processes in Water Resources Management.* PhD thesis.
University of Twente, Netherlands. June 2009.

The thesis outlines a process for selecting appropriate methods for a participatory process. The thesis is intended for scientific audiences and includes a conceptual foundation. However, it provides a detailed outline for participatory process planning in all its dimensions. Available from http://doc.utwente.nl/64058/

European Commission. 2003. *Guidance Document No 8: Public Participation in Relation to the Water Framework Directive.* Common Implementation Strategy for the Water Framework Directive (2000/60/EC). Working Group 2.9.

This report, which is intended for EU member states, provides a common understanding of public participation in the context of the Water Framework Directive. It outlines how to implement and manage such a process, including who to involve, the time frame for involvement, and the importance of selecting the right scale for involvement.
circa.europa.eu

6. EU policy

6.1 Introduction

The CLIWAT project focuses on climate change impact assessments for adaptive water management in coastal regions. Such assessments are part of the important knowledge base needed to plan required adaptation measures as described in the EU White Paper on climate change and EU directives, guidelines and reports.

Generally, climate change impacts and adaptation are not directly mentioned in the Water Framework Directive (WFD; EC, 2000) or Groundwater Directive (GWD; EC, 2006). However, the WFD and GWD require actions that at least to some extent have to consider climate change impacts and adaptation measures that are needed to develop climate proof river basin management plans (EC, 2009a,b; Quevauviller, 2011). This also includes assessment of climate change impacts on groundwater quality and quantity as a pressure on the chemical and quantitative status of groundwater. However, as described in the EU White Paper on climate change adaptation (EC, 2009a), a more strategic approach and guidelines such as the EU guidance document no. 24 "River basin management in a changing climate" (EC, 2009b), are strongly needed to describe appropriate ways to tackle the challenges of climate change.

This chapter briefly introduces relevant documents from the European Commission that have important implications for appropriate management of groundwater as an important part of river basins and the hydrological cycle in a changing climate. Generally groundwater quantitative and chemical status affects drinking water resources, the ecological and chemical status of ecosystems from springs to marine ecosystems, and the built environment. Hence, proper consideration and understanding of climate change impacts on groundwater is imperative for developing climate-proof infrastructure and for adaptive and sustainable management of water resources and groundwater dependent ecosystems in a changing climate.

6.2 Directives relevant for groundwater and river basin management

The WFD and GWD are the most important directives for groundwater and river basin management, and although they do not provide direct requirements on climate change impact assessment and adaptation they do provide a general framework for addressing this important aspect of river basin management plans as illustrated by the following quotation, Quevauviller (2011): "..several articles of the directive (WFD) provide a framework to include climate change impacts into the planning process. In particular, the requirement of the directive to collect information on the type and magnitude of 'significant pressures' affecting surface waters could be considered as including climate change with the consensus that it is at least to a certain extent caused by human activities (Wilby et al., 2006)".

Besides the WFD and GWD "the Flood Directive" (EC, 2007) also includes important requirements for river basin management in a changing climate. Other directives such as "The Habitats Directive" and "The Maritime Strategy Directive" (EC, 2008) also include requirements of relevance for the development of climate proofed river basin management plans, but these are generally covered in the WFD and GWD. The implementation of WFD and GWD in the EU member states are not straightforward. Further directives may not always be properly adopted in national laws (Stoltenborg, 2011). Hence, detailed guidelines to assist in proper implementation are strongly needed. A brief description of the most important guidances developed to assist in the implementation of the WFD and GWD in member states is provided in a later section.

6.3 Groundwater and the EU White Paper on climate change adaptation

The EU White Paper "Adapting to climate change: Towards a European framework for action" (EC, 2009a) acknowledges that: "climate change increases land and sea temperatures and alters precipitation quantity and patterns, resulting in the increase of global average sea level, risks of coastal erosion and an expected increase in the severity of weather related

natural disasters" and that the changing water levels, temperatures and runoff will affect food supply, health, industry, transport and ecosystems. Furthermore it states that two types of response are needed to address climate change – firstly, we must reduce greenhouse gas emissions and secondly we must take adaptation actions to deal with the unavoidable impacts. The White Paper recognises that even if we reduce greenhouse gas emissions we will face climate changes in the coming decades due to the effects of the greenhouse gases that are already in the atmosphere and that we need to take measures to adapt.

The White Paper sets out a framework to reduce the EU's vulnerability to the impact of climate change, and it describes the needs to develop the knowledge base, integrate adaptation into EU policies and increase the resilience of the following areas:

- Health and social policies
- Agriculture and forests
- Biodiversity, ecosystems and water
- Coastal and marine areas
- Production systems and physical infrastructure

Although groundwater of course is mainly related to "biodiversity, ecosystems and water" it is worth noticing that groundwater quantity and quality has relevance for all the other areas to varying degrees, for instance as water supply for irrigation, a media for transporting nutrients between agricultural soils and surface waters or stabilising/destabilising physical infrastructure such as roads and railways. Hence climate change impacts on groundwater quantity and quality have major implications for society and nature.

Under the heading "Biodiversity, ecosystems and water" the White Paper describes that while the first river basin management plans (RBMPs), which were finalised in 2009 in most memberstates, to some extent include climate change considerations the second generation of RBMPs due in 2015 should be fully climate-proofed. Further, climate change must be properly integrated in the implementation of the "Floods Directive" (EC, 2007).

The White Paper lists the following required actions under the heading "Biodiversity, ecosystems and water":

- Explore the possibilities to improve policies and develop measures which address biodiversity loss and climate change in an integrated manner to fully exploit co-benefits and avoid ecosystem feedbacks that accelerate global warming
- **Develop guidelines and a set of tools (guidance and exchange of best practices) by the end of 2009 to ensure that the River Basin Management Plans (RBMP) are climate-proofed**
- Ensure that climate change is taken into account in the implementation of the Floods Directive
- Assess the need for further measures to enhance water efficiency in agriculture, households and buildings
- Explore the potential for policies and measures to boost ecosystem storage capacity for water in Europe
- Draft guidelines by 2010 on dealing with the impact of climate change on the management of Natura 2000 sites.

The highlighted action on the development of a guideline to ensure that the next generation of RBMPs is climate-proofed has been completed (EC, 2009b). This guideline (guidance no. 24) includes a range of recommendations e.g. on how to take climate change impact on groundwater into account in the context of river basin management plans. The contents of guidance no. 24 are briefly described in the following including relevant issues related to groundwater and climate change, which are not covered in the guidance.

Guidances relevant for groundwater and river basin management

The most relevant guidance for appropriate groundwater and river basin management is guidance no. 24 "River basin management in a changing climate" (EC, 2009b) as mentioned above. This guidance present and demonstrate important climate change impacts that potentially will affect groundwater chemical and quantitative status and the importance of maintaining groundwater and surface water monitoring networks that record the evolution of important parameters for evaluating the climate change impacts on the hydrological cycle. The guidance covers a range of important issues related to groundwater quantity and quality, but there are still relevant issues related to climate change impacts on groundwater, which have not been dealt with. The following brief review is based on a review of guidance no. 24 by Vermooten et al. (2011) and a review of climate change impacts on groundwater (Green et al., 2011).

The development of the RBMPs according to the WFD is based on the following procedure:

- Risk assessment
- Monitoring of the status of surface water (ecological and chemical) and groundwater (chemical and quantitative)
- Objective setting
- Economic analysis
- Programme of measures

Furthermore, the RBMPs have to take into account the requirements of the Floods Directive and the Water Scarcity and Drought Strategy.
Guidance no. 24 includes groundwater at all levels in the RBMP procedure mentioned above, but there are some issues, which are not discussed in the guideline, e.g.:

- Groundwater/surface water interaction and changed fluxes of water and contaminants to surface water (incl. marine waters)
- Change in timing of snowpack melting/glacier/permafrost groundwater dynamics
- Groundwater flooding
- Monitoring of recharge processes
- Monitoring of groundwater/surface water interaction
- Monitoring of salt water intrusion in aquifers
- Long term monitoring of groundwater levels/spring discharge
- Integrated monitoring and modelling of groundwater and surface water

The list above is not complete but indicates some important issues related to step 1 and 2 in the development of the RBMPs. Important issues mentioned in Guidance no. 24 related to groundwater and step three "objectives setting" include the WFD requirement of obtaining good groundwater chemical and quantitative status in 2015. However, it does not relate to or discuss how to handle the slow groundwater flow dynamics in this context, and how to handle climate change impacts on groundwater chemical and quantitative status e.g. how climate change may affect groundwater flow systems (Sonnenborg and Oude Essink, ch.4.5, this volume) and groundwater threshold values (Hinsby et al., 2008, 2011, 2012).The required economic analysis of climate change impact and adaptation is mentioned in broad terms, but does not mention specific problems such as the effect of varying water tables on physical infrastructure, energy costs due to increased pumping for irrigation, etc. The CLIWAT project addresses many of these issues (Pedersen et al., ch.3, this volume; Hinsby et al. 2012) providing important new data and knowledge for future climate-proofed river basin management plans in the North Sea Region. Most of the applied tools may be used globally.

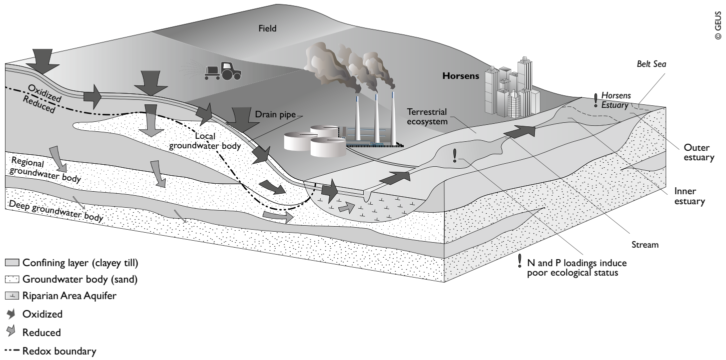


Figure 6.4.1 Conceptual model of the catchment to the Horsens estuary showing selected pressures on the chemical status of groundwater and surface water, which may increase due to climate change impacts such as increasing winter precipitation. If for instance nutrient loads to the estuary increase due to increasing runoff, future groundwater threshold values will have to be lower than estimated for the current situation, and groundwater chemical status will deteriorate compared to the current situation (Hinsby et al., 2011, 2012).

Other relevant guidances include guidance no. 18, 19, 23 and 26 (EC, 2009c-e, 2010). The most relevant directives and guidances can be downloaded via the CLIWAT website (www.cliwat.eu). Generally, the guidances recommend to use conceptual models in the understanding of e.g. the interaction between groundwater and surface water in river basins – an example is shown in Figure 6.4.1.

6.5 CLIWAT and the EU directives and guidances

CLIWAT deals with climate change impact assessments on future groundwater chemical and quantitative status according to EU directives and guidance's and provides important results for the review of the GWD in 2013 and for climate-proofing the next generation of RBMPs due in 2015. CLIWAT deals with both primary climate impacts (e.g. flood risks, groundwater recharge, water tables and runoff) as well as secondary impacts (e.g. irrigation needs/effects, eutrophication). The main focus of CLIWAT is climate change impact on groundwater chemical and quantitative status, primarily:

Saltwater intrusion (primary impact): The most imminent threat for groundwater chemical status and to some extent quantitative status is saltwater intrusion into coastal aquifers due to the expected sea level rise. In contrast to many other negative climate change impacts, which vary between different climatic regions, saltwater intrusion is a global problem of great concern as it reduces the available drinking water resource in coastal regions, globally (Oude Essink et al., 2010; Sonnenborg and Oude Essink,, ch. 4.5, this volume).

Increased contaminant loading to groundwater and dependent or associated ecosystems (secondary impact): The North Sea Region is expected to receive increasing precipitation during the winter period. The likely increase in nutrient loads, and contaminants from point sources etc., will result in decreasing groundwater and stream threshold values in order

to ensure good ecological status of groundwater dependent or associated ecosystems (Hinsby et al., 2008, 2011, 2012; Sonnenborg et al., 2011)
Issues related to quantitative status such as changes in water tables, runoff and flooding of the built environment e.g. coastal cities and effect of increasing irrigation needs (e.g Hinsby et al, 2012)

Objectives of preventing or limiting groundwater pollution by point sources as required by the WFD and GWD (EC, 2000, 2006) are needed.

CLIWAT provided input on these issues for a new document developed by the EU Working Group C "Groundwater" on climate change impact on groundwater (WGC, 2011).

6.6 Other sources of relevant information for climate change adaptation

A rapidly increasing amount of information and sources for climate impact assessment and adaptation is available on the internet, and it is impossible to give an exhaustive list of these sources. However, the following sources have extensive information about water and environmental issues including European climate change impact assessment and adaptation:

"WISE" - The Water Information System for Europe (http://water.europa.eu)

"CIRCA" – A collaborative workspace with partners of the European Institutions (http://circa.europa.eu)

"EEA": The European Environment Agency (http://www.eea.europa.eu)

6.7 The Blueprint to safeguard Europe's Water.

The EU Commissioner for the Environment has taken the initiative to put together a new policy response to protect Europe's water for all legitimate uses. The following section is taken directly from a BLUEPRINT publicity folder.

»In 2000 the Water Framework Directive (WFD) established a legal basis to protect and restore clean water across Europe and ensure its long-term, sustainable use. The general objective of the WFD is to get all water — for example, lakes, rivers, streams and groundwater aquifers — into a healthy state by 2015. But the achievement of EU water policy goals is threatened by a number of old and emerging challenges, including water pollution, water abstraction for agriculture and energy production, land use and the impacts of climate change.

The EU's policy response to these challenges is the forthcoming 2012 Blueprint to safeguard Europe's water resources. The overall objective of the Blueprint is to improve EU water policy to ensure good quality water, in adequate quantities, for all authorised uses. The Blueprint is thought to ensure a sustainable balance between water demand and supply, taking into account the needs of both people and the natural ecosystems they depend on.«

The Blueprint will synthesize policy recommendations building on three on-going assessments: 1) the assessment of the River Basin Management Plans delivered by the Member States under the Water Framework Directive, 2) the review of the policy on Water Scarcity and Drought and 3) the assessment of the vulnerability of water resources to climate change and other man made pressures. The CIRCA website is used for the daily management of the interim information generated by the supporting contracts. Final reports and official papers are stored on the WFD Circa Group.

Read more about the Blueprint to Safeguard Europe's Water on the WISE and CIRCA websites listed in the previous section.

6.8 Summary and outlook

The development of climate proof river basin management plans and climate change adaptation measures according to EU legislation requires sound climate change impact assessments. These include a sound understanding of the subsurface and the interaction between groundwater, surface water and ecosystems. Several EU directives especially the Water Framework, Groundwater and Flooding directives, and related guidelines have to be taken into account in this process. Further it is essential to recognize that the adaptation measures have to be flexible and take into account new data and scientific and technological developments. Provisions should therefore be made for the updating of relevant strategies and guidelines when new relevant data are available. Efficient on-line presentation procedures for illustration of new monitoring and climate change impact data will be an important tool for efficient implementation of adaptation measures.

7. Perspectives

The project emphasizes the importance of taking groundwater into account when dealing with climate change impact assessment and adaptation. CLIWAT deals with climate change impact assessments on future groundwater chemical and quantitative status in accordance with EU directives and associated guidances and provides important results for the review of the GWD in 2013 and for climate-proofing the next generation of RBMPs, due in 2015.

Increased winter precipitation will in many areas give rise to the formation of more groundwater. However, in low-lying areas such as the polder areas in especially the Netherlands and Belgium, the delicate management of the water table during the year leads to the formation of less freshwater. In addition the sea water intrusion leads to negative impacts on groundwater chemical and quantitative status. This is also the case for the Wadden Islands and in coastal areas where the increased sea level will enhance the sea water into coastal groundwater bodies and lower the amount of extractable fresh water. This calls for increased focus on optimized the management of the extraction wells and water conservation campaigns.

During summertime most climate models predict longer dry periods for the region, which will increase the need for irrigation and may create conflicts between water used and ecosystem needs. In addition, the rising groundwater table, built up during wintertime, may cause challenges to existing infrastructure, and increase the need for drainage of fields and cities. The investigations in CLIWAT have shown that detailed groundwater and integrated hydrological models on both regional and local scales are capable of forecasting the challenges that matter to local society, individual house-owners, etc. The CLIWAT project demonstrates that the ability to integrate results from local and regional scales is necessary to cope with the many challenges.

The groundwater resource feeds many needs and interests in the nature and in the society. In the future we have to be able to create cost-effective measurements and model tools that are able to describe the climatic impacts on groundwater and dependent surface water and ecosystems on a local scale. This should be done with accuracy and detail that both planners and engineers can use in their daily planning and construction projects. However, climate change projections and impact assessment have inherent uncertainties that planners and engineers have to acknowledge and include in the development of climate proof river basin management plans and infrastructure.

The CLIWAT project has demonstrated that involving stakeholders in an early stage is important and has produced good examples of raised awareness on groundwater conditions.

The CLIWAT project has demonstrated new and efficient ways to establish the necessary understanding of current conditions. However, it also emphasize that e.g. the following tools and processes have to be improved and more widely applied for future efficient climate change adaptation:

- Cost-effective tools to characterise the subsurface, especially the shallow parts and the interface between groundwater and surface waters (e.g. geophysical, efficient drilling techniques, geochemistry, groundwater dating).
- Efficient groundwater and coupled groundwater – surface water modelling tools that describe groundwater flows in the uppermost part of the subsurface and the interaction with surface waters suitable for planning and engineering purposes on a local scale.
- Intensive and integrated monitoring and modelling of the groundwater systems on a local scale.
- A better understanding of future leaching from point sources and agricultural areas in order to develop new standards for best practice.
- An integrated stakeholder approach
- Efficient on-line data presentation and dissemination tools, which can be easily updated with new results and predictions

Climate change impact assessment and adaptation is a dynamic process that will have to be improved and developed continuously in the future. CLIWAT contributed to the initiation of this process.

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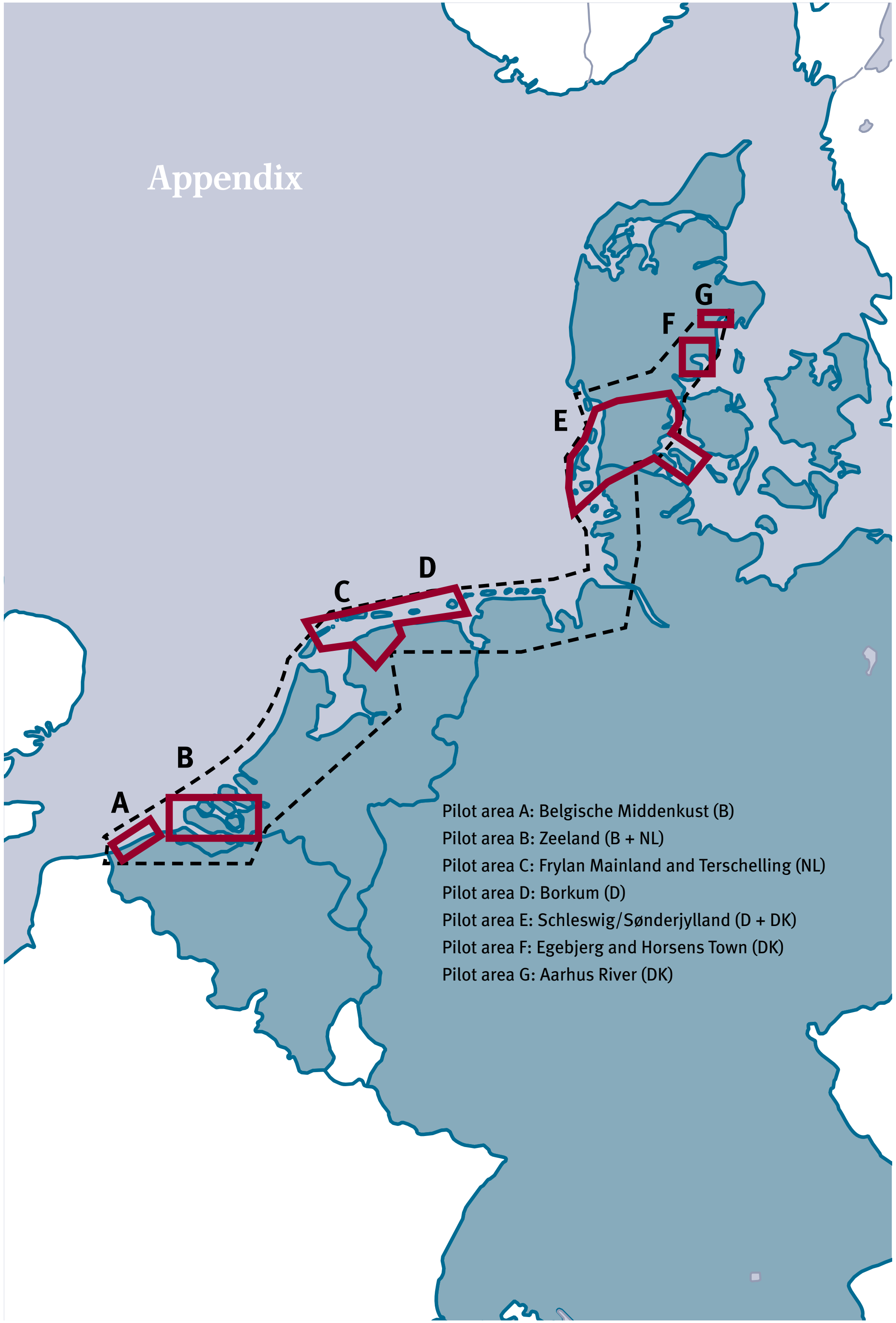
Appendix



Pilot Area A

Belgische Middenkust (B)

Introduction

The Belgian pilot area 'Belgische Middenkust' is situated in the central part of the Belgian coast between Zeebrugge en Nieuwpoort. It is the most populated part of the Belgian coast.

