Vulnerability of the deep Miocene aquifers within the Skjern and Varde river catchment

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In Denmark, all drinking water originates from groundwater.

...Groundwater, which is the basis for our drinking water production, shall be protected against pollution from Nitrate and Pesticides!

(From the water sector legislation in Denmark; [https://www.retsinformation.dk/forms/R0710.aspx?id=123527](https://www.retsinformation.dk/forms/R0710.aspx?id=123527))
However....... 

Widespread contamination in shallow aquifers generally makes them unattractive as a drinking water resource.

Mean finding depth for contaminants is increased from 37 m in 1990 to 43 m in 2009.
To ensure the groundwater resource in Jutland, Denmark, a geological mapping campaign of the deep seated Miocene (23-5 Ma) aquifers was initiated more than a decade ago. A descriptive sequence stratigraphic (S.S.) model was continuously developed and reported in numerous reports and scientific articles. The Geoscentre project MIOMOD was initiated to couple the sequence stratigraphic model to groundwater modeling.
Hydrogeological modeling of Miocene aquifers in Western Denmark

Objectives:

1. Develop and apply a methodology for characterization of deep aquifers by combining geological interpretation techniques used in oil exploration and groundwater modeling.
2. Test the applicability of different environmental tracers as tools for age dating of groundwater in the Miocene aquifers.
3. Couple numerical groundwater modeling with environmental tracer data.
4. Quantify inter-aquifer mixing and estimate vulnerability.
Papers

**Paper I:** Scharling PE, Rasmussen ES, Sonnenborg TO, Engesgaard and Hinsby K (2009) *3D regional scale hydrostratigraphical modeling based on sequence stratigraphic methods*. Hydrogeology J 17(8):1913-1933

**Paper II:** Scharling PE, Hinsby K, Engesgaard P, Sonnenborg TO, Rasmussen ES, Purtschert R (submittet to Groundwater) *Aquifer vulnerability assessment based on sequence stratigraphic and 39Ar transport modeling.*

Objective 1
Develop and apply a methodology for characterization of deep aquifers by combining geological interpretation techniques used in oil exploration and groundwater modeling.
Sequence Stratigraphy

A sequence can be regarded as one cycle of deposition controlled by relative sea level changes (base level).

Sediment source area, subject to denudation

Equilibrium profile of a fluvial system, for a given elevation of the source area

lowest level of continental denudation

sea level (~ base level)
System tracts

Catuneanu O (2002)

shelf delta, aggradation & progradation

downlap

fluvial erosion or bypass

shelf-edge delta with offlap

fluvial onlap

shelf-edge delta with topset

fluvial onlap

coastal onlap

(Forced regressive wedge systems tract)

riset fall rise

estuary

marine onlap (slope apron)

4. **Transgressive systems tract**: retrogradation and aggradation (base level rise at the shoreline and transgression)
Model area and data foundation for the 3D hydrostratigraphic model
23 surfaces and 22 units

- Landsurface
- Prequaternary
  - 10 sequence stratigraphical surfaces
  - 11 lithofacies contact surfaces

The units can be combined into major aquifer systems based on progradational events:
- (23-20 Ma)
- (20-16 Ma)
- (16-14 Ma)
Objective 2
Test the applicability of different environmental tracers as tools for age dating of groundwater in the Miocene aquifers
Environmental tracers
-Application ranges-

Newman et al. (2010)
Initial assumptions

- Water infiltrates primarily in the eastern part of the model area.
- Groundwater is flowing from east towards west.
- Groundwater in the Miocene aquifers is getting increasingly older from east towards west.
Sampled wells in transect A and B
Diffusion into the stagnant zone

In Miocene aquifers just south of the study area, age corrections around 60% has been applied on tracer dating using 14C. Tracer loss due to diffusion into the stagnant zone is largely controlled by the distribution of flow zones (sand) and stagnant zones (clay) within the aquifer (Sanford 1997).

WARNING!
The method assumes real stagnant zones.......

The diagram shows the relationship between the thickness of flow zones and stagnant zones, with different symbols indicating negligible, significant, and dominant diffusion effects.
Regional hydrostratigraphic units

-assumptions-

For both clayey and sandy hydrostratigraphic units advection is considered to dominate over diffusion.

“Real” stagnant zones can be resolved by the interlayer clay/sand distribution for each unit based on lithological logs.
Diffusion correction based on intra-layer heterogeneity

Clayey unit

Sandy unit
Diffusion correction

Regional hydrostratigraphic units

$^{39}$Ar: 39%; $^{14}$C: 57%

Intra-layer heterogeneity

$^{39}$Ar: 69%; $^{14}$C: 73%

A good fit exists between corrected $^{14}$C age and $^{39}$Ar age, even for centuries old groundwater!

$^{14}$C vs $^{39}$Ar
Fit to the numerical groundwater model

**Diffusion correction scenario**

1. Uncorrected $^{39}$Ar
2. Diffusion corrected $^{39}$Ar + regional hydrostratigraphic units
3. Diffusion corrected $^{39}$Ar + intra-layer heterogeneity
4. Diffusion corrected $^{14}$C + intra-layer heterogeneity

Taking diffusion and interlayer heterogeneity into account improves the fit to the groundwater model significantly!
Objective 3
Couple numerical groundwater modeling with environmental tracer data
The MODFLOW HUF-package is used to separate the numerical grid from the hydrostratigraphic units. The background hydrostratigraphy consists of 20 Miocene units from Scharling et al. (2009) and 6 Quaternary units from the national water resources model (Henriksen et al. 2003).

Rivers, recharge, pumping, and drainage setup all originate from the national water resources model (Henriksen et al. 2003).

Calibration is performed against 5183 piezometric head measurements and 30 river discharge measurements.
Simulation of $^{39}$Ar concentration

MT3DMS is used as transport code. Decay of $^{39}$Ar is simulated without sorption or chemical reactions.
Simulation of $^{39}$Ar concentration

-results-

Changing dispersivities and effective porosities do not affect model results significantly!

Corresponding for diffusion has major impact on improving the fit between the measured tracer concentrations and simulated concentrations.
Simulation of groundwater age

• Four numerical methods are used to simulate groundwater age

• The fit between the groundwater model and apparent tracer ages is quite good

• Groundwater age within the deep aquifer systems is generally centuries old!
Objective 4
Quantify inter-aquifer mixing and estimate vulnerability
Recharge to the deep aquifers
Young groundwater is vulnerable...
Conclusion

• A complex 3D hydrostratigraphic model based on multiple datasources was constructed based on oil seismic methods.

• Correction for diffusion improved the fit between the apparent tracer ages and the simulated ages significantly.
  • Heterogeneity within the regional scale hydrostratigraphic units has major impact on the diffusive correction for tracer ages.

• The deep Miocene aquifer systems contain water ages generally centuries old.
  • Infiltration occurs throughout the catchment and the regional clay layers do not protect underlying aquifers from infiltration from the surface.
  • The aquifers are getting replenished with a high rate; even the Aquitanian aquifers are generally receiving between 50-100 mm/yr.