3.6 Description of the Southern Jutland case study, Denmark

Title of Case Study	Southern Jutland
Location (region, Country)	The Jutland part of the Region of Southern Denmark
Other information	The included area corresponds to model four of the National Danish Water Resources model (the DK-model) that comprises seven regional models: http://dk.vandmodel.dk/in-english/. The regional models are all physically distributed and integrated groundwater – surface water models.

Description of Case Study (background information on the region)
The region is a border region between Southern Denmark and Northern Germany, which has been studied in several EU (Framework 5 and 6, Interreg North Sea) projects and national studies that included groundwater dating and groundwater flow modelling studies of the regional Quaternary and Miocene sand aquifers in the region. Depending on the location three or more confined or semi-confined sandy Quaternary or Miocene aquifers are located from 0 – 400 m below surface where shallow aquifers are frequently contaminated with nitrate and pesticides and deep aquifers or shallow local discharge areas contain groundwater recharged at lower temperature during the late Pleistocene based on primarily ^{14}C, $\delta^{13}C$, heavy noble gases, $\delta^{18}O$ and δD measurements in samples collected from monitoring wells in the aquifers. Locally, the aquifers are affected by saltwater intrusion primarily in the western part of the region (Meyer et al., 2019).

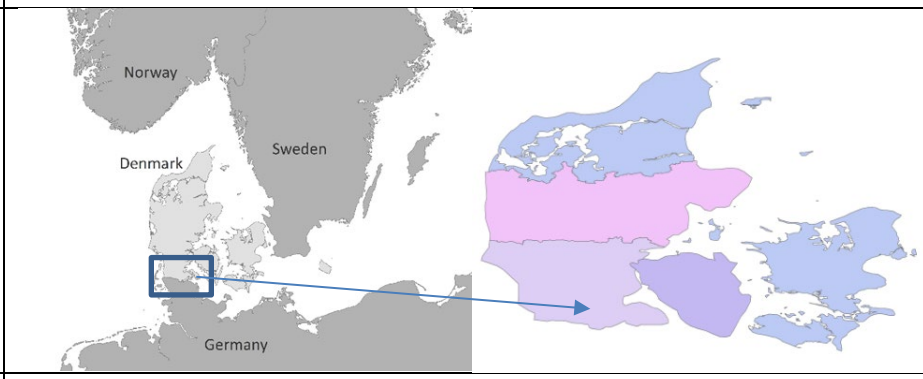
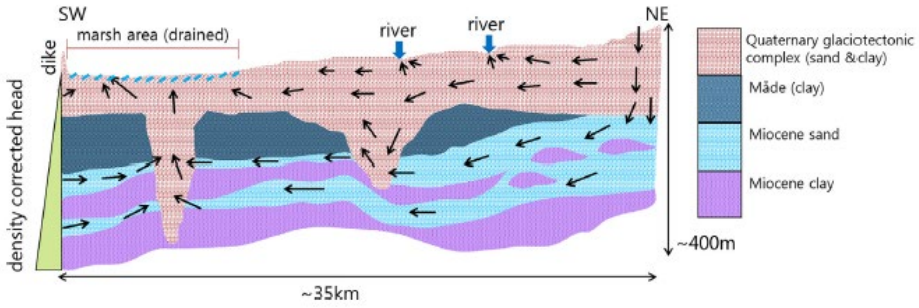
Description of problem (why is this location chosen for a Case Study)
The investigated regional aquifers were included as the region were part of the PALEAUX project on evolution of coastal aquifers in Europe (Edmunds and Milne, 2001) in the EU Framework five program and BASELINE of the EU Framework six programme (Edmunds and Shand, 2008). The region was selected as it has several important Quaternary (e.g. buried valleys) and Miocene aquifers exploited by drinking water and irrigation wells, which are very important for the region. Several previous studies conducted during the past 25 years provide insights about groundwater travel times, paleoclimate indicators, saltwater intrusion, Pleistocene and Holocene evolution of groundwater quantity and quality. Paleoclimate indicators (heavy noble gases and stable isotopes) combined with isotope data from primarily ^{14}C and ^{39}Ar indicate local presence of Pleistocene and Little Ice Age groundwater with ages of more than 10.000 and 300 years, respectively. The data is important for assessment of the vulnerability to pollution from the surface and natural groundwater quality (natural background values) of the aquifers.