The pilot area is characterized by a shore, dunes and polder area. The width of the shore varies between 200 and 500 m and has one of the highest sea level fluctuations of the North Sea with an amplitude of almost 2.5 m during spring tide. Dune area is relatively small, between 50 and 1500 m. This results in a large variation in the extension of the freshwater lenses underneath the dunes. Polders are low-lying areas (between 0 and 3 msl) which need drainage by a dense network of ditches and canals. The drainage level is about the mean seawater level. The polders contain a complex fresh-saltwater distribution which is the result of Holocene transgression combined with geologic and geomorphologic evolution and the human intervention (e.g. land reclamation).

Present situation

Freshwater reserves in the dunes (because of the limited width) and polders (because of the complex fresh-saltwater distribution) are limited. Meeting demands for freshwater is thus a major challenge. Polders are further an artificial, by man created landscape and hydrology must be carefully managed. Projected evolutions of climate change add to this constant management. The varying width of the dune makes that there are several weak points in the coastal defence with potential inundation threats.

Historical maregraph measurements (1925-2004) in Oostende show an increase in the mean sea level of 14,4 mm per decade over this measuring

period. Globally, during the period 1961-2003 sea level rose 18 mm per decade. Because of sea level rise and the presence of a limited dune belt, seepage of water in the polder area is likely to increase. In many areas this will lead to an increase in salt load having a negative influence on crop yield.

Change of climatologic parameters will influence recharge and recharge patterns. Subsequently, this has an influence on drainage and repercussion for the hydraulic management of the polder area.

It's expected that periods of high rainfall and severe storms will occur more frequently in the future. Due to insufficient drainage at such severe events, flooding can arise. This will result in the infiltration of additional freshwater in the aquifer. Flooding can also be the result of severe storm events whereby sea water inundates parts of the dune and polder area. In this case, saltwater will enter the aquifer. Consequently floods will alter temporally groundwater flow and could have a long-lasting influence on fresh-saltwater distribution.

What kinds of problems/issues have been investigated?

The complex fresh-saltwater distribution was first mapped in the early 1970s by De Breuck et al. (1974). In the following 40 years, a lot of new data have been collected but never interpreted on the scale of the pilot area. Consequently, this data (chemical and geophysical data) has been integrated within the old map.

Geochemistry has been so far investigated in small study areas in the coastal plain but not on a large scale. The chemistry data collected to update the fresh-saltwater distribution is also used for that purpose. Key question is what chemical reactions determine the overall composition of the fresh, brackish and salt water.

Characterising fresh-saltwater distribution on a field scale is a difficult task. Moreover, its distribution is driven by a number of different processes. It was therefore investigated how different kinds of data and techniques (chemistry, hydraulic heads, borehole geophysics, aquifer tests, temperature logs, environmental tracers, flow and transport modelling) can be combined and contribute to this.

So, it was investigated how geophysical borehole logs (electrical conductivities of the deposits and the natural gamma radiation) will help us in the schematization of the groundwater reservoir. In hydrogeological literature a number of estimation methods of the hydraulic conductivities are known. These estimations are based either on the natural gamma radiation of the deposits or on the electrical matrix conductivity of the deposits. These matrix conductivities are however not directly measured and should indirectly be deduced by the joint interpretation of the two geophysical borehole logs. By this joint interpretation of the logs it was also possible to derive the variation of the porosity and of the electrical pore water conductivity versus the depth. The depth variation of the pore water conductivity is important to derive the fresh-salt water distribution; the depth variation of the porosity is important to estimate the depth variation of the hydraulic conductivities of the deposits.

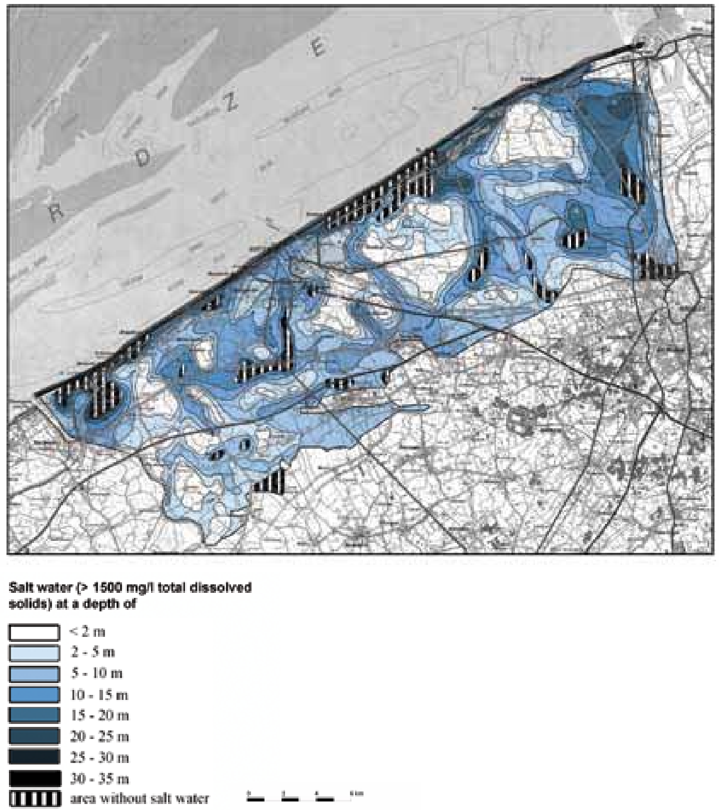
Finally, a 3D density-dependent flow and transport model has been made of the central area of the pilot area. The current fresh-saltwater distribution is simulated and with this as starting point to simulate influence of sea level rise. Special attention goes to the change in freshwater reserves and salt load on the surface.

De Breuck, W., De Moor, G., Tavernier, R., 1974. Depth of the fresh-salt water interface in the unconfined aquifer of the Belgian coastal area (1963-1973). Proc. 4th Salt Water Intrusion Meeting, Gent, annex-map, scale 1/100000.

What are the outcome/results?

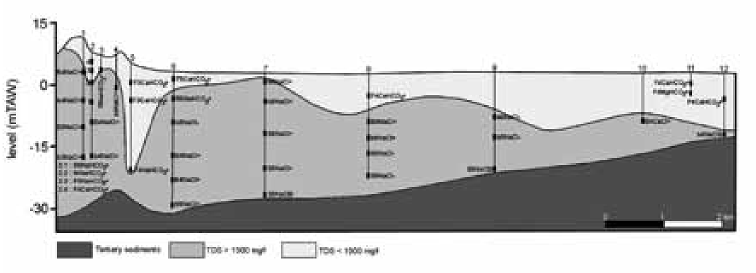
Fresh-saltwater distribution (Vandenbohede et al., 2010)

- Data collected in the last 35 years are in general in good agreement with the map of 1974.
- An updated map was made, see figure below.
- With the exception where (hydraulic) interventions were done (e.g. harbour infrastructure) current fresh-saltwater distribution is in equilibrium with the hydraulic boundary conditions.
- Map gives a good and representative distribution at large scale, at small scale (hundreds of meter) additional research is recommended.



Geochemistry of pore water (Vandenbohede and Lebbe, 2011)

- Holocene transgression, consequential geologic and geomorphologic changes and human intervention (impolderdering) influenced pore water chemistry in the pilot area. Two hydrosomes (bodies of water of the same origin) are found (see figure below): brackish and saltwater dating from before the impoldering and freshwater dating from after the impoldering.
- Mixture of fresh and saltwater, carbonate mineral dissolution, cation exchange, and some oxidation-reduction reactions (organic matter, pyrite) determine water quality.
- A clear chromatographic sequence due to cation exchange is visible in the fresh water hydrosome. This hydrosome originates because of the displacement of saltwater with freshwater because of the impoldering.
- Older brackish and saltwater contain the signature of both freshening and salinization illustrating the complex evolution of the coastal plain from the last ice age until the impoldering.



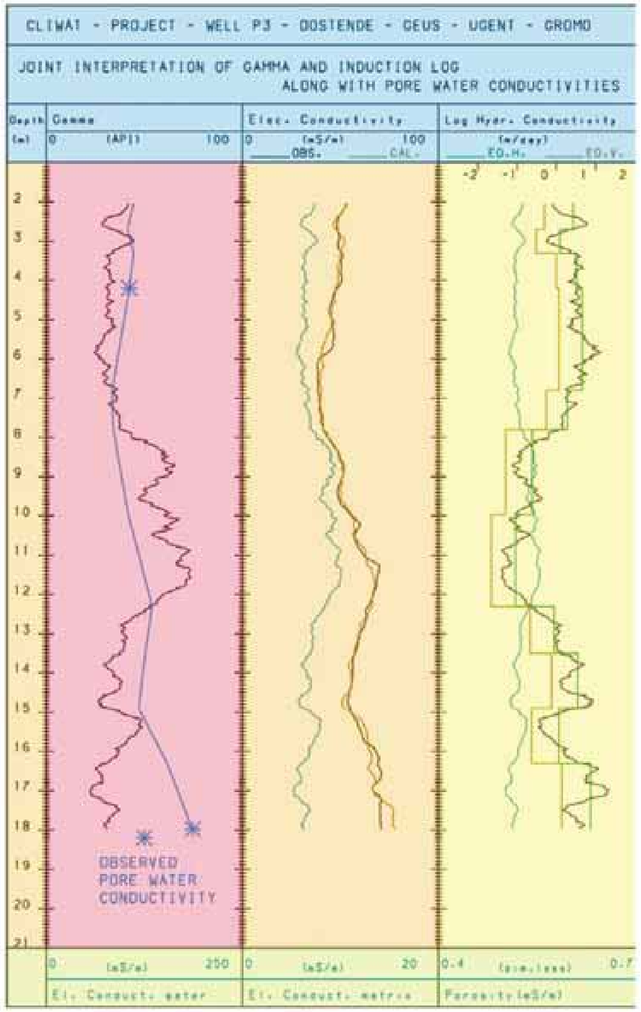
Combination of different methods to characterize aquifers (Vandenbohede et al., 2011)

- Tracer data can serve to derive parameters related to groundwater systems or can be used in the calibration of transport and flow models. In this part of the study, we used temperature, 3H/3He (age dating) and hydrochemical data, together with head measurements, borehole logs and an aquifer test to obtain insight in the groundwater flow and fresh-saltwater distribution of a small area in the pilot area (Snaeskerepolder).
- Flow and transport model code SEAWAT acted as the integration medium for the different data. Each data type has its own interpretation technique and delivers pieces to add to the model. Additionally, the aim of using different data is to perform verification of results. For instance, fluxes from temperature logs and the SEAWAT model, water quality and age dating all provide information of flow to and velocities in the vicinity of drainage ditches.
- Different data also provide information on different scales. Temperature logs and aquifer tests act on a small scale, groundwater age is influenced by larger scale flow and water quality is determined by the general flow of the area.

With this part of the study we aimed to illustrate that integration of different kind of geological, hydrological, geophysical and geochemical data is an important way forward in our modelling efforts and understanding of (coastal) groundwater systems. And this is a prerequisite for simulating effects of climate change.

Depth variation of hydraulic conductivities estimated from geophysical borehole logs

A method is developed to estimate the equivalent horizontal and vertical hydraulic conductivities of a defined depth interval of sediments based on geophysical borehole logs (electrical conductivities of deposits and natural gamma radiation) and on a limited number of electrical conductivities of extracted pore waters. This method is developed using the observations of two double pumping tests performed at two different sites in the Belgian pilot area. In this estimation method a number of well established relations are applied such as: the law of the parallel electrical conductivities, the relation between the natural gamma radiation and the electrical conductivity of the matrix and the relation between the formation factor F, pore water conductivity and electrical matrix conductivity. Beside the estimation of the equivalent horizontal and vertical hydraulic conductivities of well defined depth intervals also the depth variation of the total salt content of the pore water, the porosity and of the electrical matrix conductivities is estimated. All these valuable data about the electric and hydraulic parameter derived from the geophysical allows us the schematization of the groundwater reservoir (succession of pervious and semi-pervious layers and their heterogeneity). So, the borehole data will not only deliver data about the present salt-fresh water distribution but also about the hydraulic conductivity of the groundwater reservoir. These are both valuable data for the 3D density-dependent flow and transport model.



Future effects of sea level rise

Fresh-saltwater distribution in the area of Oostende, central in the pilot area is simulated. Subsequently, this distribution is used a starting point to simulate the effect of sea level rise. Some results of this are shown in the section 5 'Future situation, including aps/figures illustrating the scenario(s)'.

Vandenbohede, A. Courtens, C. Lebbe, L., De Breuck, W. (2010).
Fresh-salt water distribution in the central Belgian coastal plain: an update. Geologica Belgica, 11/3, 163-172.

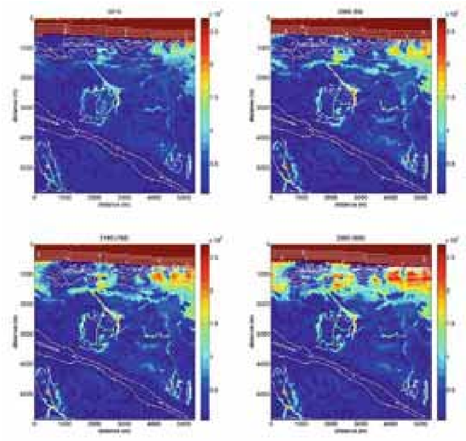
Vandenbohede, A, Lebbe, L. 2011.
Groundwater chemistry patterns in the phreatic aquifer of the central Belgian coastal plain. Applied Geochemistry, doi:10.1016/j.apgeochem.2011.08.012.

Vandenbohede, A., Hinsby, K., Courtens, C., Lebbe, L., 2011.
Flow and transport model of a polder area in the Belgian coastal plain: example of data integration. Hydrogeology Journal, DOI: 10.1007/s10040-011-0781-7.

Future situation, including maps/figures illustrating the scenario(s)

By using a 3D density dependent model to study the effects of climate change in the coastal area central in the pilot area the following conclusions were obtained:

Sea level rise results in the decrease of the volume of freshwater in the freshwater lenses present under the dunes. This means that freshwater reserves in the dune area become even more limited than they currently are. A second effect is the increased salt load in the upper part of the aquifer. Mean increase in salt load for the first km inland from the coast is already 1.25 times larger than in the current situation. It is expected that this will have its effects on the land use and culture which will be possible in the future. Further from the coast, sea level rise mainly results in an increased flow of brackish to saltwater to the drainage channels. Increase of salt load on intermediate land is limited. Figure below shows the evolution of the mineralisation of the groundwater (in mg/L) at the top of the aquifer.



Challenges and future possible solution – recommendations for adaptation or further investigations

Predictions for the future are heavily dependent on our present-day system understanding. Some recommendations for this are:

Ditches are a vital part of the drainage system for the management of the polder area. However, not much is known about the water balance of these ditches (base flow, run-off capture, sensonal fluctuations in drainage capacity etc.). A first step was made with the project to determine and verify with different methods groundwater fluxes to two ditches in the Snaeskerkepolder but obviously, more data is necessary on this groundwater-surface water interaction.

Additionally, few data are available of the water quality (e.g. total dissolved solutes, TDS) in the ditches. Monitoring this, for instance by measuring the electrical conductivity which is function of TDS, would therefore be a valuable contribution for our understanding to the drainage system.

Pilot Area

B Zeeland (B-NL)

Introduction

The Dutch pilot area 'Zeeland' is situated in the South-West of the Netherlands. The province of Zeeland has 380.000 inhabitants in thirteen counties. 70% of the landuse in Zeeland is agriculture, while tourism and recreation are important economic activities. Large parts of Zeeland are below mean sea level and dikes prevent the land from flooding. The most northern island 'Schouwen-Duiveland' is of particular interest in the project CliWat. Dunes are located in the western part of Schouwen-Duiveland, the parts with the lowest surface elevation are the reclaimed salt marshes and there are some creek deposits on the island.

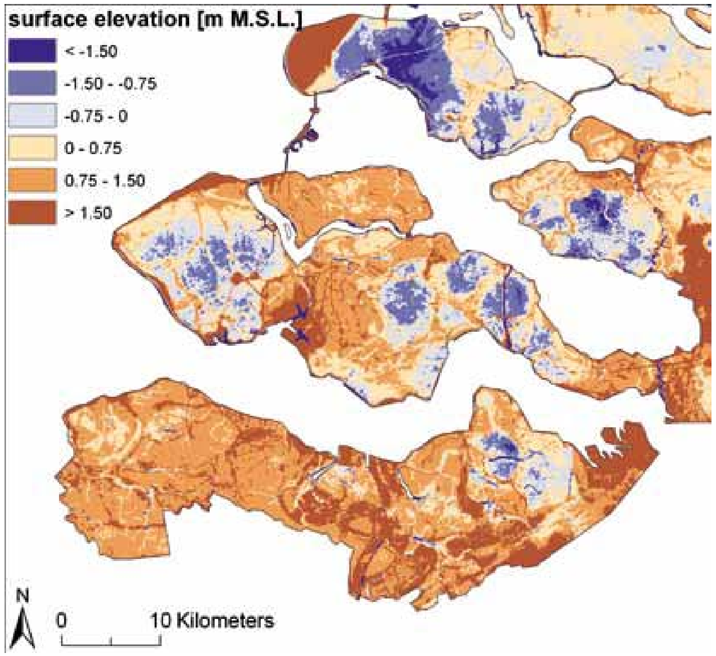


Figure 1: The province of Zeeland in de South-West of the Netherlands. Schouwen-Duiveland is the island in the north .a. surface elevation [laser-altimetry] and b. island Schouwen-Duiveland [from Intereg IV-b project CPA].

Present situation

Most of the groundwater and surface water of Schouwen-Duiveland is saline. The ecological reserves in the dunes are relying on fresh water, all other ecological reserves areas are of brackish / saline nature. There is infiltration of fresh water (transported from outside the dunes) into the dunes for drinking water supply. Agriculture and nature reserves on the other hand are self-relying for their fresh water supply. Irrigation is rare on Schouwen-Duiveland and salt and drought damage to crops occurs during dry summers. There are sources of fresh water available at Schouwen-Duiveland: 1. precipitation surplus (mean last 10 years: 200mm/year); 2. fresh groundwater in the dune area (up to 50-100m below surface level); 3. fresh groundwater in the creek deposits (up to 5-15 m below surface level) and 4. rainwaterlenses in saline seepage areas (less than 5 m below surface level). The dynamics and dimensions of these fresh water resources are not known exactly end these fresh water resources are probably not optimally used.

