3.7 Description of the Central Jutland case study, Denmark

Title of Case Study	Central Jutland
Location (region, Country)	Part of Central Jutland, Denmark
Other information	The included area covers part of the National Danish Water Resources model (the DK-model) http://dk.vandmodel.dk/in-english/ for the Central Jutland region.

Description of Case Study (background information on the region)
Groundwater in the investigated Miocene (Burdigalian) aquifer flow from the eastern part of the area towards the North Sea at the western coastline of Jutland. The area is primarily located to the west of the Main Stationary Line of the last glaciation, which e.g. has resulted in clay tills at the surface and confined or semi-confined aquifers in the eastern part of the area, and mainly outwash sands a the surface and unconfined aquifers in the western part of the area. The project included a PhD study (Scharling, 2009, 2011) funded by GeoCenter Denmark (https://www.geocenter.dk/ to investigate the distribution and extent of Miocene sand aquifers in Central Jutland (Rasmussen, 2007) including the vulnerability towards pollution from the surface and the general distribution of groundwater age and transit times (Sonnenborg et al., 2016). Depending on the location three or more confined, semi-confined or unconfined sandy Quaternary or Miocene aquifers occur at different depths between 0 – 200 m below surface (or <20 - < -200 meter above sea level). Applied tracers include ^{39}Ar, ^{85}Kr, ^{14}C, $\delta^{13}C$, $\delta^{18}O$, and δD measurements in samples collected from monitoring and irrigation wells in the aquifers. The groundwater flow, age and ^{39}Ar distributions were simulated by the use of various techniques (Sonnenborg et al., 2016).

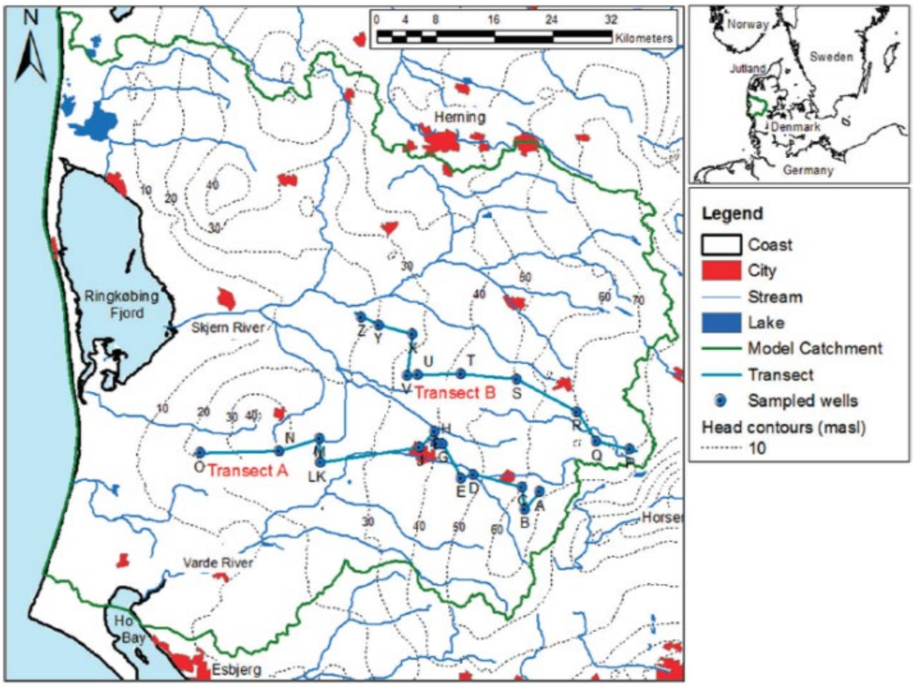
Description of problem (why is this location chosen for a Case Study)
The relatively deep lying Miocene sand aquifers in central and southern Jutland (see also specific pilot description for Southern Jutland) have attracted special attention during the past couple of decades due to increasing pollution of the shallow Quaternary aquifers in the area. The Miocene aquifers may be well protected against pollution and constitute an additional important strategic reserve. The data obtained in this study are important for assessment of the vulnerability of the Miocene aquifers to pollution from the surface and natural groundwater quality (natural background values) of the aquifers. The results demonstrate that the investigated Burdigalian aquifer is more vulnerable to pollution from the surface than previously thought, but that it is an important water resource primarily for water supply and irrigation.

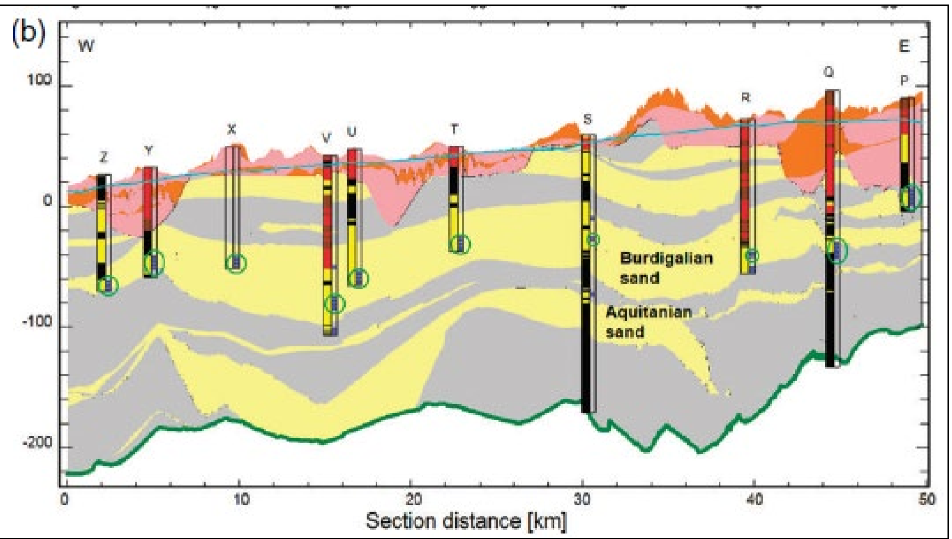
Methods to be used in the Case Study (analytical and isotope techniques, modelling)
The case study includes the application of the following groundwater age and paleoclimate indicators ^{85}Kr, ^{39}Ar, ^{14}C, $d^{13}C$, $^{18}O$and δD. Model codes and techniques applied include MODFLOW, MTD3MS, RTD3 and PEST (Sonnenborg et al., 2016). The ^{85}Kr and ^{39}Ar sampling and analyses were conducted by the research group on environmental radionuclides at Climate and Environmental Physics, University of Bern.