Methods to be used in the Case Study (analytical and isotope techniques, modelling)
The case study include the application of a wide range of groundwater age and paleoclimate indicators including: $^{3}H/^{3}He$, ^{85}Kr, ^{39}Ar, ^{14}C, $d^{13}C$, ^{18}O, ^{2}H, ^{4}He, heavy noble gases (Xe, Rn) as well as groundwater flow modelling by MODFLOW and the National Danish Water Resources Model, demonstrating the distribution of young potentially contaminated waters, Holocene and Pleistocene (Paleowater) groundwaters in regional aquifers.

Results from this Case Study
The tracer and groundwater flow modelling studies conducted in the investigated area demonstrate that the groundwater evolved in the regional aquifers from modern/young polluted groundwater in the eastern part of the area to late Pleistocene groundwater in the deepest and/or most westerly parts of the aquifer. Pleistocene groundwaters have been found in aquifers at depths more than 300 meters below surface in east, central and western parts of the aquifer as well as in some shallow wells in the discharge areas close to the North / Wadden Sea at depths less than 50 meter. Groundwater flow modelling studies e.g. partly based on the distribution of groundwater dating tracers and paleoclimate indicators also provided insights to salt water intrusion during the Holocene as the level rise induced salt water intrusion to aquifers and occasionally flooding as the sea level increased from more than 120 meter below the surface at the last glacial maximum to the present day level (Hinsby et al., 2001; Meyer et al.,). They furthermore provide insights to the general assessment of the vulnerability of the aquifers and drinking water wells in the area (Hansen et al.).

Impact - how this Case Study contributes to the overall project aims
The case study was part of and contributes with information on the evolution of coastal aquifers in Europe since the late Pleistocene (Edmunds and Milne, 2001, Edmunds et al., 2001) – here exemplified for aquifers located in a border region between Denmark and Germany. The case study area is located between the South-Eastern part of the North Sea and South Western part of the Baltic Sea demonstrating the wide application of groundwater dating and the estimation of travel times and groundwater age distributions in regional coastal aquifers in different geological settings. The Studies include investigations of the natural groundwater quality and the natural background levels of groundwater in the Miocene sand aquifers of the region (Hinsby and Rasmussen, 2008) related to activities in HOVER WP3 on natural background levels, groundwater vulnerability to pollution from the surface related to HOVER WP7 (Hansen et al., 2016) and saltwater intrusion (Meyer et al. 2018, 2019) related to WP5 of the TACTIC (Tools for assessment of climate change impacts on groundwater and adaptation strategies) project.

<table>
<tr><td colspan="2">Name of pilot area / aquifers / type:
Southern Jutland / Quaternary and Miocene sand aquifers / porous</td><td colspan="2">Country: Denmark

Region: Southern Jutland (DK-DE border aquifers)</td></tr>
<tr><td>Study level</td><td colspan="3">Transboundary : ☐ Regional: x Local: ☐ Single well(s): ☐</td></tr>
<tr><td>Type of observations
(choose one of the options, create separate template if needed for each type if each type need specific information)</td><td colspan="3">x Short screened observation wells (not pumped)
x Long screened observation wells (not pumped)
☐ Pumped wells, long screens in one aquifer
☐ Pumped wells, long screens over multiple aquifers
☐ Springs
☐ Other (eg. research wells; indicate type and information on pumping):</td></tr>
<tr><td>Approximate location of pilot (WGS84):
minX: 8.456955
maxX: 9.671778
minY: 54.916425
maxY: 55.246433</td><td colspan="3"> 
</td></tr>
<tr><td>Geological cross section / conceptual model of the pilot area:</td><td colspan="3"> 
</td></tr>
<tr><td colspan="2">Name of Shape- / Geopackage file defining the area:
HoverDKPilotsSub.shp</td><td colspan="2">Projection to be used:
WGS84 (Epsg4326)</td></tr>
</table>

Hydrological parameters:	**Mean annual precipitation (mm or range in mm)**	**Mean annual groundwater recharge (mm or range in mm)**	**Mean annual groundwater recharge temperature (°C)**	**Thickness of unsaturated zone (range in m)**
	800-1000	300-400	9	5-50

Pumped wells only	**Typical pump discharge of sampled individual well (m^3/day):**	**Typical pump discharge of complete well field (m^3/day):** *If relevant*
List of aquifers and aquitards in pilot area	**No. of confined or semiconfined aquifers in pilot area: 2**	**No. of unconfined aquifers in pilot area: 1**

Aquifer no. (aqf): 3 Aquitard no. (aqt): 2 Aquiclude no. (aqc): 1	**Aquifer/aquitard type and/or name**	**Lithology *(Resource WP6 terminology)***	**Depth range (m)**	**GW age range (yr)**
Aqf-1:	Quaternary sands locally confined by clay till aquitards	Fine sand to gravel	0 – 100 (400)	5 - > 10,000
Porosity type	Porous: X	Fissured: ☐	Karst: ☐	Fissured and porous / dual porosity: ☐
Aqt-1:	Miocene marine clay	Silty clays		
Porosity type	Porous: X	Fissured: ☐	Fissured and porous / dual porosity: ☐	No hydraulically active porosity: ☐
Aqf-2:	Miocene sands	Fine sand to gravel	100 - > 250	100 - > 10,000
Porosity type	Porous: X	Fissured: ☐	Karst: ☐	Fissured and porous / dual porosity: ☐
Aqt-2:	Miocene marine clay	Clay		
Porosity type	Porous: X	Fissured: ☐	Fissured and porous / dual porosity: ☐	No hydraulically active porosity: ☐
Aqf-3:	Miocene sands	Fine sand to gravel	250 - 400	1000 - > 10,000
Porosity type	Porous: X	Fissured: ☐	Karst: ☐	Fissured and porous / dual porosity: ☐
Aqc-1:	Oligocene clay	clay		
Porosity type	Porous: X	Fissured: ☐	Fissured and porous / dual porosity: ☐	No hydraulically active porosity: ☐

Applied tracer age indicators (^{3}H, $^{3}H/^{3}He$, ^{85}Kr, ^{39}Ar, ^{14}C, ^{36}Cl, ^{81}Kr, ^{4}He, CFCs, SF_6, etc.) **Applied recharge temperature indicators** (^{18}O, D, noble gases)	**Aquifer-1** ^{3}H, $^{3}H/^{3}He$, ^{14}C, ^{4}He, ^{18}O, D noble gases
	Aquifer-2 ^{3}H, $^{3}H/^{3}He$, ^{14}C, ^{4}He, ^{18}O, D noble gases
	Aquifer-3 ^{3}H, $^{3}H/^{3}He$, ^{14}C, ^{4}He, ^{18}O, D noble gases
Number of sites (wells/springs) with age indicators	**Aquifer-1** **1-5: ☐ 5-10: ☐ 10-25: X >25: ☐**
	Aquifer-2 **1-5: X 5-10: ☐ 10-25: ☐ >25: ☐**
	Aquifer-3 **1-5: X 5-10: ☐ 10-25: ☐ >25: ☐**
GW age range (GAR) **GAR-1: Modern (< 60 yr)** **GAR-2: Old (> 60 yr and 10 kyr)** **GAR-3: Paleowaters (> 10 kyr)**	**Aquifer-1** **GAR-1: 1-10%: ☐ 10-25%: X 25-50%: ☐ >50%: ☐** **GAR-2: 1-10%: ☐ 10-25%: ☐ 25-50%: ☐ >50%: X** **GAR-3: 1-10%: X 10-25%: ☐ 25-50%: ☐ >50%: ☐**
	Aquifer-2 **GAR-1: 1-10%: X 10-25%: ☐ 25-50%: ☐ >50%: ☐** **GAR-2: 1-10%: ☐ 10-25%: ☐ 25-50%: ☐ >50%: X** **GAR-3: 1-10%: X 10-25%: ☐ 25-50%: ☐ >50%: ☐**
	Aquifer-3 **GAR-1: 1-10%: ☐ 10-25%: ☐ 25-50%: ☐ >50%: ☐** **GAR-2: 1-10%: ☐ 10-25%: ☐ 25-50%: ☐ >50%: X** **GAR-3: 1-10%: X 10-25%: ☐ 25-50%: ☐ >50%: ☐**
Groundwater age ranges (GAR) estimated by:	**Tracer based estimates ☐** **Flow and age model simulations ☐** **Combination of model and tracer estimates X** **Expert judgement: ☐**

Objective of age dating studies:

Basic research or General groundwater management	**Assessment of pollutant history**	**Assessment of the efficiency of remediation and mitigation measures**	**Indication of vulnerability of aquifers and water supply wells**
x			

Water Usage *(not relevant for observation wells)*	**Water supply**	**Irrigation**	**Industry**	**Other**
	x	x	x	?

Geoenergy related activities *(not relevant for observation wells)*	**Shallow Geo-T**	**Deep Geo-T**	**Hydrocarbons**	**Nuclear waste disp.**	**CO_2 storage**
	x				

Mining activities *(not relevant for observation wells)*	**Construction materials**	**Minerals / metals**	**Coal**	**Other**
	x			

REFERENCES	
OPEN Access reports and papers (PDF versions made available in EGDI repository making them downloadable via maps and keyword / free text searches):	**Reports and papers with restricted access:**
Remarks / other relevant information:	