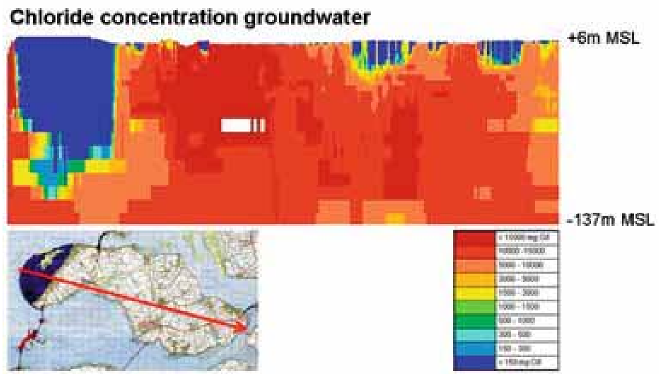


Figure 2: Profile of the Chloride concentration of the groundwater of Schouwen-Duiveland.

What kind of problems/issues has been investigated?

In many coastal areas groundwater is saline because of sea water intrusion and marine transgressions. Large parts of the province of Zeeland is situated below mean sea level and saline groundwater may reach the surface by upward groundwater flow. This upward seepage of saline groundwater causes salinization of surface waters and mixes with shallow fresh water bodies making it unfit for irrigation, drinking water supply and industrial use. Rainwater lenses develop on top of saline groundwater by infiltration of rainwater. These rainwater lenses act as fresh groundwater storage in the study area. The lenses are generally thin (< 3 m) in the low-lying seepage areas and may reach greater depth in the infiltration areas in sandy creek ridges (5 to 10 m) and at the dunes (> 20 m). Future rises in sea level and climate change are expected to increase the seepage and salt loads to surface waters and decrease the availability of both fresh surface and groundwater.

The research objective of pilot area B – province of Zeeland – is to describe the characteristics and spatial variability of rainwater lenses and determine the main factors that control these characteristics. Different in-situ (including TEC-probe, ECPT, groundwater sampling) and ex-situ field techniques (including CVES, EM31, HEM) are used to map the characteristics of the rainwater lenses (e.g. thickness rainwater lens, width of mixing zone, depth fresh-saline groundwater interface). Complementary to the field measurements we used numerical groundwater models to determine the controlling factors of the different lens characteristics and to explain their spatial variability. With the model we also calculated the effect of climate change and sea level rise on lens characteristics and fresh water availability.

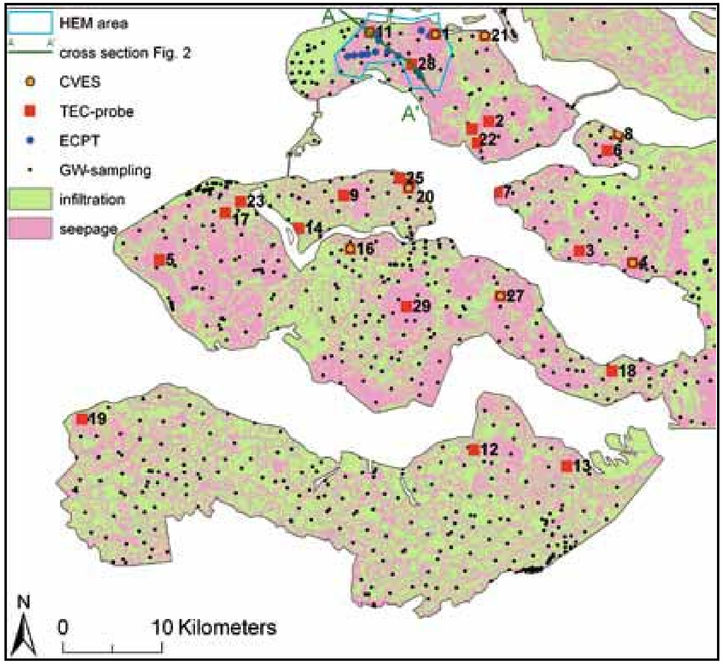


Figure 3. Position of field measurements in pilot area B: province of Zeeland.

What are the outcome/results?

The outcome of the research of pilot area B are:

1. Field measurements that show the characteristics of rainwater lenses in different kind of areas;
2. Extrapolation of rainwater lens characteristics to larger areas using HEM: map of rainwater lens thickness;
3. An analysis of the most important factors that control the development of rainwater lenses;
4. Improvement of the 3D-chloride distribution map of Schouwen-Duivenland;
5. Simulation of the present groundwater system (heads, fluxes and Cl-concentration) with a numerical density dependent groundwater model of Schouwen-Duivenland;
6. Quantification of the effects of climate change and sea level rise on the groundwater system of Schouwen-Duivenland.

Characteristics of rainwater lenses

The in-situ measurement show that the centre of the mixing zone between rainwater and saline groundwater varies between 4 and 11 m depth (e.g. ECPT 32 and ECPT 4 in Fig. 4). At the dunes or nearby the dunes the fresh water lens may reach depths greater than 50 m (e.g. ECPT 12 in Fig. 4). In the seepage areas the rainwater lenses are much thinner; mixing of saline seepage with rainwater occurs no deeper than 3.5 m and the centre of this mixing zone is found as shallow as 1.0 to 2.5 m below ground level (e.g. ECPT 31 and ECPT 13 in Fig. 2). There is no sharp boundary between infiltrating fresh rainwater and saline seepage groundwater but a gradual transition zone with an average width of 2.0 m. As the mixing zones manifest at shallow depth, their depth and width is of great importance for the fresh water availability for the growth of crops. In most seepage areas, we did not find any fresh groundwater. The upper groundwater is therefore already a mix of seepage and rainwater, which indicates that part of the mixing process occurs in the unsaturated zone.

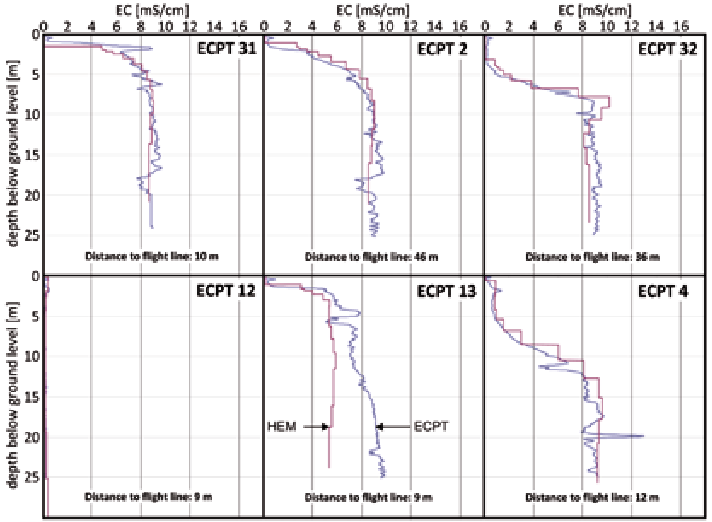


Figure 4. Comparison of six ECPT soundings and smooth 15-layer HEM inversion models (for location see Fig. 1)

Mapping rainwater lens thickness using Helicopter-borne electromagnetic measurements (HEM)

The combination of the applied techniques made it possible to extrapolate the detailed in-situ measurements at point scale (groundwater sampling, TEC-probe, ECPT) to field scale (CVES, EM31) and even to large areas with helicopter-borne electromagnetic measurements (part of the island Schouwen-Duivenland, 56 km^2).

The HEM data inverted to layered-earth resistivity depth models reveal the spatial distribution of the electrical conductivity down to depths of about 20-30 m in the lowlands and more than 60 m in the dune area. The results of the smooth 15-layer HEM models agree very well with nearby ECPT measurements (Fig. 4). From the HEM- inversion models we made a map of the thickness (D_{mix}) of the rainwater lenses for the entire airborne survey area (Fig. 5). Thicker rainwater lenses occur in the eastern part of the survey area (D_{mix} = 5-10 m), close to agricultural field 11 and the adjacent the fossil sandy creek (D_{mix} = 8-20 m) and, of course, in the dune area (D_{mix} > 30 m).

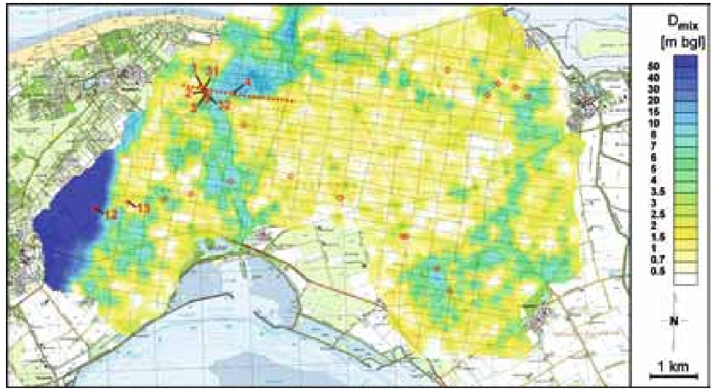


Figure 5. Estimated depth of D_{mix} (average position of the mixing zone) derived from HEM inversion models. All flight lines (black lines) and the location of the ECPTs (red circles, those shown in Fig. 4 are numbered) are plotted on top of the depth map.

Future situation, including maps/ figures illustrating the scenario(s)

In the Netherlands 4 climate scenario's are used to predict the climate for the year 2050:

Tabel 1: Climate scenario's 2050 KNMI (Klein Tank en Lenderink, 2009)

Scenario	G	G+	W	W+
Worldwide				
Windcirculation	un-changed	changed	un-changed	changed
Temperature (°C)	+1	+1	+2	+2
Summer the Netherlands				
Mean temperature (°C)	+0,9	+1,4	+1,7	+2,8
Mean precipitation (%)	+2,8	-9,5	+5,5	-19.0
Mean evaporation (%)	+3,4	+7,6	+6,8	+15,2
Winter the Netherlands				
Mean temperature (°C)	+0,9	+1,1	+1,8	+2,3
Mean precipitation (%)	+3,6	+7.0	+7,3	+14,2
Sea level rise				
Sea level rise (cm)	15-25	15-25	20-35	20-35

There are different causes for future salinization of the groundwater and surface water system:

1. autonomous proces (no equilibrium yet in the low lying areas; the saline groundwater from historical transgressions goes in upward direction which results in salinization of the shallow groundwater)
2. sea level rise
3. changing groundwater recharge
4. land subsidence
5. antropogenic (f.e. groundwater extractions)

The autonomous process is dominant in the salinization proces (figure 6b). Due to sea level rise or land subsidence the difference between the level of the sea and the level of the locks increases, the seepage flux increases and

salinization is accelerated. The salinization of the shallow groundwater (at bottom Holocene layer) due to climate change scenario W+ increases mainly (figure 6c).

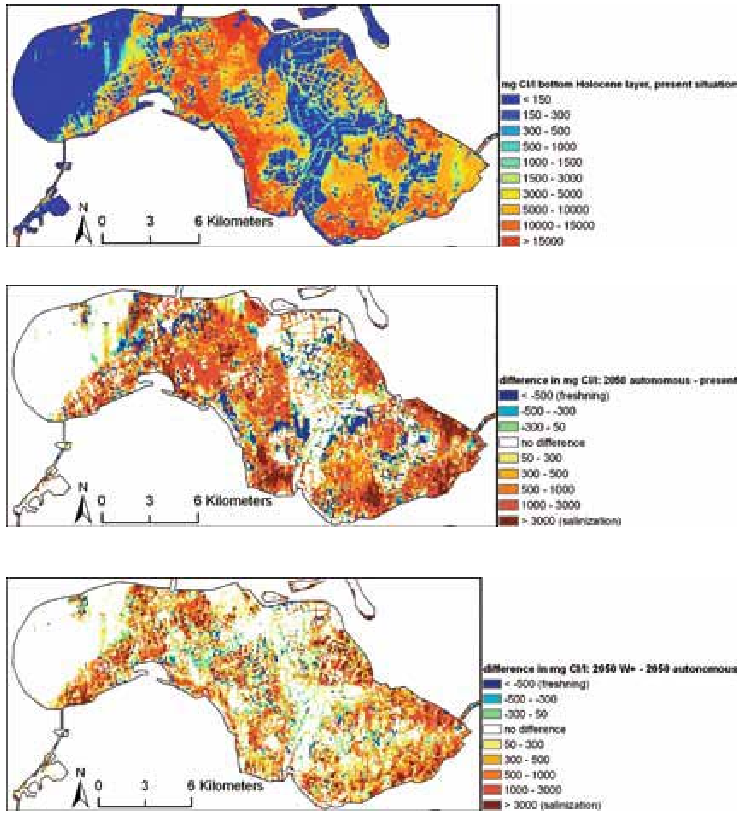


Figure 6: a. chloride concentration groundwater at bottom of Holocene layer, present situation; b. salinization/freshening due to autonomous processes 2050 and c. salinization/freshening due to only climate scenario W+ 2050.

Challenges and future possible solution – recommendations for adaptation or further investigations

Recommendations for adaptation
In the present situation, the fresh precipitation and the fresh seepage from the dunes and sandy creeks is quickly drained out of the island in order to avoid damage from too much water. These fresh water resources are quickly mixed with salt surface water. For each subarea of Schouwen-Duiveland the fresh water supply for agriculture can probably be improved. But the best measure depends (among others) on the available amount of fresh water nearby, the kind of landuse, the surface elevation and soil. Some examples are shown in figure 7.

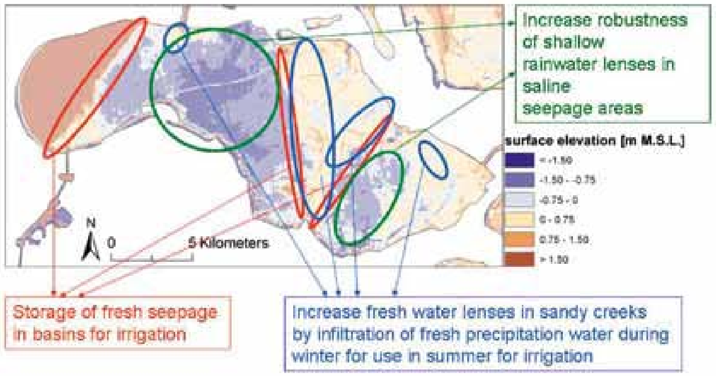


Figure 7: some measures in order to increase the fresh water availability for agricultural use.

Recommendations for further investigations

- Research on the effect of climate change and in particular the increase of heavy rainfall and drought on the groundwater discharge and therfore on the dynamics of the fresh water resources (shallow rainwater lenses and fresh water in sandy creeks).
- Research on the resolution of the model on the seepage fluxes to the surface water system.
- Where is the most uncertainty in the quantification of the influence of the climate scenario's on the salinisation in the year 2050 (geologie, hydrological parameters, climate scenario, ...)?
- Pilot study on the possible increase of the fresh groundwater resources in the sandy creeks: where is artificial infiltration of water during the wet season possible?; how much can the fresh water resource be increased?; will there be too much fresh seepage near the infiltration/ what is the risk?; is this measure economically interesting?
- Can the shallow rainwater lenses in saline seepage areas be made more robust by smart drainage systems?; In what kind of soils can this be done?
- Can there be more interaction in the subject of fresh water supply between the different kinds of land use: urban areas, agriculture, nature and recreation?

Pilot Area C

Fryslân Mainland (NL)

Introduction

Fryslân is situated in the north of the Netherlands. The CLIWAT pilot area of the Main land of Fryslân covers a part the coastal area of the Wadden Sea (figure 1). The area is characterised by low surface elevation. In large parts of the area the surface elevation is even below mean sea level. This necessitates among others an appropriate management of surface water levels and a complex water infrastructure to maintain these levels and to protect the land from water flooding. Furthermore the surface water has to be flushed frequently with fresh water from the IJssel Lake, to remove the salt water in the surface waters, which originates from salt seepage from the shallow subsoil.

Typical for this area is the shallow depth of the fresh / saline boundary of the groundwater. Near the coast the thickness of the fresh groundwater body is only 2 to 5 meters. Further from the coast this depth increases to over 100 meters. The thickness of the fresh groundwater body, or groundwater lens, varies during the seasons. At the end of the winter (wet season) the thickness is maximum. At the end of the summer however, the fresh groundwater lens shrinks considerably, and in few cases even completely disappears. This may cause severe problems for agriculture. It is expected that, due to climate change, especially changes in precipitation, and also by changes in seawater levels, the problems with salt (ground)water will increase in the near future.

It should also be mentioned that climate change and rise of seawater levels are not the only reason for salt groundwater intrusion. The present salt distribution very much reflects the Holocene transgression of the sea. Furthermore the effects of the last 200 years of water management, the effects of groundwater abstractions, and of mining salt and gas from the deep subsoil, considerably contribute to an ongoing salt groundwater intrusion.

Present situation

In the present situation relatively few farmers encounter problems with salt groundwater. There is, in many cases, a delicate balance between fresh water needs of the crops and the availability of fresh groundwater in the thin fresh groundwater lenses. Nevertheless, especially in the low lying areas, there is an increasing number of farmers, who encounter problems with their crops and or cattle, because of the salt.

Recent studies also confirm that an increasing number of farmers expect to be confronted with increasing salt problems in the near future.

What kind of problems/issues has been investigated?

First of all the present salt groundwater situation has been mapped using various geophysical, geotechnical, geohydrological field techniques. In addition the subsurface has been characterised in detail in 3D.. Finally, by means of a groundwater model, the effects of climate change and seawater level rise have been calculated.

What are the outcome/results?

- determine the present distribution of salt groundwater in the subsoil
- determine the structure of deposits in the subsoil (clay, sand, etc.).
- improved geological and geohydrological model
- improved geohydrological, parametric model
- quantify present regional groundwater flow patterns and flow rates by improved groundwater model
- quantify present regional patterns of salt water seepage to surface waters by improved groundwater model.
- quantify changes in regional groundwater flow patterns and –rates due to climate change and sealevel rise.

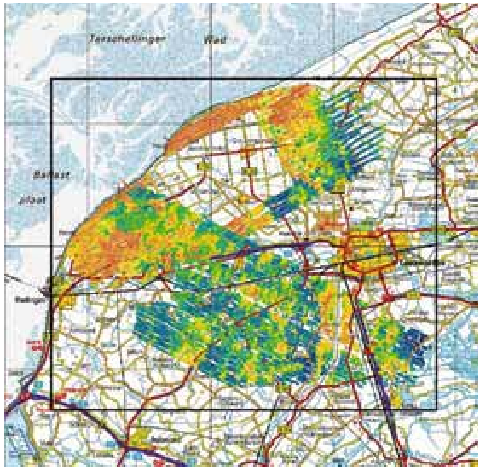


Figure 1: map of the CLIWAT pilot area in the main land of Fryslân.

Challenges and future possible solution – recommendations for adaptation or further investigations

The CLIWAT study indicates which parts of the project area will most likely encounter problems with salt groundwater and salt groundwater seepage. Additional studies will have to be implemented to minimise the risks of salt groundwater. Especially the role of drainage and surfacewater level will have to be studied in detail at local scale.

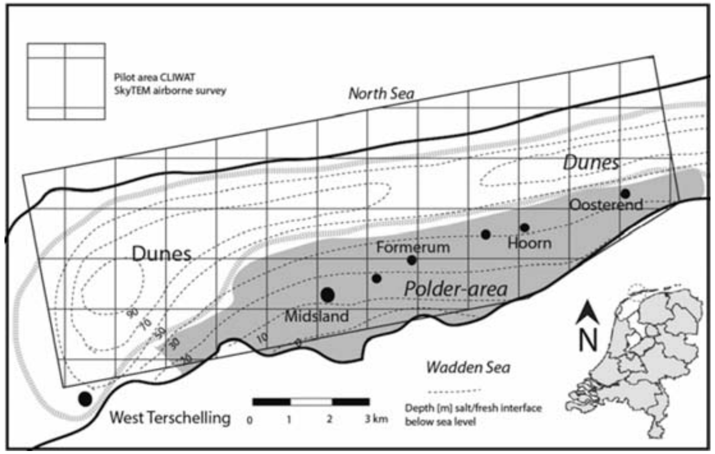
Furthermore the airborne geophysical measurements proved to be very successful, and it resulted in very detailed maps of saltwater distribution and geohydrological characterisation of the subsoil. For this reason it is recommended to extend this fieldwork to other parts of Fryslân. Further to extend the density driven groundwater flow model to other parts of Fryslân.

Pilot Area C

Terschelling (NL)

Introduction

Terschelling is one of the Dutch Frisian Wadden islands. The island is 30 km long and 4 km wide. Based on the Ghyben-Herzberg principle, a fresh groundwater lens has been established under the Dutch Wadden Islands. This lens is the "beating heart" of the hydro geological cycle and the drinking water supply of the islands are in many cases depending on this lens. For salanization risks, i.e. as an effect of climate change, the knowledge of the variation (in time) of the depth of the salt and fresh water interface is essential. The presence, distribution and time variation of a fresh water lens depends on the lithology, topography, rainfall and (of course) exploitation.



Present situation

The aim of this project is to research the effects of sea level rise and climate change on the equilibrium between salt and fresh groundwater. This problem is an essential issue in a relative flat and sandy costal areas, like The Netherlands, Germany and Denmark.

According to the principle of Ghyben-Herzberg a fresh water lens has developed locally under the island up to 100 meters thickness in the dune area and up to 60 mtrs in the polder area. This lens was also detected below the North Sea locally up to a depth of 60 mtr, this was already confirmed with a field survey in 2007. This salt and fresh water interface as a part of the hydrological system was also calculated with a density driven geohydrological model (MODFLOW-SWI). This modflow model of Terschelling is used for calculating the hydrological effects or salanization risks of groundwater withdrawal and will also be used for the effects of climate change upon the distribution of the lens in time.

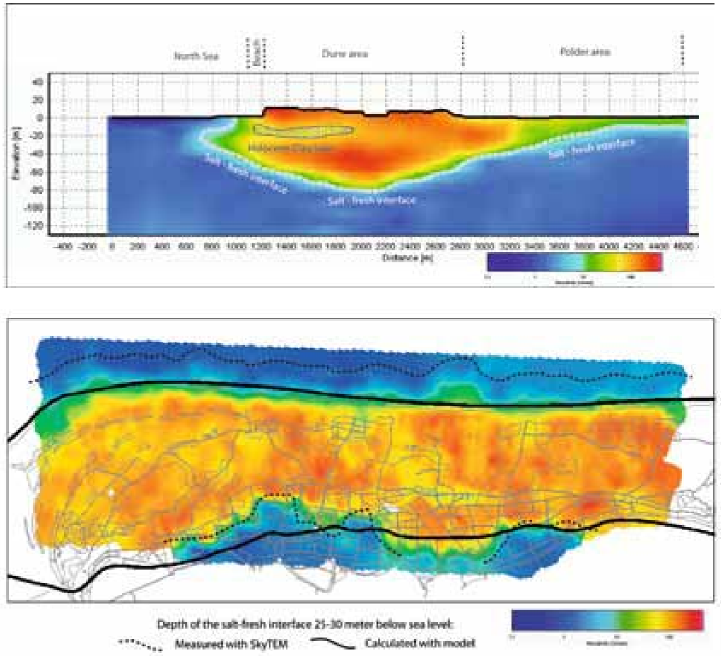
At this moment the island is not self supporting in their drinking water supply. For 66% the drinking water is coming via a pipe line from the main land. Water supply company Vitens is busy with a pilot study. The aim of this study is to investigate if a self supporting water supply is possible in the future. Knowledge about the equilibrium between salt and fresh groundwater and changes caused by sea level rise is therefore essential.

What kind of problems/issues has been investigated?

With the SkyTEM survey it was possible to 'map' the whole fresh water lens, not only under the dunes but also in the polder area, but also north of the beach, outside the coast line.

What are the outcome/results?

Based on the SkytTEM data and many field measurements a detailed 3D model of the distribution of fresh water was the result. These results are compared with the calculated boundary based on the results of the geohydrological model (Modflow-SWI) of the island. Conclusion was: in some areas the fit was quite good, in others it could be better.



With the SkyTEM data (distribution of the salt fresh interface and consistent low-intermediate resistivity layers) it was possible to refine the geohydrological model. This model is now calculating the measured interface.

Challenges and future possible solution – recommendations for adaptation or further investigations

Field measurements are essential to calibrate hydrological models. Normally this calibration is based on point information. Often we do not know what happens between these points. SkyTEM makes an ´old fashioned´ and sometimes forgotten EM-technique very useful. In a very short time this system is able to map a large area in a very detailed scale. Combined with a few calibration measurements SkyTEM is a very powerful and cost-effective tool, for hydrological survey. Results of SkyTEM data, like the distribution of the salt fresh interface or consistent low-intermediate resistivity layers are very useful to calibrate the hydrological model.

Pilot area D

Borkum

Introduction

The German North sea island Borkum is the westernmost and largest of the East Frisian Islands. Ranging 10 km from east to west and maximum 7 km from north to south it covers an area of about 31 km². The 5500 inhabitants are living mainly in the village of Borkum, lain on the western side of the island. The main source of income is tourism and about 280000 tourists visit the island during summertime.

The drinking water supply of Borkum is autonomous and there are two water works. The wells of water work I (Waterdelle), located in the western part, reach down to a depth of 10 m and those of water work II (Ostland), located in the eastern part, reach a depth of 40 m.

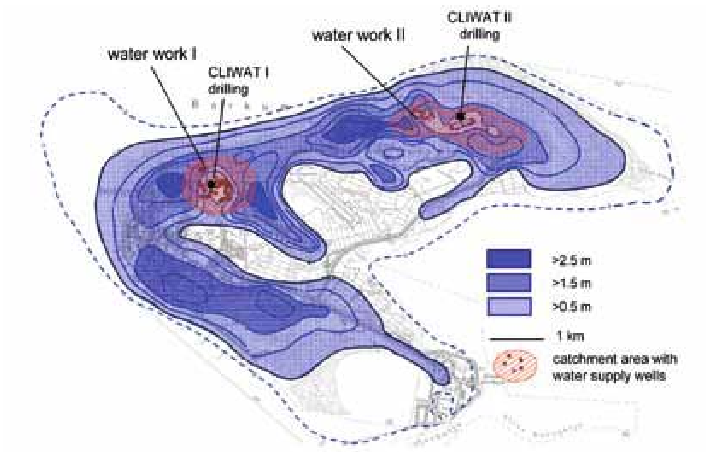


Fig.1: Map of Borkum with ground water table and catchment areas of water supply wells

Fig.1 shows a map of Borkum combined with the groundwater table and the catchment areas of the water works. The fresh water lens of the island is limited more or less to the dune areas and exhibits in the areas of the water works thicknesses of about 50 m. Two vertical electrode chains have been installed in the course of the CLIWAT project in the deep drillings CLIWAT I and CLIWAT II, which are located in the vicinity of the well fields Waterdelle and Ostland, to monitor the temporal and spatial behaviour of salinity in the vicinity of the saltwater/fresh water transition zone in a depth between about 45 and 65 m.

The aquifer exhibits 4 different levels, each separated by more or less leaky aquitards. In the area of the water supply well fields there are extended clay layers, protecting the drinking water from pollution from above and up coning salt from below. The Tertiary basement of the aquifer is located in a depth of about 180 m (Fig. 2 left). The uppermost three Quaternary aquifers are used for drinking water supply and reach down to a depth of about 50 m.

The delivered water generally is of good quality, though in several wells high concentrations of iron occur. After delivery the water has to be threatened by some standard procedures. The chloride concentration in all wells is lower than 100 mg/l. From water work I an amount of 340 thousand m^3/a drinking water is delivered (permitted 400 thousand m^3/a) and from water work II an amount of 530 thousand m^3/a (permitted 800 thousand m^3/a). According to the seasonable pattern of the tourism the annual variation of the abstraction is considerable and varies usually during one year between 30 and 120 m^3/month for all supply wells.

Present situation

Former studies indicate a limited fresh groundwater resource and a level of water abstraction (0.9 million m^3/year) that is just in balance with the amount of recharged fresh groundwater. Climate changes are expected to adversely affect this balance and decrease the potential fresh water supply by salinization. In addition, the waterworks may use the entire permissible amount (1.2 million m^3/year), which could lead to problems of salinization

from overexploitation. Waterworks (administrated by Stadtwerke Borkum GmbH) abstract vital amounts of groundwater in water work I and II and supply the island of Borkum with drinking water. Increasing salinization in the deep screen of water work II even now is a problem.

The groundwater resources in Borkum must be protected to meet the current and future demands for domestic water. The need to adapt to the predicted climate changes is urgent and the Borkum project and the CLIWAT project in general, will provide the basis on which adaptations can be made.

What kind of problems/issues has been investigated?

The main objectives of the Borkum pilot area are to develop a 3-D hydro geological model, map the spatial distribution of subsurface ground water bodies, and to evaluate quantitative and qualitative effects of climate change on groundwater from simulations generated by a numerical model which is based on the hydro geological model. The hydro geological model is mainly based on geophysical data like airborne electromagnetic data (HEM), seismic data and the statistical evaluation of drilling data. The total model area attains 133 km^2 and is four times as large as the is-

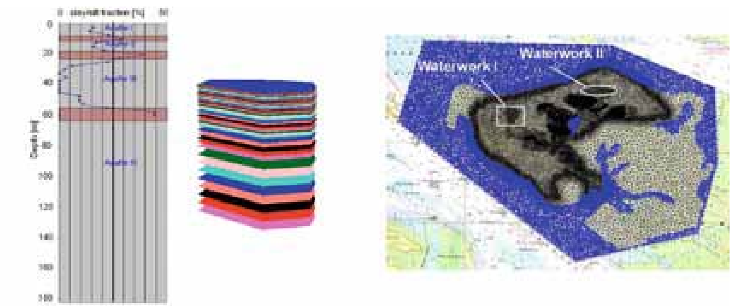


Fig.2. Hydrogeological model (Fig. left). Numerical model, setup with 39 vertical layers (centre of the figure), discretization of the model in 1 m depth (const. mass boundary conditions for sea water are marked blue) (Fig. right).

land of Borkum itself because considerable parts of the Wadden Sea have to be incorporated into the numerical computations (Fig.2. centre and right). For the numerical modelling the 3D-finite elements code FEFLOW (www.feflow.de) was used.

The numerical model will use data from the Intergovernmental Panel of Climate Change (IPCC) climate scenarios (A2), in particular for the German North Sea coast. The results will provide an important input (as well as tool) for current and future quantitative and chemical status assessments of groundwater according to the Water Framework- and Groundwater directives, as well as for the planning of strategies for flood defence. The results will also be accompanied with guidelines and recommendations for the management of the water supply and the protection of the groundwater resources.

What are the outcome/results?

The following are the main outcomes from the pilot area.

- Determination of the local effect of climate changes on groundwater resources
- Quantification and visualisation of the changes to the groundwater table, salinity for different depths and surface water flows
- Evaluation of protection strategies and methods for groundwater reservoirs and catchment zones (well fields) under changed climatic conditions
- Evaluation of protection strategies against salinization of delivered drinking water due to climate change
- Protective measures against land loss due to permanent flooding by increased sea level.
- Development of protective measures for low lying polder areas under storm flood conditions

Future situation, including maps/ figures illustrating the scenario(s)

Using a distributed hydrological simulation model, a study of projected regional climate change effects for the different German federal states like Niedersachsen on temperature and precipitation has been carried out by the "Deutsches Institut für Küstenforschung" for different IPCC emission scenarios. After the IPCCA2 Scenario an average annual increase in temperature of 2.9 °C and for the annual precipitation of about 10 % (summer -5% and winter +25%) in the area of the North German coast is expected until 2100.

Climate change effects on groundwater recharge and discharge to streams were found to vary seasonally with wetter winters and dryer summers. Potential effects of climate change on water availability were also predicted to vary seasonally. These predictions are typically for the north German North Sea coast.

Using the ICPP-A2 Scenario quantification and visualisation of the changes to the groundwater table was carried out. Due to the enhanced annual precipitation scenarios with an enhanced ground water recharge of +10% (average scenario) and annul recharge of + 5% (conservative scenario) were used.

Due to the enhanced recharge and the increased sea level for the average scenario the ground water table will rise until 2100 by about 0.5 m for the average scenario and 0.3 m for the conservative scenario in the dunes areas while in the drained polder areas it will be nearly not affected. Due to the enhanced drainage the outflow from the open waters will increase by about 50% for both the average scenario and for the conservative scenario.

The model results show that sea level rise will not affect essentially the general shape of the fresh water lens. In deeper located regions changes of the lens are limited to the environment of the water works where up coning of sea water will threaten the drinking water quality.

Fig. 3 shows vertical profiles of the TDS-concentration (Total Dissolved Solids) for the pore water of the sediments at the new drillings CLIWAT I and CLIWAT II. These new drillings are located in vicinity of the well fields of water work I (Waterdelle) and water work II (Ostland) respectively. The data were computed by the numerical model which was calibrated in this area by using high precision geophysical data of the buried electrode chains and data from Helicopter electromagnetic HEM.

Computations of the TDS for the year 2100 using the IPCC-A2 scenario for ground water recharge and sea level rise show the proceeding salinization with time (blue curve). The computations illustrate that until the end of this century the salinization in the vicinity of the well fields has increased considerably and could become a problem for the quality of the delivered drinking water, in particular for the deep lying well screens of water work II.

This feature can be seen also in Fig. 4, where the TDS-concentration is computed with proceeding time during the period 2010 – 2100 for all water supply wells of the water works. A linear increase of the ground water recharge to a maximum of +5% by the year 2100 was used for the computations (conservative assumption). The figure shows that until 2100 several of the TDS-curves, in particular 3 of the 4 TDS-curves in the deep screens of WW II –Ostland, exceed substantially the permitted NaCLconcentration for drinking water. An intelligent management of the water resources is required to prevent excessive salinization of the drinking water resources.

Low-lying areas which are not protected by the great south dike or the dune belts are more and more flooded by the rising sea. Here, predominately in the natural reserves of the north and south beaches, the aquifer is getting more and more salted. Without protection measures by the year 2100 these areas are lost to the Wadden Sea (Fig. 5).

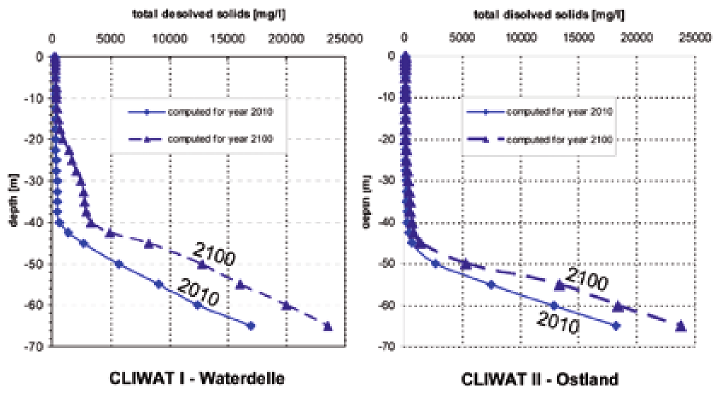


Fig. 3: Salinization with proceeding time computed at the location of the CLIWAT I (water work I) and CLIWAT II drilling (water work II)

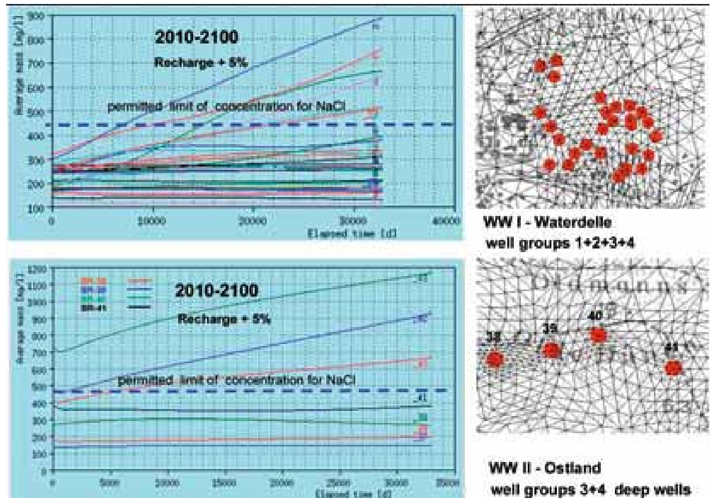


Fig. 4: TDS concentration [mg/l] computed in the screen of the water supply wells of WWI-Waterdelle (top) and WWII Ostland (below)

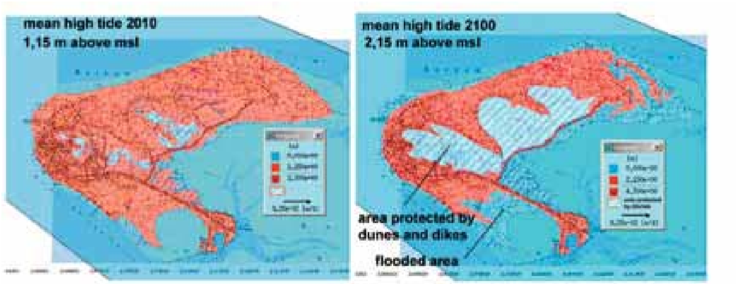


Fig. 5: ICPP-A2 scenario: sea level rise of 0.94 m by 2100, flooded areas by mean flood tide (blue), areas protected by dike and dunes shaded blue

Challenges and future possible solution – recommendations for adaptation or further investigations

Groundwater models that can predict local change need to be developed. The avaliability of local-scale data and data coverage is therefore vital for the models. Local factors more or less directly impact the adaptation strategy, e.g. in the case of waterworks of Borkum.

On Borkum protection measures are necessary to prevent the water supply from excessive salinization caused by over-exploitation and sea level rise. By means of the density driven flow model the location of the respective water supply wells in the water works can be optimized to prevent exorbitant salinization beyond the permitted limits.

Fig. 6 (left) shows the supply wells of water work I (top) and water work II (below) (red circles) together with the TDS-distribution computed for 2100 in the depths of the screens of the water works. Possible locations for new wells which could relieve the water work and prevent the wells field from up coning of salt water are marked blue and are located at positions where for 2100 sufficient water quality can be expected. Wells which should be closed because of excessive salinization until 2100 are marked brown.

The computed TDS-curves for all water supply wells (Fig 6 right) demonstrate that solutions for the well field configuration can be found to keep

water quality below the required limit for the NaCl -concentration. In this way it is possible to maintain drinking water quality without being forced to reduce the amount of abstraction for more than 100 years. Simulations with the numerical model can help to find adequate. locations for possible new wells.

The topography of low-lying areas, which are predominatly located in the south and north east of the island and which are endangered by flooding under an increased sea level (Fig 5) should be adapted to the rising sea level by sand fillings like it has been already carried out successfully on barrier islands like Sylt.

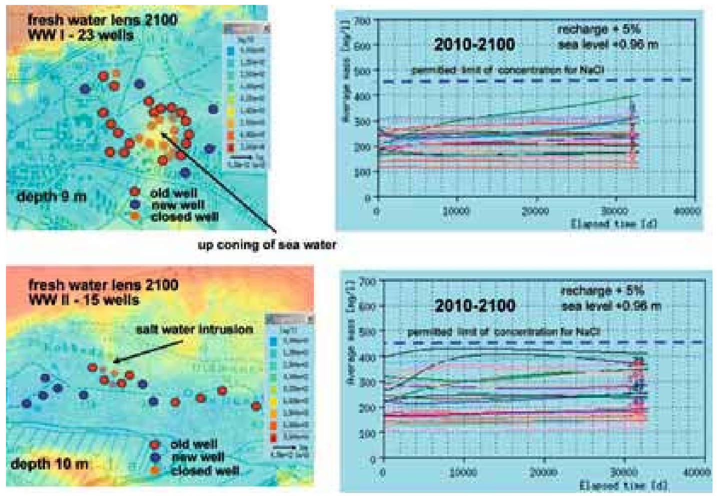


Fig.6: Spreading of well fields as protection measure from excessive salinization of the water supply. Location of old wells, new wells and closed wells (left), development of TDS concentration in the supply wells with time (right). WW I Waterdelle (top), WW II Ostland (below)

The North Sea region, in particular the German Bight, can be target of heavy storm flood events. Under extreme weather conditions and an enhanced sea level of 1 m storm floods can attain altitudes of 4 m above MLS (one in

50 years event). It will be clear, that protection measures are necessary. The altitudes of the dikes have to be controlled and adapted where required. Moreover dune valleys which could be possible gateways for the flood have to be banked up with appropriate material like sand to maintain their protection function.

The work and conclusions of Pilot area D Borkum will make an important contribution to local-scale knowledge. The same kind of modelling should be done in other North Sea islands to compare and evaluate the variability. Adaptation strategies based on national or local-scale models like those typical for North Sea islands may be quite different from regional models.

Pilot Area E

Sønderjylland/Schleswig (DK/D)

Introduction

The Pilot Area E Sønderjylland/Schleswig extends over nearly 6.000 km² on both sides of the Danish-German border and covers all typical landscape elements of southern Jutland and Schleswig. This are the islands of Föhr in the North Sea and Als in the Baltic Sea, flat marshlands at the west coast, outwash plains and older moraine areas in the middle part and a district with younger moraines in the east.

The highest ground level elevations, which define the water divide between the runoff of surface water towards the Baltic Sea and towards the North Sea respectively, are found in the areas of younger moraines in the eastern parts. Therefore most of the streams flow towards the lowlands on the west coast. The general direction of the groundwater flow is also influenced by the morphology of the landscape.

Characteristics of the groundwater conditions in this area are:

- Quaternary and Tertiary aquifers
- Deep Quaternary aquifers in buried valleys
- Two fault zones (Tarper Trog and Tønder Graven) and several salt structures
- Artesian confined aquifers in some parts of the area as e.g. around Flensburg and Løgumkloster
- Saline groundwater in the flat marsh plains, freshwater/saltwater boundary inland between coast and the western boundary of the outwash plains
- Freshwater lenses surrounded by saltwater on the islands

The structure of the subsurface is very complicated due to the genesis of the strata. Quaternary sediments show a profound variation in thickness, extension and permeability of the different layers. Furthermore the deposition of Pre-quaternary rocks was strongly influenced by tectonic processes caused by the activities of salt structures and two large fault systems in the area. In the run of buried valleys, the base of the Quaternary strata has been cut deeply into the underlying rocks, caused by the erosional activity of buried valleys during the ice ages. For these reasons the investigation and interpretation of the hydrogeological and hydraulic conditions in the pilot area are very complicated.

The land use in this region is mainly agriculture in the rural areas and some small to medium-sized industry in the urban surroundings of the cities. The public water supply is performed by approximately 90 small to medium size waterworks in the Danish part and 21 small to large waterworks south of the border. The total annual amount of abstracted groundwater is around 30 mio m^3 in Schleswig and almost 30 mio m^3 north of the border. Additionally, a lot of private wells for e.g. drinking water supply for private consumers, irrigation or industrial users also extract water

Fig.: E1_1 Pilot Area E with the focus areas Hørløkke, Als and Föhr

from the subsurface. The depth of the production wells varies from a few meters down to 290 m, located in Quarternary and Tertiary Aquifers. In many parts of the area, these aquifers are protected by thick layers of clay and till.

Present situation

Preliminary studies indicate that in the catchment areas of the water works groundwater abstraction and recharge are in balance. In general, the groundwater quality, especially of the deeper seated aquifers, is good. Though inside and along the northern 'shoulder' of the Tønder Graven water abstracted from deep seated resources may be miscoloured (light brown to black) because of increased content of organic constituents. Furthermore, many wells in shallow aquifers in the rural areas mainly located on the outwash plains are influenced by human activities, which can be traced back to e.g. agriculture in the form of nitrate and pesticides. In urban areas the groundwater quality may be poor e.g. due to the use of pesticides or road salt. Additionally, the water quality of some wells may be threatened by contamination from old landfills or from industrial activities.

Currently, unconfined aquifers are influenced by leaching of nitrate and pesticides from agricultural activities during the winter season. The amount of available leachable species, dilution, and change of redox and degradation conditions determines the resulting concentrations. An increased demand for irrigation during dry summers may also affect the groundwater quality, especially if the water is abstracted from shallow, unconfined aquifers.

In coastal near parts of the area and on the outwash plains the groundwater level is close to the terrain surface leading to occasional flooding.

On the islands of Als and Föhr and in the coastal areas the development of the boundary between salt and fresh water is mainly sensitive to changes of the sea level. These islands and the landfill in Hørløkke were locations for focussed investigations.

Hørløkke is a small old landfill located near Vojens, Denmark, in an area very close to the primary groundwater divide. Household waste and industrial waste including chlorinated solvents have been disposed off directly on the original soil surface. The underlying sandy aquifer has an average groundwater level one meter below soil surface. A small creek north of the landfill drains the upper groundwater during winter and spring.

Investigations have been going on at the landfill since 1986 and therefore geological, geophysical, and chemical data from a large number of local deep drillings were already available before this project. A massive plume of chlorinated solvents leaching from the landfill to a depth of more than 50 m in the aquifer has been delineated. The plume extends more than 500 m downstream from the landfill. Even a small general increase in the groundwater level due to climate changes is expected to lead to occasional flooding of the waste in the landfill and a change in the leaching potential. An increased groundwater level may also change the location of the water divide and the length and the direction of the plume.

What kind of problems/issues has been investigated?

Main objectives of the Sønderjylland/Schleswig pilot area were to develop 3D geological and hydrological models that can be used to evaluate quantitative and qualitative effects of climate change on groundwater and surface water. The hydrological models use data from the Intergovernmental Panel on Climate Change (IPCC) climate scenarios (A2 and B2). The models were separated into a generalised model for the mainland and more detailed models for the islands of Föhr and Als and for the Hørløkke area. Besides drilling results, these models were backed by geophysical results mainly from aeroelectromagnetic surveys (SkyTEM and HEM) covering large parts of the project area and reflection seismic surveys at selected locations.

Special problems that have been investigated were, e.g.,:

a) on the mainland:

- a border crossing system of buried valleys within the area of Süderlügum-Tønder.
- the course of the fresh/saltwater boundary in the march areas along the coastline

b) on the island of Föhr:

- delineation of the freshwater body
- the course of a system of buried valleys
- glacial induced thrust structures in the PreQuaternary layers
- a geological 3D-model and a hydraulical model for the island of Föhr was installed to estimate quantitative and qualitative effects of climate change on groundwater and surface water.

c) on the island of Als

- based on a geological model which has been revised and enhanced during the project period an existing groundwater model has been rerun to estimate quantitative and qualitative effects of climate change on groundwater and surface water.

d) Hørløkke

- five new drillings have been established near the landfill during the project period to map the pollution plume and to describe the local geology in more details
- IP investigations have been carried out to determine the extension of the plume
- a helicopter-borne geophysical survey has been conducted in a 50 km^2 area around the landfill to map the semi-regional geology
- a geological model and a dynamic 3D hydrogeological flow and transport model has been developed
- the historical plume development from 1980-2010 has been modelled
- the possible climate change effects on groundwater divide location, flow direction, and leaching potential have been modelled

What are the outcome/results?

On the mainland especially the results of the SkyTEM surveys, in combination with new seismic lines delivered important new information about the border crossing ground water systems and the distribution of saltwater.

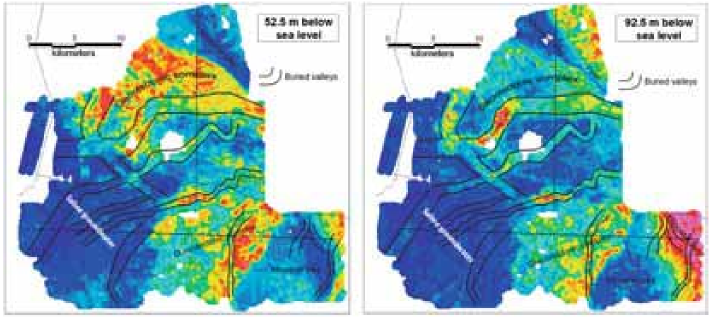


Fig. E4-1: The horizontal resistivity slices show several generations of buried valleys which are up to 350 m deep and 2 km wide. Yellow and red colours mean sandy deposits with higher resistivity; bluish colour means clayey sediments and/or saltwater with lower resistivity. The dotted lines give the position of the cross section in Fig. E4-2.

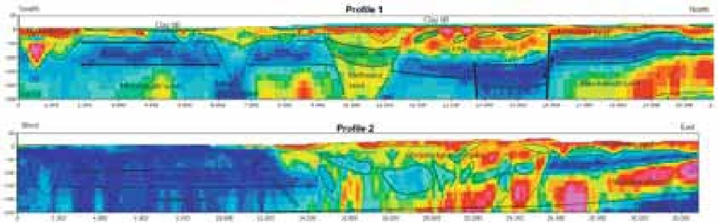


Fig. E4-2: The top shows the north-south profile indicating the complicated geological conditions in the project area with a deep buried valley in the middle and the depth shift of the Prequaternary layers due to the Tønder Graven in the northern part (right). The bottom shows the west-east profile south of the border with saline ground water in the western part and a deep reaching glaciotectonic complex in the middle part.

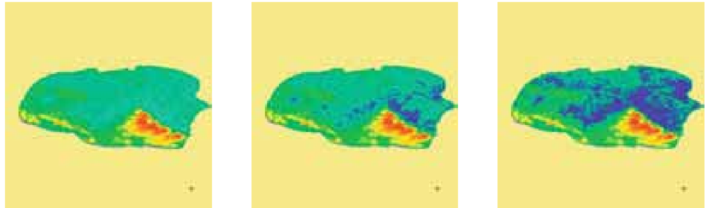


Fig. E4-3: On the Island of Föhr a rising sea level will impact especially the hydrological conditions in the marsh lands. Blue areas are indicating areas below the mean sea level (sea level rising: left = 0, middle = +0.7 m, right = + 1.0 m)

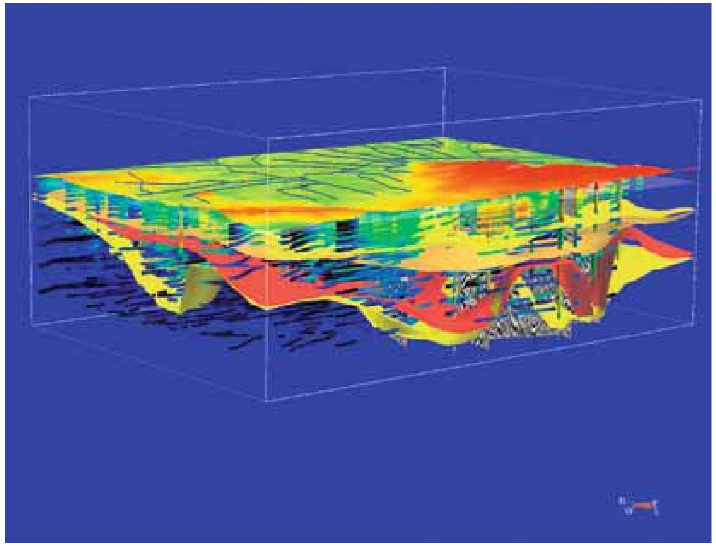


Fig. E4-4: Detailed section of the geological 3d-Model of Föhr showing some of the model layers in combination with geophysical data (SkyTEM, seismics). This model provides a basis for the ground water model and the modelling of the climate change impacts.

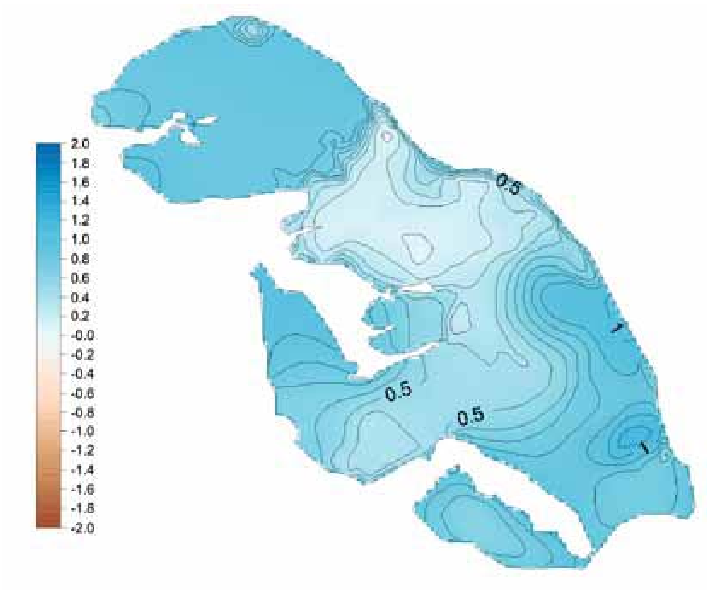


Fig. E4-5: Changes in groundwater potential (m) for the primary aquifer for the A2 climate scenario compared to reference model. Island of Als, Denmark.

On Als the hydrogeology and groundwater regime has been subject to ex- and intensive investigations over the years with the purpose to manage and administer the fresh water of the island. Lately a revised detailed geological model has served as part of the basis for a refined ground water model for Als. In the CLIWAT project this model is used for calculations of effects of IPCC climate scenarios A2 and B2 on key ground water hydraulic issues. These issues include changes of hydraulic head levels in the coastal areas, of abstraction zones of public water works and qualitative assessments of the risk of saltwater intrusion the aquifers.

The outcomes of the project are discussed in details in a special issue of the HESS journal (Hydrology and Earth System Science, European Geosciences Union). As an example, the results of the project area Hørløkke are shown.

The geological model of Hørløkke is based on MikeGeoModel-software (for more details visit www.dhigroup.com). The model was established on the basis of existing and new drillings in the investigation area. Also a number of new geophysical data (helicopter EM conducted by the BGR as part of the CLIWAT project) and existing geophysical data (SkyTEM, PACES and MEP) were used. The model shows that the thickness of the Quaternary sediments is 30 to 50 meters, consisting mainly of melt water sand, which is superimposed with till in certain parts of the area. Under the quaternary deposits, we find a sequence of Miocene sediments consisting of the sand-rich Bastrup and Odderup Formation, alternating with the clayey and silty marine Klintingehoved and Arnum Formations. The Miocene sediments are located down to about 250 meters below the surface (Fig. E4-6).

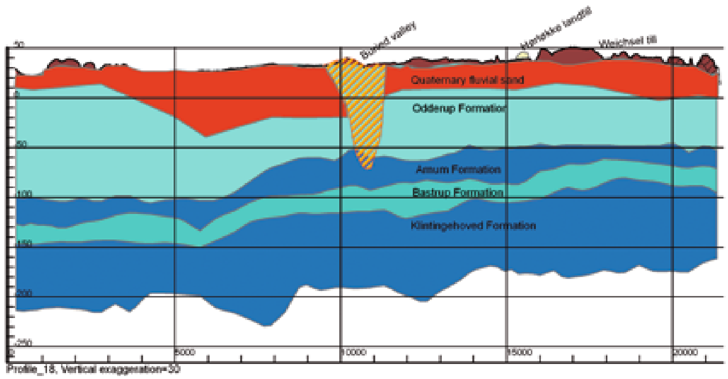


Fig. E4-6 west to east cross-section of the lithostratigraphy in the model area.

The boundary between the Klintingehoved Formation and Bastrup Formation is associated with some uncertainty in the model area, because it's mainly based on the geophysical data. The clayey Arnum Formation separates the Odderup Formation and the Bastup Formation. Only a few wells penetrate the Arnum clay and its location is based on a combination of well information, geophysical data and biostratigraphy.

From well data it is difficult to differentiate between the Quaternary fluvial sand deposits and the Tertiary Odderup sand below. Therefore the Odderup sand and the Quaternary glaciofluvial sand are treated as one homogeneous sand formation in the hydrogeological model. The total thickness of this sand formation is about 60 meter around Hørløkke landfill.

Over the Quaternary fluvio-glacial sand deposits are later Weichsel till deposits. It has a greater thickness in the eastern part of the model domain and is absent in the lower parts of the western area. The till has a thickness of 5 to 30 meters. The till is rich in clay and in many areas drained, suggesting a low permeability.

The model domain is crossed by several buried valleys. The valleys are cut into the Quaternary sand and Odderup sand formations. In the case where the buried valley consists of sand it is not possible to distinguish it from the sand formation around it, but in the area, where the buried valley deposit consists of clay rich materials, they are easy to recognize. These valleys have been located in several TEM points and in a few wells. The base of the burried valleys rarely reaches the Arnum clay and the base of the valleys have been estimated by interpolation between the elevation of the clay rich base of the valleys and by extrapolating outside the area for the geophysical prospecting area.

Based on the geological model a dynamic hydrogeological solute transport model including degradation of the chlorinated solvents has been set up based on HydroGeoSphere (hydrogeosphere.org/) to simulate the development of the landfill plume from 1980 to 2010 and afterwards to model the development of the plume in a future climate scenario. The fate of the chlorinated solvents will not be discussed in this chapter, please confer the paper in the HESS journal.

The model consists of 32 numerical layers. Most layers are located in the Quaternary and Odderup sand, where the pollution plume from the landfill is located. This sand deposit has been subdivided into 28 layers in order to get a good representation of the contamination in the model. It includes the top till and the burried valley clay. Two layers are representing the Arnum clay and two layers are used for the Bastrup sand making it possible to calculate transport through the Arnum clay to the lower Bastrup sand. The model uses a minimum layer thickness of 1 m. The cell size varies between 10 m in the focus area around the landfill and 100 m in areas

far from the landfill. Calibration of the model is based on historical head observations from wells in the model area.

The model simulation shows how the pollution plume expressed as chloride has developed downstream from the landfill until now (Fig. E4-7 above) and how the plume is expected to develop in the year 2100 (Fig. E4-7 below) in an unchanged climate. The plume will continue to expand through the modelling period and the flow direction will change to a more northern path in the front of the plume. This change in flow direction is caused by the creek as it is in contact with the groundwater and therefore works as a drain throughout the year in the western part of the focus area. Annual fluctuation in groundwater level controls the flow direction and thereby also the direction of the plume. The fluctuation in groundwater recharge introduces a dispersion of the plume.

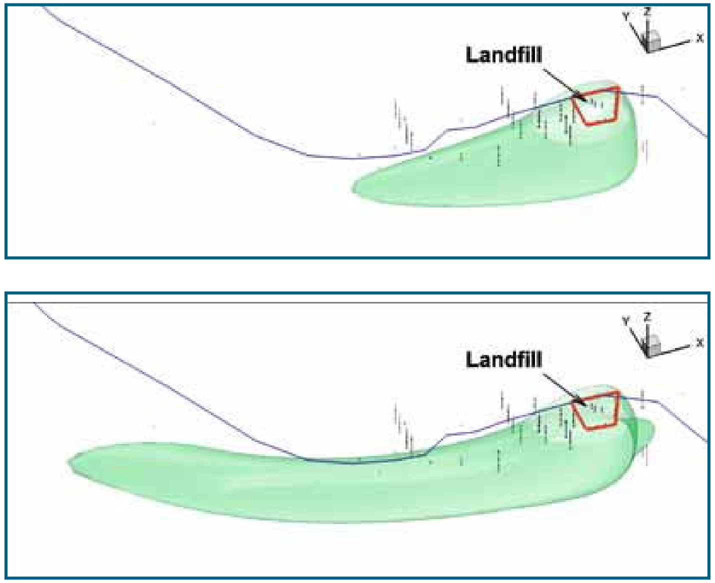


Fig. E4-7: Horizontal development of the pollution plume expressed as chloride in 2010 (above) and in 2100 (below) under unchanged climate conditions.

Future situation, including maps/figures illustrating the scenario(s)

Hørløkke:
Both the A2 and B2 climate scenarios has been implemented in the model to evaluate the changes in the hydrogeological system in year 2100. No relevant differences were found between the results of A2 and B2, so only the A2 results are show.

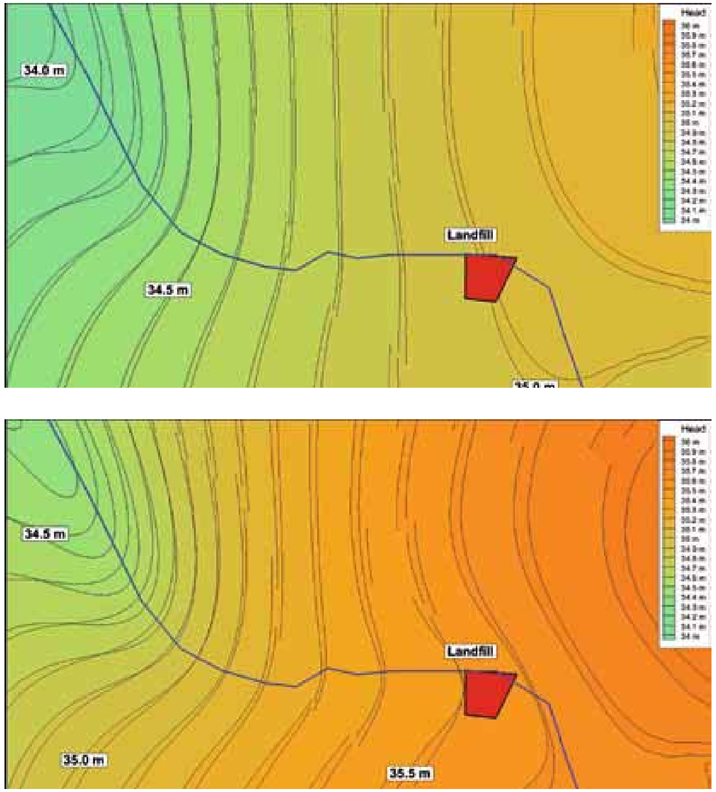


Fig. E5-1: Groundwater head in the Quarternary fluvial sand and the Odderup sand shown as contours for top and bottom of the aquifer in 2010 (above) and for the A2 scenario in 2100 (below). The iso-interval is 10 cm.

Fig. E5-1 shows groundwater head for the Quarternary fluvial sand and the Odderup sand formation. The two contours represents the groundwater head at the top and bottom of the aquifer. The uppermost figure shows the sitution for 2010 for normal climate, whereas the (E5.1 buttom figure) figure shows the situation in 2100 with the A2 climate scenario. The groundwater head is much higher in the A2 climate scenario (present time) than in the normal scenario leading to flooding of the areas near the creek. The higher head also causes a more northern groundwater flow direction as well as a flow towards the creek which shows that the creek drains the aquifer throughout the year and in the whole focus area. Where two curves are seen there is either a downwards flow direction as seen south and north of the creek, or an upward flow direction as seen in both figures where the creek has changed into a more northern direction. This illustrates that the creek also influence the groundwater flow in the deep part of the aquifer.

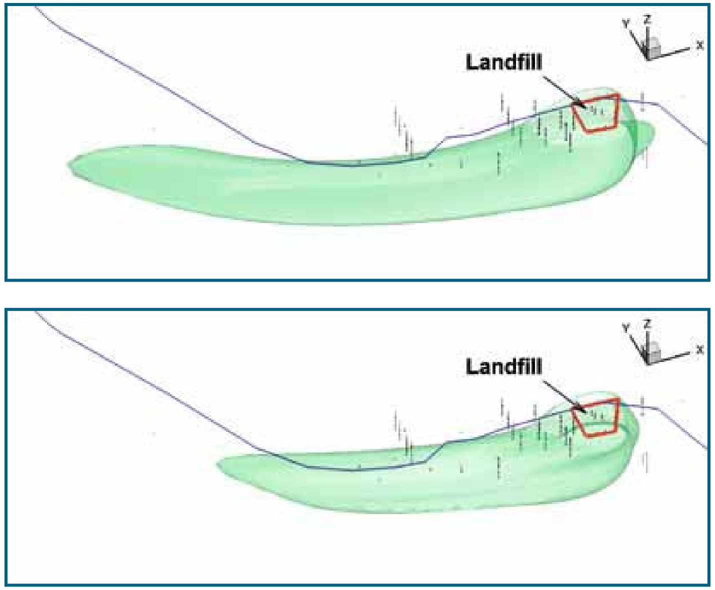


Fig. E5-2: Horisontal development of the pollution plume in 2100 in a normal climate (above) and in the A2 scenario (below).

As expected the model shows that the increased groundwater recharge in the A2 scenario will cause a higher groundwater flow through the landfill which will mobilize more contaminants into the aquifer. Fig. E5-2 shows the development of the pollution plume in 2100 in a normal an in the A2 scenario. It is seen that the increased groundwater flow and solute transport in scenario A2 did not cause the plume to progress further downstream as expected. Instead the front and the centerline of the plume is fixed under the creek without any expansion. Again this is caused by a more intensive drainage of the aqufer by the creek.

Challenges and future possible solution – recommendations for adaptation or further investigations

It was shown that the combination of geological/geophysical surveys, geological modelling and hydrogeological modelling is a powerful tool for the prediction of climatic change effects on the groundwater conditions. In Schleswig-Holstein these investigations should be continued at other locations, e.g. at the lowlands of the Eider-Treene-Sorge region. Of special interest is also the future development of swampy areas, because these areas are an important storage of CO_2. On the northern side of the boarder the result of the project will enhance the means for administering and protecting fresh water ressources.

The model simulations regarding the Hørløkke landfill have illustrated that it is necessary to understand the geo-hydrological system to predict the direction and the expansion of a pollution plume when the climate is changing. Initially, we had a clear expectation that the pollution plume from the landfill would expand in a future climate with more precipitation, but model simulations showed, however, that the pollution plume declines. The reason for this is that the nearby creek works as a drain when the groundwater table rises and makes contact with the creek. Therefore, it is not possible with simple assumptions to predict a pollution plume direction and development. We therefore recommend always to use a hydrogeological model to predict the fate of a pollution plume, especially in changing climatic conditions.

Pilot Area F

Egebjerg, Denmark.

Introduction

The Egebjerg area is situated in eastern Jutland, near the city of Horsens. The model area is approximately 200 km² and its central part (90 km²) is the main focus of CLIWAT (see Figure 1). Land use is mainly agriculture with a few villages. The area supplies Horsens city and other villages with groundwater from wells located in aquifers 20–140 m below the surface. The aquifers are located in two or three levels, protected in most places by thick layers of clay tills/clays. The general geological setting is clay-domi-

Figure 1. Map of the Egebjerg Pilot Area. Blue colours identify areas with groundwater resources containing particularly valuable aquifers.

nated. Buried valleys dominate the subsurface geology and complicate the interpretation of groundwater flow and its interaction with surface water. In general, the groundwater quality is good though there are problems with naturally occurring arsenic. However, most of the waterworks are able to deal with the arsenic problem using simple water treatment. Waterworks abstract approximately 3.5 million cubic metres of water every year in the central Egebjerg area.

Present situation

Preliminary studies indicate a limited groundwater resource and a level of water abstraction that is just in balance with the amount of abstracted groundwater (3.5 million m3/year). Climate changes are expected to adversely affect this balance and may affect the potential water supply. Changes are possibly a decrease in precipitation during the summer period and a increase during the winter period. In addition, the waterworks may well use the entire permissible amount (6.5 million m3/year), which will almost certainly lead to problems from overexploitation.

Waterworks (administrated by the municipality of Horsens) abstract vital amounts of groundwater in Egebjerg and supply domestic water to Horsens and nearby villages. The groundwater resources in Egebjerg must be protected to meet the current and future demands for domestic water. In this respect, it is vital that the effects of the predicted climate changes are known. The Egebjerg project and the CLIWAT project in general, will help to provide a basis on which new ways of managing the groundwater resources can be made. Table 1 shows the present overall water balance for the Egebjerg area before the CLIWAT modelling. Illustration no. 2 shows the data coverage of the area for the present water balance.

What kind of problems have been investigated

The main objectives of the Egebjerg Pilot Area F are to develop a 3-D geological model, map the spatial distribution of subsurface groundwater bodies, and to evaluate quantitative effects of climate change on groundwater

Table 1 Present water balance in Egebjerg Area

Area	66 km²
Net precipitation (from Danish model)	389 mm/year
River discharge (station no. DDH 27.01)	-333 mm/year
Recharge	56 mm/year
Abstracted amount (permitted in 2008)	-50 mm/year
Outflow ("surplus") groundwater	=6 mm/year

The numbers are compiled of different sources before the modelling in the Cliwat project and therefore only to be used as an guide to the overall water balance

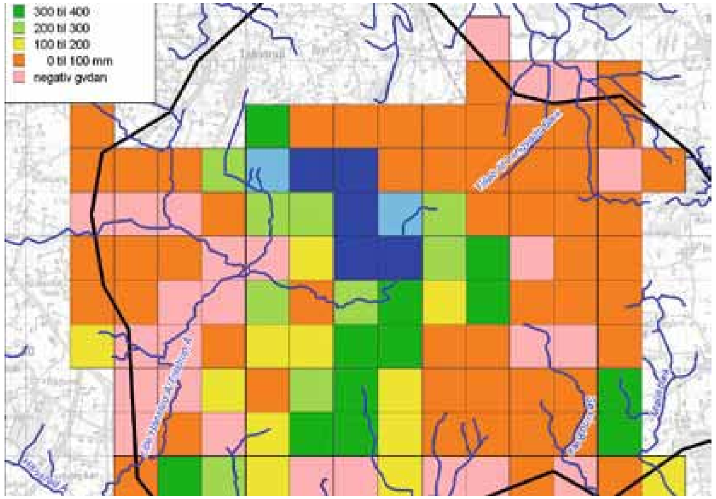


Figure 2. Recharge (mm/year) calculated from the national Danish model. Grid size is 1 x 1 km.

and surface water from simulations generated by an integrated hydrological model. The hydrological model has used data from the Intergovernmental Panel of Climate Change (IPCC) climate scenario (A1B and to some extent A2). The results will provide an input (as well as tool) for current and future quantitative status assessments of the groundwater resource in the pilot area. It is hoped that the results and conclusions will be used in recommendations for the management of the water supply and the protection of the groundwater resources.

The overall results for model work in Egebjerg

We have determined the local effect of climate change on groundwater resources located in the clay-dominated geological settings in this pilot area. The Egebjerg area work has resulted in two types of integrated models:
A state-of-the-art 3-D geological model. This model provides highly detailed maps of subsurface groundwater bodies (aquifers). Geophysical mapping methods were used in the interpretation of the geology, e.g. SkyTEM, seismic and MRS. See figure 3 and figure 4 for examples of some of the results.
A hydrological model with climate scenarios, based on the geological model. The hydrological model provides climate scenarios (A1B and A2) which are especially focused on the capture zones, water balances (run-off) and changes in the general groundwater table (hydraulic head). See figure

The modelling work was carried out in cooperation with the Geological Survey of Denmark and Greenland (GEUS). In particular, the hydrological model was modified in relation to the Egebjerg local area and the objectives of the CLIWAT project. The geological modelling software application is called GeoScene3D (for more details visit www.i-gis.dk), and the integrated hydrological modelling uses the MIKE SHE software application (for more details visit www.dhigroup.com). The geology was modelled in voxels (volumetric pixels) in blocks of 5 x 100 x 100 metres.

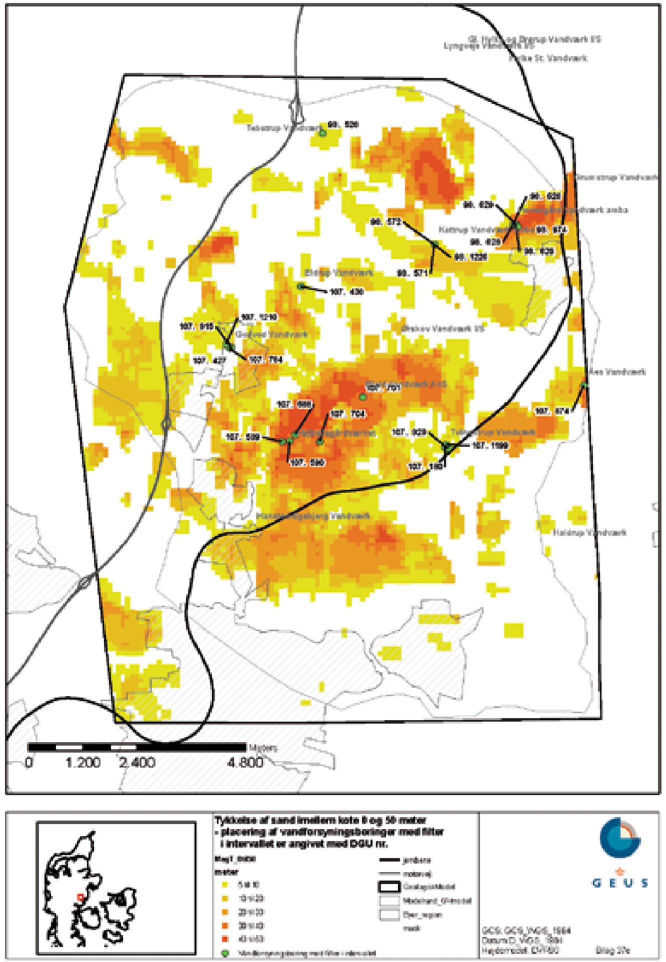


Figure 4. An example of the mapped groundwater bodies (aquifers) at 0–50 m elevation above sea level. The groundwater bodies have been mapped in voxels (volumetric pixels) of 100 x 100 x 5 m. The result gives a highly detailed view of a very complex subsurface structure with many individual reservoirs which to some extent are hydraulically interconnected. The more reddish the colours are, the thicker the groundwater body is on the map.

Future situation – results and conclusions of climate simulations

The results from the climate simulations are based on two IPCC scenarios: A1B and A2.

Table 2. IPCC scenarios

Present reference scenario	A1B scenario	A2 scenario
Present climate reference period for Egebjerg is 1991-2010. (abstracted amounts of groundwater is an average of 2000-2004)	Echam/KNMI 2081-2100 ref. 1991-2010 (ENSEMBLES) A1B is a medium-strong climate scenario compared to CO_2 and temperature changes. In the data-set, there are however no results for the A2 emissions scenario.	2071-2100 ref. 1961-90 Van Roosmalen et al. (Dataset PRUDENCE) A2 is a quite strong climate scenario compared to CO_2 and temperature changes.

Part of the difference between A1B and A2 is the differences in reference periods, where the A1B use the 'present period' (~1991-2010), where already an increase has taken place in precipitation and temperature compared to the classical reference period used in A2 scenario (1961-1990). Climate modelling of the A2 scenario compared to A1B scenario resulted in twice as much winter precipitation, evaporation is also higher in the A2 scenario. These are some of the main differences between the two scenarios which are versions adapted to the Danish area. The IPCC scenarios are described in more detail at www.ipcc.ch.

Results

The comparison of present (ref. situation) and future climate (IPCC A1B and A2 scenarios by the end of this century) gives us the following overall results in Egebjerg area:

- There are only a few percentage differences in defining catchments (capture zones) and groundwater forming areas to well fields (water works). See example figure no. 5.
- Changes in the water table (hydraulic head in the primary upper aquifers) in a changed climate (A1B) are typically from 0 to 0,5 meter. However, in some local areas the level may rise by 1-1,5 metres. In the A2 scenario the results is almost twice as high increase in water tables: This means 0,5 to 1 metres and locally 2-3 metres. The water table may rise up to 2-5 metres in the primary lower water table (deeper aquifers). These deeper aquifers are often located 20-40 m below the ground surface, which in this case limits the problem of groundwater flooding. However, a change of several metres in the groundwater reservoirs may alter the groundwater chemistry and thereby cause water quality problems. The available groundwater resource has relatively increased. The rise in the surface near aquifers is limited by drains and is bypassed into the rivers and thereby increasing the runoff. See figures 6,7 and 8.

- Maximum river runoff as predicted in A1B scenario increases slightly but significant, while the minimum runoff is largely unchanged. The duration of minimum run-off will be extended into the autumn period. See table 3.

- Maximum river runoff as predicted in A2 scenario increases and is very notably, while the minimum runoff is reduced moderately. The duration of minimum run-off will be extended into the autumn period. See figure 9 and table 3.

- The overall water balance at the end of 2100, result in a minor surplus (few percentages) of groundwater formation in the primary upper and lower groundwater reservoirs. The main net effect of more precipitation in clayey geological settings is more run-off in the rivers, especially caused by the relatively extensive drainage of agricultural areas. Scenario A1B and A2 are listed below for more comparison.

Subject	A1B scenario impact	A2 scenario impact	Comments
Upper aquifers groundwater table	Rise in water table is 0 – 0,5 meter in general but rise locally up to 2 meters. In areas where today's high ground water table (0-1 m below surface) will increase groundwater recharge will be drained into drains and water-courses.	Rise in water table is 0,5 – 1,0 meter in general but rise locally up to 3 meters. In areas where today's high ground water table (0-1 m below surface) will increase groundwater recharge will be drained into drains and water-courses.	The significantly changing groundwater levels (at 1 meter or more) of the ground-water bodies near the surface (and in the unsaturated zone) in a future climate could lead to altered leach-ing and pollution loads from point and diffuse sources. The need for drainage or maintain of drainage could be comprehensive
Deeper aquifers groundwater table	Areas with a certain depth to the up-permost groundwater table (depth› a couple of meters) will experi-ence some changes in groundwater level corresponding to overall increases of 0 - 0,5 meter locally 2-3 meters.	Areas with a certain depth to the up-permost groundwa-ter table (depth› a couple of meters) will experience significant changes. The deeper aquifers experience the highest impact with an overall increase of 0,5 – 1.0 meters up to 3 – 5 meters locally.	Changes in ground-water levels may require more effective drainage in areas where there currently is not drained. It is the model assumed that there are drains everywhere, and that therefore the land will be drained likewise in the future climate. Direct effects of cli-mate change will lead to increased pressure level in the deeper aq-uifers. This will have a positive effect on the possibility of water extraction from these deeper aquifers.
Run-off period Sep.- Nov.	Reduction in runoff of magnitude of 0 to 2% which is practically no change at all.	Reduction in runoff of magnitude 5 to 25%	There will be a risk of drying up of rivers and wetlands as the runoff is reduced in late summer and autumn months.

Subject	A1B scenario impact	A2 scenario impact	Comments
Run-off period Jan.-Mar.	Maximum water flow will increase. For Ll. Hansted river basin (St. 27.1). Winter runoff increas-es at an average of 7-22%, and increases in maximum runoff in the same magnitude	Maximum water flow will increase. For Ll. Hansted river basin (St. 27.1). Winter runoff increas-es at an average of 30-45%, and increases in maximum runoff in the same magnitude.	This is a significant challenge to keep the increased amounts of water and suspended materials in the hin-terland during winter and early spring as climate change will not compromise such a risk of flooding downstream, e.g. in Horsens city or sub-stance flow to Horsens Fjord.
Capture zones to well fields	There is almost no change (‹2%) I the area when compared to reference situation	There is almost no change (‹2%) I the area when compared to reference situation and A1B scenario	The changes in captures zones due to climate changes are marginal – Changes in abstraction during the year (e.g. pump strat-egy, new wells) has a relatively greater im-pact than the induced climate changes.
Groundwa-ter forming areas to well fields	There is almost no change (‹2%) I the area. The relative formation of ground-water is however a bit higher than A2 scenario	There is almost no change (‹2%) I the area when compared to reference situation and A1B scenario.	See the comments above
Water bal-ance (aver-age year)	Minor – moderate sur-plus of groundwater formation and minor surplus in run-off	Minor - moderate sur-plus of groundwater formation and minor -moderate surplus in run-off	The overall conclusion is that the increased precipitation leads to more available groundwater. However in a clayey area the run off is increasing which may cause problems for the rivers (erosion e.g.). Extreme events like late sum-mer droughts and severe rain showers are predicted to cause some water stress.

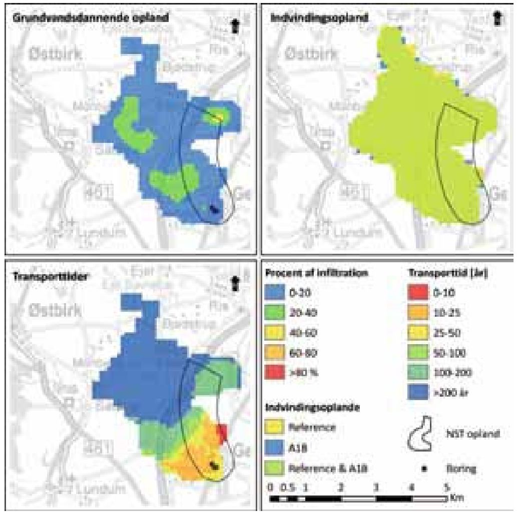


Figure 5. Map is showing capture zone and groundwater forming zone compared with the reference situation for A1B scenario for one medium size well field (water work Gedved north of Horsens).

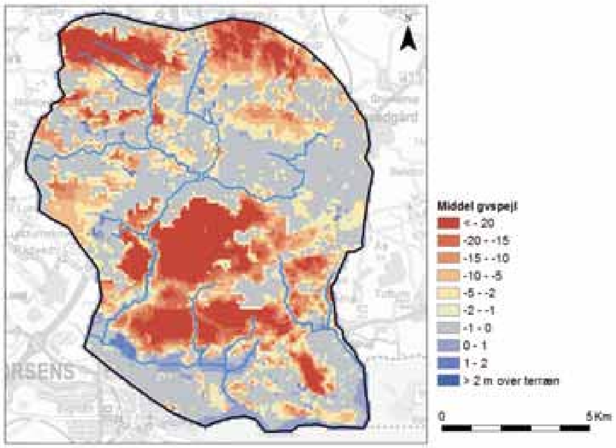


Figure 6. Map is showing average depth (under terrain) to ground water table for the reference situation (1991-2010)

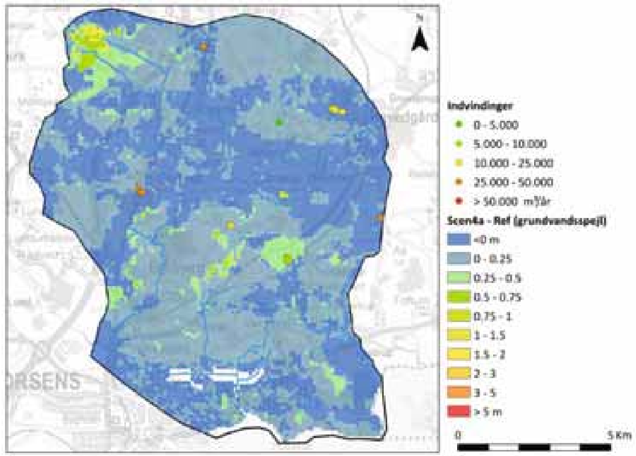


Figure 7. Map is showing the changes in depth of ground water table. Reference situation compared with A1B scenario

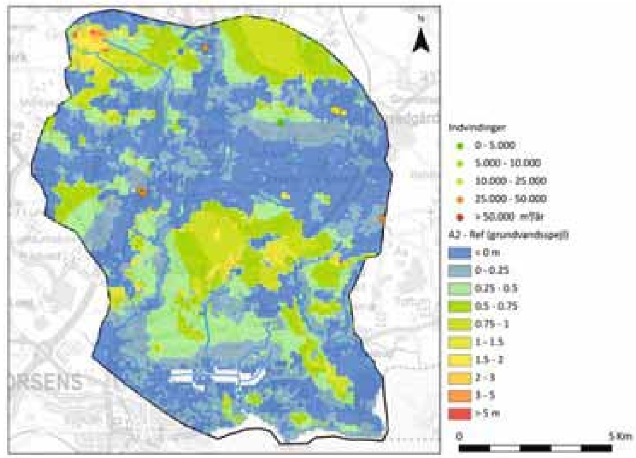


Figure 8. Map is showing the changes in depth of ground water table. Reference situation compared with A2 scenario

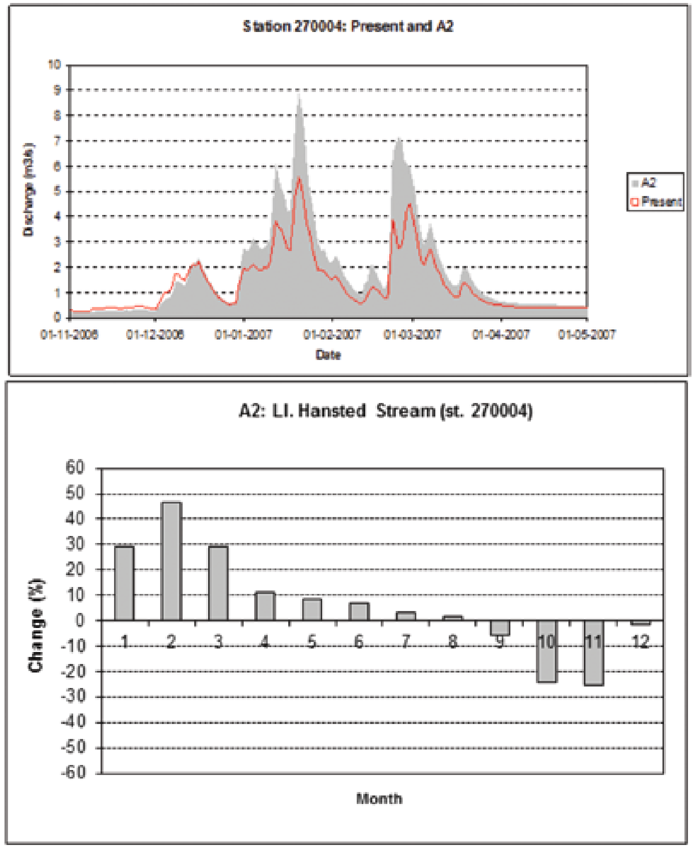


Figure 9. Diagram is showing the simulated changes in streamflow (run off) during a year for the A2 scenario. Changes for winter period and late summer/autumn period are quite significant.

The main results of the study shows that in an area like Egebjerg, which is characterised by deep buried valleys and a clay-dominated geological setting, the groundwater systems are not affected dramatically by climate changes. Note however that:

- Slightly more groundwater is to be formed and thereby more groundwater is potentially available for abstraction in a future climate due to the (in general) increased groundwater levels for deeper aquifers
- As the climate behaves more extremely with droughts occurring more frequently, the local groundwater resources may be challenged during the summertime and/or autumn period. The availability of water at the near-surface aquifers may be limited and thereby more vulnerable due to abstraction
- A significantly increase in run off during the winter period is likely to cause flooding and/or increased erosion in the rivers/streams. Suspended material and leaching of harmful substances might increase as well.

The overall increase in hydraulic head for the surface near aquifers may challenge the land use. Drainage systems are challenged in terms of need for more drainage if land use at the same type is to be maintained (agriculture).

Climate change in an area like Egebjerg is likely to result in altered drainage or water abstraction requirements due to the overall increase in precipitation and more extreme changes in river runoff (floods versus droughts). Protection measures against river flooding and river droughts should be devised.

Inspiration for the Egebjerg modelling

Using a distributed hydrological simulation model, van Roosmalen et al. (2007) conducted a study of the projected regional climate change impact on groundwater recharge, storage and discharge to streams in Denmark. Increases in precipitation, temperature, and potential evapotranspiration were predicted in each of the two 30-year climate scenarios (IPCC A2 and B2). Groundwater recharge and resulting subsurface storage and discharge were predicted to increase in sandy soils, while only small changes were predicted in clayey sediments and soils. Climate change effects on groundwater recharge and discharge to streams were found to vary seasonally. Potential effects of climate change on water availability were also predicted to vary seasonally. The geological factors are evaluated as being vital for the results of the modelling. The results and methods of van Roosmalen et al. (2007) where used as a "pathfinder" for the investigations and modelling work done in Egebjerg. The Egebjerg area represents a local scale (clayey sediments) and compared with the outcome of the Roosmalen study (regional scale), the overall results were the same. Climate change studies on the different main geological settings at varous geographical scales is recommended to be carried out.

Perspectives

The National Groundwater mapping project and other national databases means that there is a lot of groundwater and geophysical data that is readily available in Denmark. On the basis of the existing data and models, it is possible to illustrate the effects of climate change on a national scale but not on a local scale. Groundwater models that can predict local changes need to be developed. The avaliability of local data and data coverage is therefore vital for the models. There is however a need for more hydrological as well as geological data for climate modelling on a local scale in order to minimise the uncertainties and to achieve more specific results. This is especially required for the uppermost 5-10 meter where there is a lack of good quality data needed for development of improved conceptual and numerical models of interacting surface water and groundwater flow systems.

Adaptation strategies based on national or local models may be quite different. Local factors more or less directly impact the adaptation strategy, e.g. in the case of waterworks. The work and conclusions of Pilot Area Egebjerg F increase our knowledge on a local scale, especially in clay-dominated sediments. The same kind of modelling should be done in other geological settings, so that variability can be compared and evaluated.

References:

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***van Roosmalen, L., B.S.B. Christensen, and T.O. Sonnenborg (2007)**, Regional differences in climate change impacts on groundwater and stream discharge in Denmark, Vadose Zone Journal, 6, 554-571, doi:10.2136/vzj2006.0093.*

***Hans Jørgen Henriksen & Lars Troldborg.** 3D hydrologisk strømningsmodel for Egebjerg området. Kvantificering af grundvandsressourcen og afgrænsning af indvindingsoplande ved nuværende og fremtidigt klima.*
GEUS rapport 2011/101

***Hans Jørgen Henriksen & Lars Troldborg.** 3D hydrologisk strømningsmodel for Egebjerg området. Beskrivelse og uddybning af A2 klima scenariet med henblik på CLIWAT projektet.*
GEUS rapport 2011/126

www.klimatilpasning.dk

http://www.naturstyrelsen.dk/Vandet/Klima/

http://www.dmi.dk/dmi/index/klima.htm

Pilot Area F

Horsens Town (DK)

Introduction

The current subsurface groundwater conditions in Horsens have been investigated as well as the potential effects that changing climate will have on the quantity and quality of groundwater in the future and what measures need to be taken.

The study area focuses on Horsens town, which is located in the inner part of the Horsens Fjord. The fjord is a shallow and eutrophic estuary located on the east side of Jutland, Denmark within the European Water Framework Directive catchment area Horsens Fjord. The surface area of the Fjord is approximately 46 km^2, the mean depth is 2.9 m and it has a narrow shipping channel whose depth varies between 7 and 22 m. The Horsens Fjord catchment area is 517 km^2 and it is dominated by agriculture (75%). The remaining 25% is covered by forests, wetlands, lakes and urban areas. The catchment area is drained by two main rivers; the River Bygholm å and the River Hansted, located in the inner part of the fjord. Both rivers flow through the town. Several smaller streams are located on the north coast and south coast of the estuary. The wastewater treatment plant for Horsens town is located close to the mouth of the River Bygholm.

The near-surface sediments in the low-lying parts of Horsens town are dominated by post-glacial, finely-grained sediments, such as gytja, silts and clays with a high content of organic matter. Coarser materials such as sands are interbedded within the fine-grained sediments. The aquifers are located in these coarse grained materials and in man-made backfill which is the result of land expansion, road and pipe installations. On the elevated areas, the uppermost geology is dominated by glacial tills and diluvian sands.

The old part of the town is located in a low-lying area between 0 and 2 m above sea level. The groundwater level of these aquifers is situated near the surface. The location of the town leaves it exposed to the changing water cycle caused by climate change.

Most recently, in November 2006, there was a flood of port riparian areas, including the Town Hall parking lot. The flooding was caused by a storm surge that pushed sea water from the North Sea into Kattegat and further into Horsens Fjord.
A changing climate and more frequent floods entering the town raise several issues:
What is the interaction between the fjord, river and the shallow groundwater in the city?

What is the quality of this water when it is returned?

Aims of the study:

- Examine the quality of groundwater below Horsens and analyse how a changing climate will affect quality and whether there is a need for additional water management of domestic and wastewater systems
- Quantify and visualise the effects on the surface groundwater and analyse possible changing patterns in a future climate

Present situation

The near-surface aquifers in Horsens are a result of their low-lying location situated close to the terrain. The dominant parts of the aquifers are unconfined and low-yielding. The dominant flow direction is west-to-east; towards the fjord. The tidal influence in the inner fjord is around 0.6 m.

During the storm of 2006, the sea level in Horsens Fjord was registered as high as 1.76 m above normal. The increased level caused flooding of the low-lying harbour areas, including the town hall parking lot located around 700 m from the harbour. Locals reported that the parking lot was under approx. 40 cm of water. Streets and buildings where seriously affected by the rising sea level during the storm and in the days and weeks to follow. The town hall used sand bags as protection against the flooding. Similar extreme events are forecast to happen more frequently. When the flood water needs to be drained away, its quality is of importance to the surrounding ecosystem.

An analysis of historical and contemporary maps has been carried out to increase the knowledge of town areas that are built on backfill. The map below (Figure 1) shows the extension of the area covered by sea in 1876 (Blue filled area).

The extension is based on a historical map of the Horsens area. The map shows that around 2.5 km^2 of the harbour near town areas are built on areas previously covered by the sea. This includes a southern landfill covering 0.5 km^2. The blue line is the 2.5 m elevation curve showing the outline

Figure 1: Map showing 2.5 m curve based on the present topographic elevation curves. The blue-coloured area is the area covered by the sea in 1876

of the preliminary area at risk of flooding in the future. This is based on a future sea level and an expected groundwater level increase around 0.75 m and a major storm like the one in 2006, where the sea level was 1.76 m above normal.

What kind of problems/issues has been investigated?

To get a better understanding of the general quality of the near-surface water in the town, a number of drillings have been made. The drillings were shallow and the groundwater samples were taken from the uppermost aquifer, which was identified during the drilling. Sample depth varied from 1.5 to 8 m below surface.

The map below (figure 2) illustrates the location of the CLIWAT drillings

Figure 2: CLIWAT drillings and surface water sampling sites in the Horsens area

The water from the samples has been analysed for 80 potential contaminants and the preliminary conclusion is that the water is characterised as being influenced by human activities. The analysis showed evidence of contamination caused by point sources (industrial sites, landfills etc), but also activities referring to the sewers and roads.

Outcome/Results

Hydrology

Several wells, especially those close to the port, have shown a good hydraulic contact between the seawater and the groundwater. This is demonstrated by logging the water levels in wells over a longer period.

The curves showed clear tidal influence. Some of the head measures in the wells showed clear tidal influence especially B6, B7, C7021, C7024 and B8 have a clear response to the sea level, while the others only respond directly to actual precipitation.

During the logging period of around five months, there have been registered a change between 20 cm and 1.49 m in the wells. The change in head varies over short distances and wells situated a distance of 400 m away can be very differently affected by tidal changes. The tidal amplitude is around 0,6 meters in the Horsens fjord. The study indicated that a former extension of a stream in the city has a great influence on the contact to the fjord. The groundwater levels in a well situated 800 m from the port showed clear tidal influence, while wells closer to the port showed no affect from the tidal change.

On the current basis, we have a reason to believe that the contact between inlet and groundwater may be due to the River Bygholm's former location. This means that present and former anthropogenic made sub surface structures have a strong impact on the groundwater levels and the groundwater flow in the town.

In the graph below (Figure 3) is an illustration of what will happen if the sea water level increases by 75 cm and there is a connection between the

fjord and the groundwater aquifer. The result is a groundwater level above surface. The result will be an increased need for drainage and the important question in this context is the quality of the water.

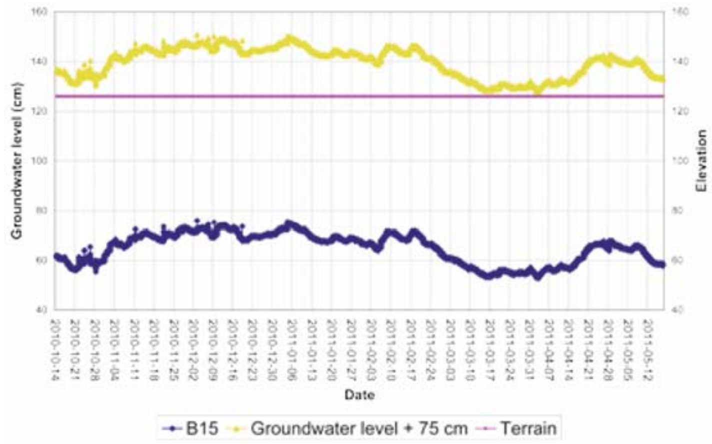

Figure 3: Groundwater levels in the present and future climate. Blue graph is present level and yellow is estimated future level including a ground water/sea level rice of 75 cm.

Chemistry

To get a better understanding of the general quality of the near-surface water in the town, a number of water samples were collected from ditches (2), drillings (16) and the Fjord (1). Most of the drillings are made for the CLIWAT project but the investigation also includes a few existing wells that are used to monitor landfills. The CLIWAT wells are shallow; the screens for ground water extraction are set in the uppermost aquifer, which was identified during the drilling. The depth of the screen varies from 0.2 to 8 m below terrain.

Water samples from the wells, ditches and fjord has been analysed for 80 potential contaminants, salts and wastewater parameters. The conclusion is that the water is characterised as being influenced by human activities. Many different kinds of substances were identified in the samples, e.g. chlorinated solvents, tar substances, pesticides and caffeine. The substances behave differently in the environment; as some are absorbed and become fixed in the soil matrix, while others are more mobile and thus easily spread to the surrounding environment.

The source of pollution varies. In some areas the pollution was assumed to derive from the sewage system, while other sources are derived from the roads and a few have a point of origin in industrial sites. The analysis showed evidence of contamination caused by point sources (industrial sites, landfills etc), but also activities related to the sewers (caffeine) and roads. Especially the water in the two ditches is heavily contaminated and clearly influenced by wastewater, the wastewater probably origins from sewage overflow.

Future situation, including illustrative maps/figures

A groundwater model with a discretization of 50 x 50 m has been set up in the area. The results from the model indicate changes in groundwater levels in Horsens town of up to 0.50 m with an A2 scenario. The results from the model is illustrated in figure 4

This means that on top of the sea level change planners in Horsens city have to prepare for raising groundwater in the future.

In addition, the increased groundwater level is expected to lead to an increase in the amount of contaminant being washed out from former industrial sites because of an increase in water passing by such sites.

In the future the uppermost groundwater and the ditchwater can be expected to be more influenced by contamination due to sewage overflow and increased pressure on the sewage system which leads to a higher amount of sewage water leaching into the aquifers.

On Figure 5 contaminants in the aquatic environment and their sources of pollution is illustrated. Pollutants from the land use e.g. former or present industry, gardens etc. are contaminating the surface near soil and ground-

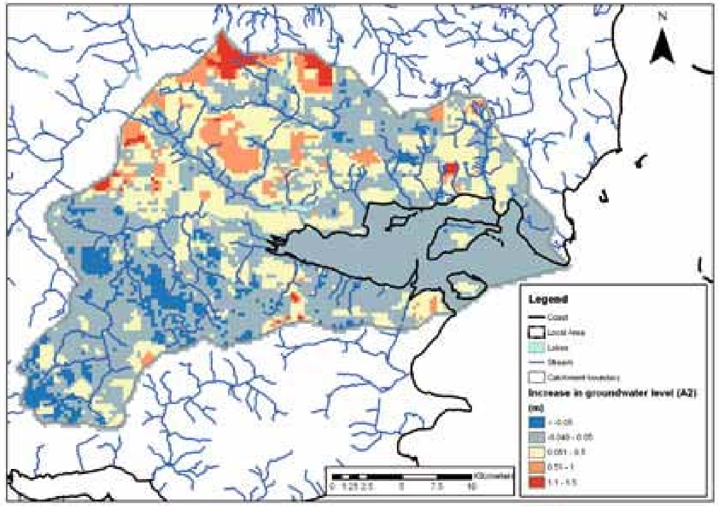

Figure 4: Change in mean groundwater level for the Horsens Catchment when the climate is changed from the present to A2-conditions. The model does not include sea level change.

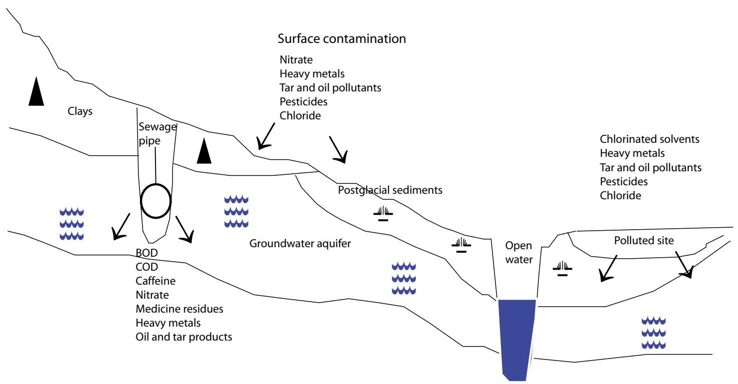

Figure 5: Simplified diagram of the hydrogeology and water quality in Horsens

water. Further this is distributed to the open ditch and fjord. In addition contaminants from the leaking sewage systems are percolating towards the aquatic environment and receiving eco systems.

Challenges and future solution – recommendations for adaptation or further investigations

The investigations have shown clear evidence of the linkage between surface water, sea water and groundwater in a Danish coastal town. Further the study also shows that antropogenic sub surface structures affects the flow and creates hydraulic connection between structures in the underground.

The change in groundwater levels in the town will increase the need for drainage. This means that open water channels, ditches or underground drainage systems will need to be established to prevent flooding.

This study shows that the quality of the water and the sources of contamination varies. This means that if water managers are to lower the groundwater table in the town, we have to be aware of the quality of the water. This can be done by monitoring the quality of the drained water and by distributing some water to treatment plants where the xenobiotics and other environmentally-hazardous compounds can be cleaned and thus prevent from affecting the estuary and receiving eco systems.

The authorities dealing with adaptation to climate change should have a strong attention to the linkages in the hydrological cycle and include all the components when planning and preparing for future development and restoring existing infrastructure.

The survey underlines that geological and hydrological sub surface characterizations can be a strong tool for understanding the linkage between surface and groundwater systems. And further the importance of a well characterized subsurface and a better understanding of the subsurface when dealing with climate change. This means that equivalent studies should be undertaken in other low laying cities with in the North Sea region to improve the understanding of the entire hydrological cycle and make a more resilient planning in the future.

Leaking sewage systems affect the groundwater quality. In a future climate; heavy rainfall is predicted to increase the amount of water flowing into the sewage system. This scenario calls for separated storm water drains and wastewater pipe systems.

The study is described in detail in:
Region Midtjylland 2011:
Undersøgelser af grundvandets kvantitet og kvalitet i Horsens by.

Pilot area G

Aarhus River (DK)

Introduction

The Aarhus River pilot area is located in eastern Jutland, near the city of Aarhus (see figure 1 and figure 2). It is an old landfill site situated in the flat meadows along Aarhus river. Waste was dumped here up until early

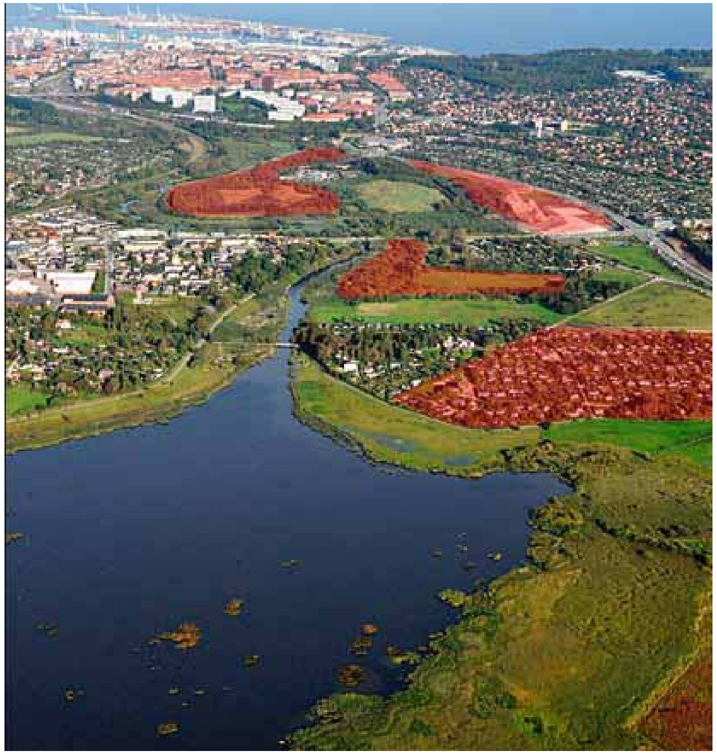

Figure 1 Aerial view of the area facing east. Landfill-areas are marked with red.

1980ties without any kind of membrane, leachate capture or isolation system. The leachate from the landfills pose a treat to the aquatic system of the river and Aarhus bay and the groundwater resource below which is used as the main drinking water resource for the town of Aarhus. The area is now used for recreational activities and allotment gardens. The water level in the river occasionally rises to flood parts of the landfill area during heavy rainfall events or when a storm pushes water up the river from the bay.

The primary focus for this pilot area is to understand the effects of climate change on the hydraulic system and how it will affect the flow of contaminants from the landfills.

Geologically the area consists of a buried pre-quaternary valley, filled with quaternary sediments of alluvial sand, gravel and clay-till. The deeper sand-layers are used as the main drinking water resource for the town of Aarhus.

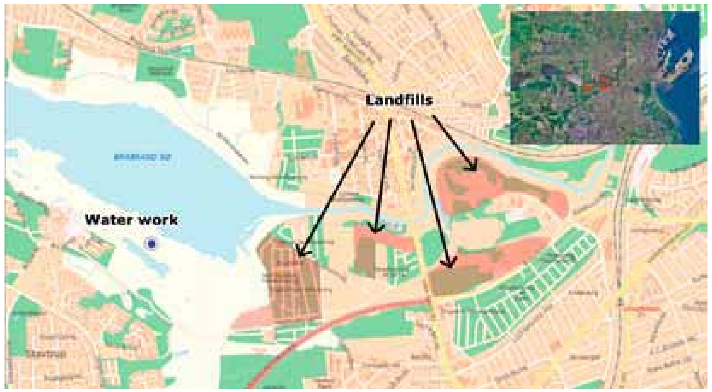

Figure 2 Map showing the pilot area.

Present situation

The nearest drinking water abstraction well is situated less than 1,5 km from the landfill sites (see figure 2).

Water is pumped from sandy aquifers between 80 and 100 meter below the surface. It is not entirely clear to what extend these deeper aquifers are in hydraulic contact with the upper aquifers under the landfill sites.

The waterwork pump approximately 2.1 million m^3 per year with a maximum permit of 3.7 million m^3.

The landfills are uncontrolled landfill sites. Municipal-, construction- and industrial waste was dumped in the soft meadows by the Aarhus river. The river flow was even moved further north several times to allow more space for the dump deposits. After landfilling was stopped in the early 1980ties the landfill was covered with a thin topsoil cover.
The landfills have been monitored for many years, and a remediation system is pumping contaminated groundwater and drainage water, to prevent contaminants from entering the surrounding environment and seeping into the deeper groundwater resource. During high water level in the river, the drainage pumping system has to be stopped to prevent pumping river water. At present high water level is predominantly occurring during winter following heavy rainfall or melting snow in the upland. Occasionally a storm surge pushes water from the bay up the river increasing water level. This occurs currently quite rare once or twice every 5 to 10 years.

Methane gas has been detected at the landfill site. Methane gas is a strong greenhouse gas about 25 times more potent than CO_2. Reducing or capturing methane gas from the landfill would reduce the climate impact of the landfills.

What kind of problems/issues has been investigated?

In the Cliwat project a lot of field work has been carried out in the pilot area. The primary objective has been to gain more knowledge of the geology, the hydraulic system and the water quality. In addition it has been an objective to develop new investigation techniques and to learn how to take advantage of the diversity of the data collected.

The field work includes the following:

- Well logging using special well-logging equipment and age-dating of water samples
- A pumping test.
  - To better understand the hydraulic connections between the upper aquifer and the deeper aquifers used for drinking water purposes, a pumping test was carried out in a deep well on the site.
- 3D Landfill and plume mapping using IP geophysical methods.
- El-log drilling
  - To investigate geo-electrical properties of the subsurface as input for the IP surveys.
- A temporary shut down of the remediation system.
  - To investigate how increased groundwater level affects the hydraulic system around the landfill. This involved measuring the water table and leachate using loggers and water sampling.
- Investigation of river-landfill flow using water table data-loggers in new boreholes close to river, flow of water to from the landfill was monitored.
- Quantification of methane flux using mobile extractive FTIR technique. This method is based on emission of tracer-gas in combination with measurements of emission- and tracer-gas concentrations in the downward wind plume.

Based on the finding from the field work and previous studies a 3-D hydrogeological model was developed to map the geology and hydraulic connections of the subsurface.

The hydro geological model consist of 7 layers, where the lower four consist of two sandy aquifers and two aquitards of glacial clay and till. Above these two layers are post glacial sediments related to the valley; peat and marine sand. The uppermost layer is the urban fill and includes the waste deposit (see figure 3).

Figure 3 West-East profile through Stautrup well field and Eskelund deposit showing major hydrogeological units.

Finally a model of the hydraulic system was set up using a finite element model called HydroGeoSphere. This model system is able to fully integrate all the hydraulic systems. By running the model using different scenarios it has been possible to test how the climate change effect might change the hydraulic flow and the leaching of contaminants from the landfills. Several scenarios including changes in groundwater abstraction at water work and changes in the remediation system has also been examined.

The model boundaries are natural fixed head or no flow. Climate data and water abstraction from 1980 to 2010 has been implemented in the model.

The model is calibrated and validated against groundwater heads and river flow. Focus on the calibration has been the waste deposit area.

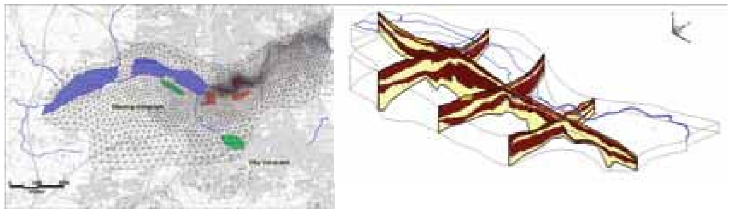

Figure 4 Left: Model mesh with smaller triangles in the focus area at the waste deposit. Red area is landfill, green is water work well fields and blue is lake and river. Right: 3D hydrogeology in model (looking north-west).

What are the outcome/results?

The following are the main outcomes from the pilot area.
Results from the pumping test and the investigation of water table and ground water age has been inconclusive on the extend to which the landfill is in contact with the deeper groundwater. However the results do show that if a connection exists it is not very strong. The pumping test also showed that there is only a very small leakage from the river.

The shutdown of the remediation system resulted in clearly increased water table and surface runoff of iron rich leachate. However due to the relatively short shutdown period it has not been able to see any significant effects on groundwater quality.

Methane investigations identified several hotspots where methane was seeping out from the surface area and ponds. The innovative flux measurements were also able to give a good estimate on the total flux of methane from the entire area.

The results are now being used further in another project attempting to reduce methane emissions using compost heaps.

Landfill mapping using IP measurements was able to clearly identify the landfilled area. The figure below show an example of a map from the IP measurments. The area with high chargeability correspond well with the landfilled area. It also indicated possible landfilling or a leachate plume south of the currently identified landfill area. This has lead to further investigations of the landfill boundary.

The hydrological model has been used to evaluate different objectives.

First a model on a short timescale has been evaluated to simulate the mobilization of contamination in a situation with high sea level and wet conditions. Four different scenarios have been tested for the situation with and without active remediation at the waste deposit site; a) normal conditions without a flood situation, b) a situation simulating a flooding situation in 2006 where the sea level rose to +1.7 m, c) a situation simulate to

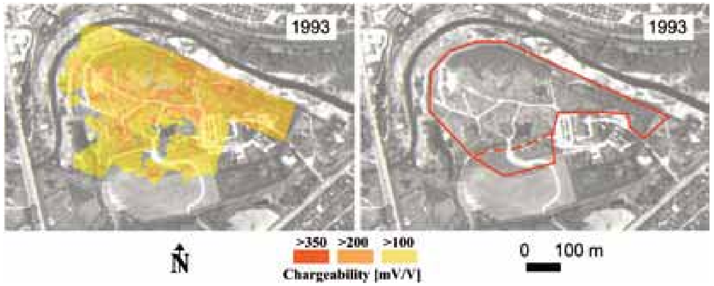

Figure 5 Map of IP measurements overlaying aerial map from 1993.

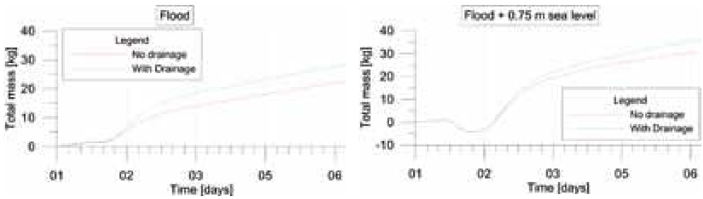

Figure 6 The cumulative transport in the two flood situations with and without active remediation.
The higher the water level is, the more total mass is released, and is around 30-40 % higher, independent on the scenario. The hydraulic properties of the waste deposit are assumed homogeneously throughout the whole waste deposit and therefore there are some uncertainties to the absolute values of the model results. The increase in the total mass release in the active drain situation may relate to the situation where there is a general higher circulation of water through the contaminated zone, thereby mobilizing more salts.

b) but in the future where sea level is an additional +0.75 m, and finally d) a situation as c) but with very wet conditions from rainfall and high river discharge.

The results from these scenarios show a complex interaction between river flow and transport from the waste deposit to the river. With the high water level in scenario c, the river reverses its flow and the same water volume

then passes the waste deposit several times. On each passage, contaminants enter the water. The raise and fall in river level causes an increase in the transport of contaminants from waste deposit to the river, and the model predicts that there is an increase in the mobilization of contaminants ion the situation where the drainage system is active. The active drain actually increases the total transport with 10-20 %.

In the second objectives, the model is used to examine the future extend of the contamination below the waste deposit under different climate scenarios as well as drainage systems and water abstraction from the nearby water works.

Future situation, including maps/ figures illustrating the scenario(s)

The transport model has been simulating the contamination expansion from year 1980 to year 2100 using three different climate scenarios, present day, A2 and B2. The present day [1980-2009] precipitation, evapotranspiration and temperature have been extrapolated to future condi-

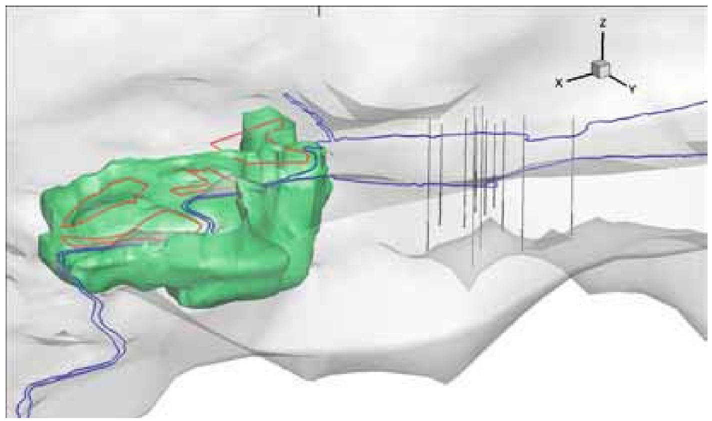

Figure 7 Three dimensional view of the waste deposit and contaminated ground water (to the left) and the water work well field (to the right)

tions using a monthly delta transfer function. The present day situation has an average groundwater recharge of 248 mm / year. Scenario A2 has an average groundwater recharge of 295 mm / year and scenario B2 has 363 mm / year.

The results from these scenarios show that there is in practical no difference between the total volume of contamination released in the different climate scenarios. There is a slightly larger cumulative transport of contamination in the situation where the abstraction from at the water work is increased. The simulation also shows that the plume reaches a certain volume and overall appears to stop expanding, but following a rhythm of annual and decadal dry and wet periods.

The reason for the small climatic effect lies in the hydrogeological system and the location in the river valley. The contamination of the aquifer system below the waste deposit is confined by the regional flow system. The large catchment makes the river valley a natural drainage system. Water is pushed through the system from the high located areas through the lower aquifer and below the river at zones with high contact, water enters the river. This mechanism fixates the contamination. An increase in the precipitation may increase the flow but not the total mass of contaminants in the aquifer.

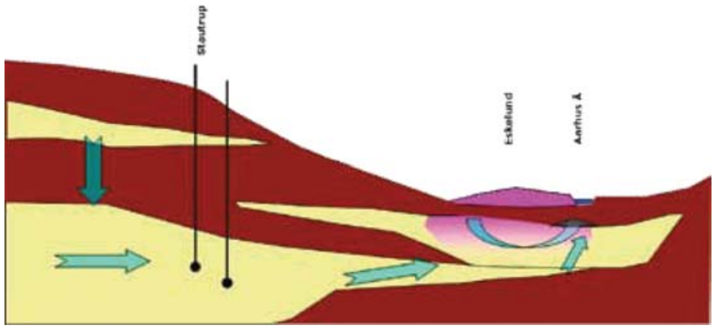

Figure 8 Conceptual understanding of the regional flow system confining the contamination.

Model results show that an increase in the water abstraction did not increase the total mass below the aquifer, - but a tendency for the contamination plume to be located closer to the Stautrup well field. The tipping point of where there is a direct inflow of contaminants to the well field is at present time unknown and relies on further investigations due to uncertainties of the hydrogeological parameters.

Challenges and future possible solution – recommendations for adaptation or further investigations

Integrating information from the different field work results proved very beneficial for understanding the system. The investigations also highlighted the importance of good quality data and the importance of long term monitoring data. This is vital for setting up a representative geological and hydrogeological model.

The flooding scenarios showed that an increase in the river head would flood the lower parts of the waste deposit and contaminants would enter the river. The higher water level, the more total mass would be released. In the future, a weir at the harbour end of the river will be build, preventing flooding of the inner city. This weir will prevent extreme water flooding and thereby prevent release of contaminant due to flooding from the sea.

Flooding from the river side may still occur and here investigation of the efficieny of the remediation system should be evaluated as the model results show that the remediation causes a greater flux through the system.

The model results show that there is only little – if any – climate effect on the contamination. This is a consequence of the location of the waste deposit in the river valley, where the contamination is confined by a regional groundwater flow system.

The biggest threat in the system lies in the future water demand from the well field. The model did not show any direct contamination of the water supply abstraction wells, but showed that the contamination moved towards the abstraction wells when abstraction rate was increased. Further investigation are required here . This includes:

- Model uncertainty analysis to investigate the tipping point, where contamination enters the abstraction wells
- Recommendation to implement an active warning system between waste deposit and well field.
- Evaluation of the remediation system on a long term.

The investigations at this pilot area did not show any significant climate change effect under the used climate change scenarios. However this does not imply that the same result would be the same for other similar landfill sites. It all depends on the local conditions; geology, topography, hydrology etc.

The key component is how often the landfill will get flooded and the hydraulic conductivity of the land filling. Sites that are very low lying will naturally be most vulnerable to climate change effects, but a limited top cover and a land fill volume with good hydraulic conductivity plays a major role.


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