(https://www.climate.unibe.ch/research/research_groups/environmental_radionuclides/index_eng.html)

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 less than 60 years old to groundwater older than 300 years without human impact. Both tracers and groundwater flow models demonstrate that young potentially polluted groundwater is more widespread than anticipated and hence that the groundwater resources in the Miocene (Burdigalian) sand aquifer typically at a depth of 50 - 100 meter is more vulnerable to pollution from the surface than expected.

Impact - how this Case Study contributes to the overall project aims
The case study investigate the vulnerability, groundwater age and travel time distributions of important aquifers in the Central part of Jutland, Denmark, and hence it contributes to the objectives of WP6 on groundwater age and travel time distributions as well as related studies in HOVER WP5 and 7 on travel times for nitrate and pesticides and the vulnerability of aquifers, respectively. The location of the study site and the references cited in the text above can be found in the following information template. The PhD thesis, Scharling et al. (2011), and the open-access paper by Rasmussen et al. (2007) can be downloaded from the EGDI repository.

Name of pilot area / aquifers / type: Central Jutland / Miocene (Burdigalian) delta and marine sand aquifer / porous	**Country:** Denmark **Region:** Central Jutland
Study level	Transboundary : ☐ Regional: x Local: ☐ Single well(s): ☐
Type of observations *(choose one of the options, create separate template if needed for each type if each type need specific information)*	X Short screened observation wells (not pumped) X Long screened observation wells (not pumped) X 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):
Approximate location of pilot:	
Geological cross section / conceptual model of the pilot area:	A geological cross-section at Transect B on map above is shown below with indication of sampled sceens (green circles)

				
Name of Shape- / Geopackage file defining the area: HoverDKPilotsSub.shp		**Projection to be used:** WGS84 (Epsg4326)		
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)**
	700-1100	300-500	9	1-30
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: 3**		**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 - > 300 (expert Judgement)
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	No hydraulically active porosity: □

			porosity: □	
Aqf-2:	Miocene sands	Fine sand to gravel	< 20 - 100	< 60 - > 300
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 (Burdigalian) deltaic and marine sands	Fine sand to gravel	30 - 180	< 50 - 500
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**		
		Aquifer-2		
		Aquifer-3 ^{39}Ar, ^{14}C		
Number of sites (wells/springs) with age indicators		**Aquifer-1** **1-5: □ 5-10: □ 10-25: □ >25: □**		
		Aquifer-2 **1-5: □ 5-10: □ 10-25: □ >25: □**		
		Aquifer-3 **1-5: □ 5-10: □ 10-25: X >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%: □ 25-50%: □ >50%: □** **GAR-2: 1-10%: □ 10-25%: □ 25-50%: □ >50%: □** **GAR-3: 1-10%: □ 10-25%: □ 25-50%: □ >50%: □**		
		Aquifer-2 **GAR-1: 1-10%: □ 10-25%: □ 25-50%: □ >50%: □** **GAR-2: 1-10%: □ 10-25%: □ 25-50%: □ >50%: □** **GAR-3: 1-10%: □ 10-25%: □ 25-50%: □ >50%: □**		
		Aquifer-3 **GAR-1: 1-10%: □ 10-25%: X 25-50%: □ >50%: □** **GAR-2: 1-10%: □ 10-25%: □ 25-50%: □ >50%: X** **GAR-3: 1-10%: □ 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			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**

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):

Rasmussen, Erik S., Thomas Vangkilde-Pedersen, and Peter Scharling. 2007. "Prediction of Reservoir Sand in Miocene Deltaic Deposits in Denmark Based on High-Resolution Seismic Data." Geological Survey of Denmark and Greenland Bulletin, no. 13: 17–20. https://doi.org/10.34194/geusb.v13.4966 .

Scharling, P.B. 2011. Hydrogeological modeling of Miocene aquifers in western Denmark. PhD thesis, University of Copenhagen, Copenhagen, Denmark.

PB Scharlings PhD thesis mentioned above has been uploaded to the EGDI document repository

Reports and papers with restricted access:

Scharling, Peter B., Erik S. Rasmussen, Torben O. Sonnenborg, Peter Engesgaard, and Klaus Hinsby. 2009. "Three-Dimensional Regional-Scale Hydrostratigraphic Modeling Based on Sequence Stratigraphic Methods: A Case Study of the Miocene Succession in Denmark." *Hydrogeology Journal* 17 (8): 1913–33. https://doi.org/10.1007/s10040-009-0475-6

Sonnenborg, T.O., P.B. Scharling, K. Hinsby, E.S. Rasmussen, and P. Engesgaard. 2016. "Aquifer Vulnerability Assessment Based on Sequence Stratigraphic and39Ar Transport Modeling." Groundwater 54 (2). https://doi.org/10.1111/gwat.12345.

Remarks / other relevant information: