Unit 6:
Identification and assessment of pollution and uncertainties in groundwater modelling

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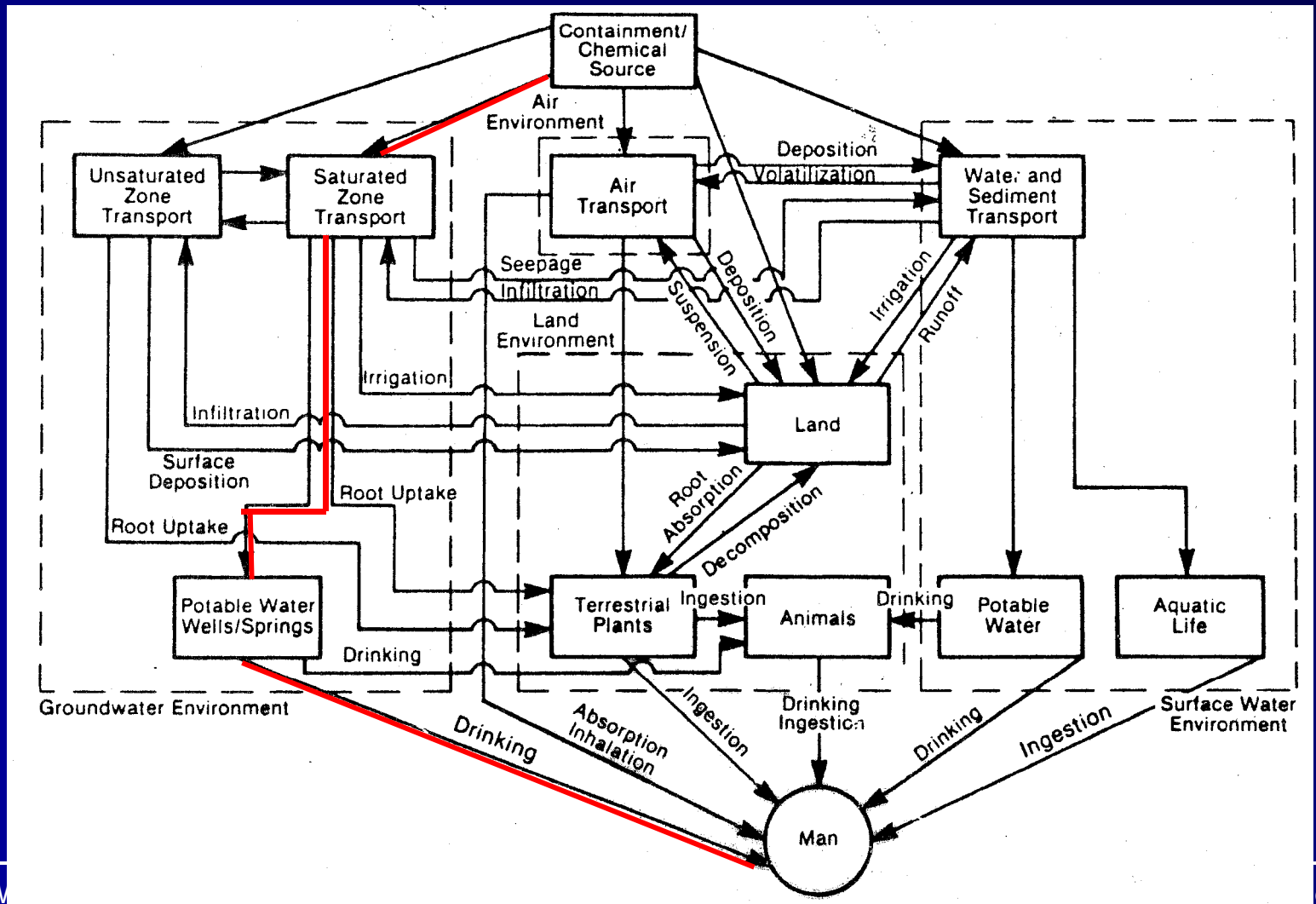
Structure of the Presentation

- Objectives
- Introduction and background
- Methodology
- Application
- Conclusion and results

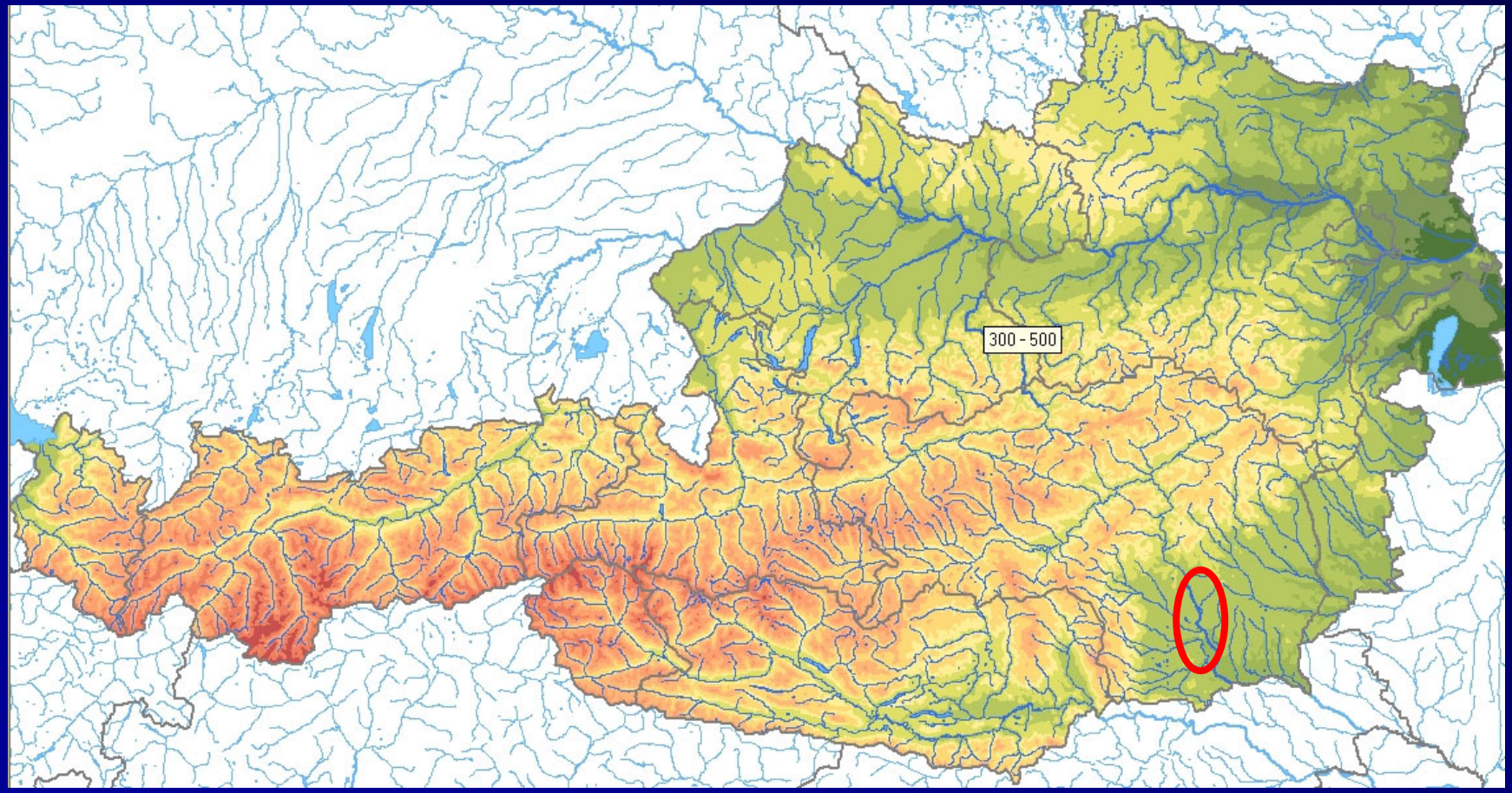
Objectives

- A regional groundwater system suffers from nitrate pollution originating from different sources
- The groundwater system is used for regional drinking water supply
- The pollution sources have to be identified and the spatio-temporal variability of nitrate concentration has to be assessed to assist in water supply management

From Exposure to Dose: Environmental Transport Processes



Introduction and Background



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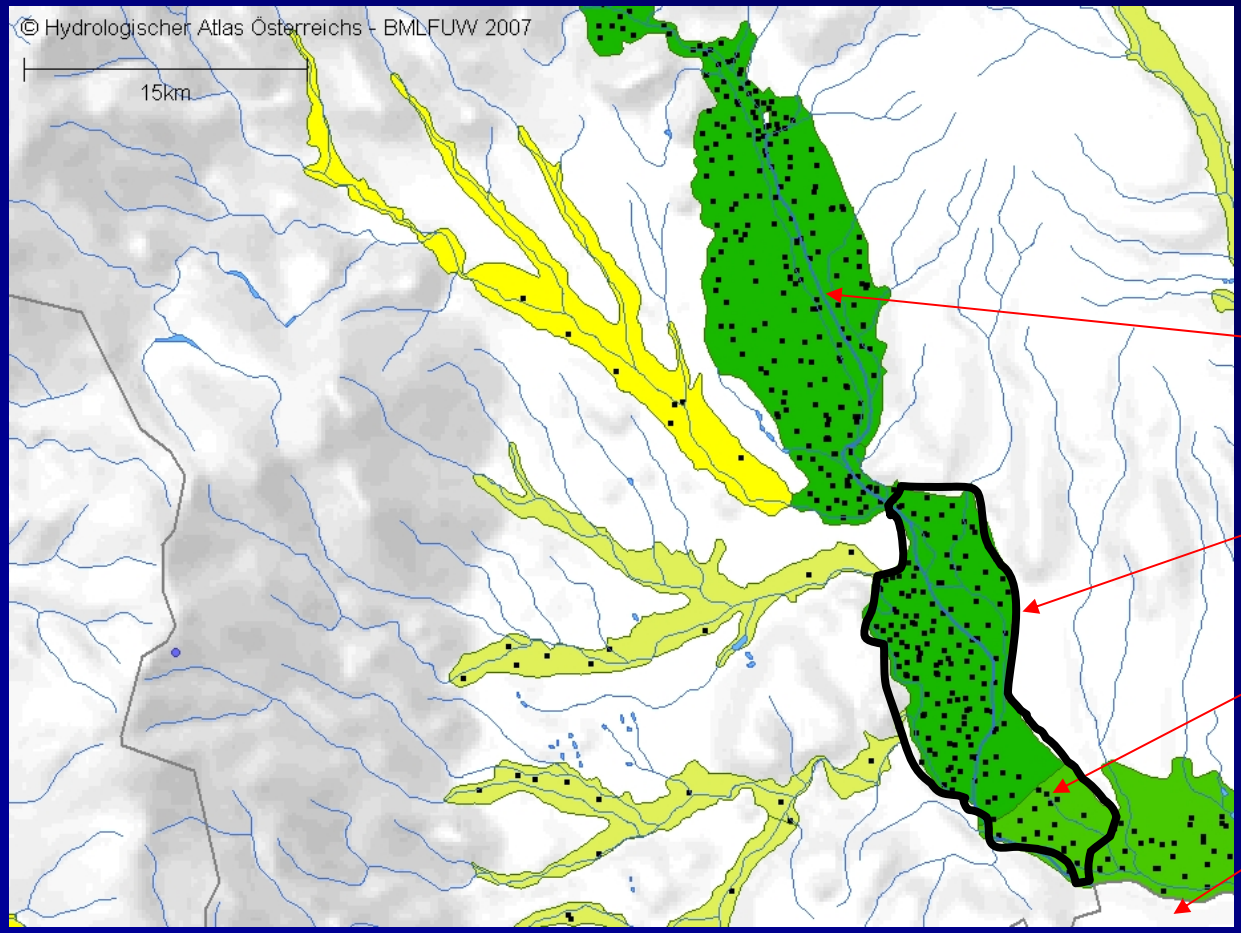


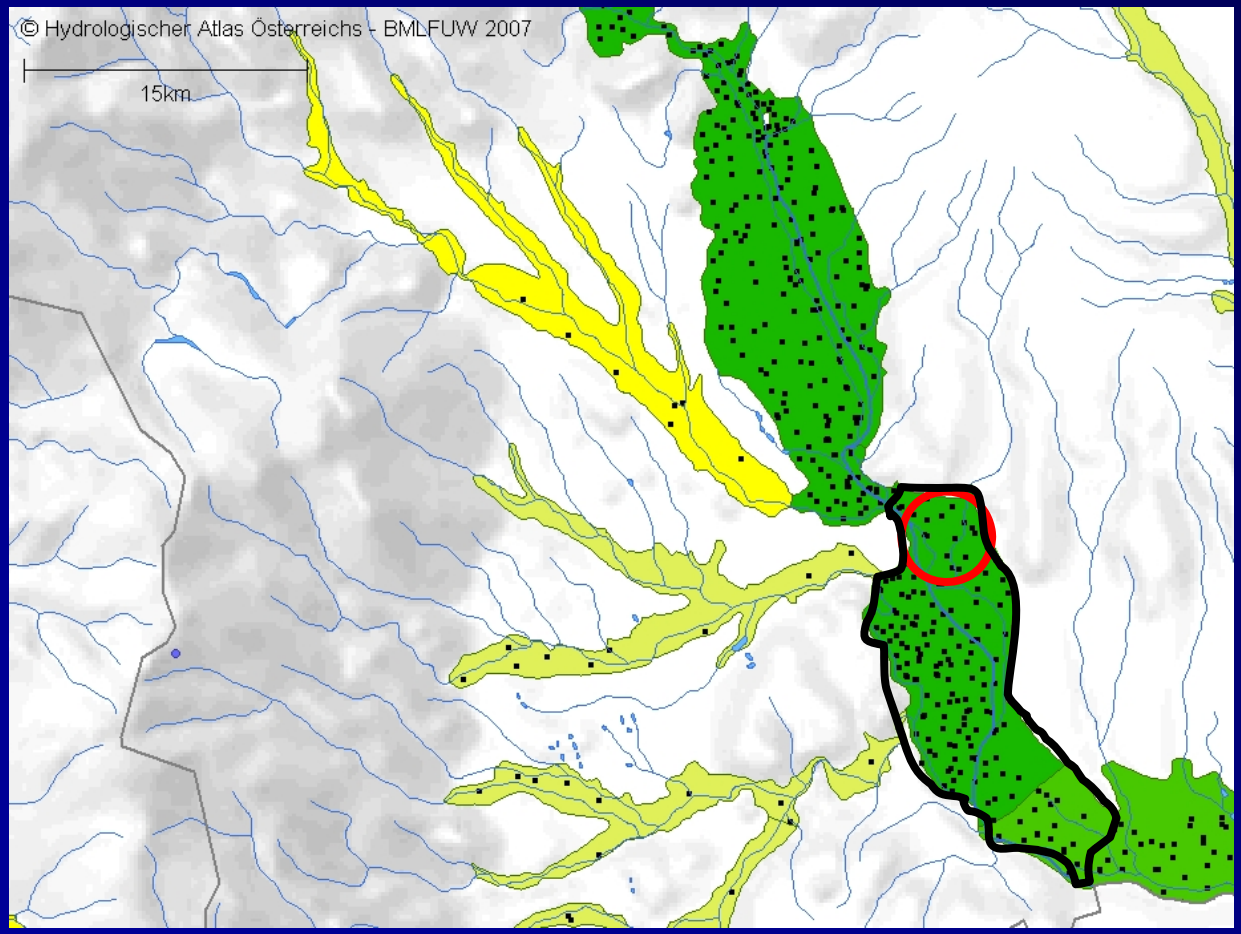
River Mur

Project area

Observation wells

Slovenija

Introduction and Background



Detailed analysis

Introduction and Background

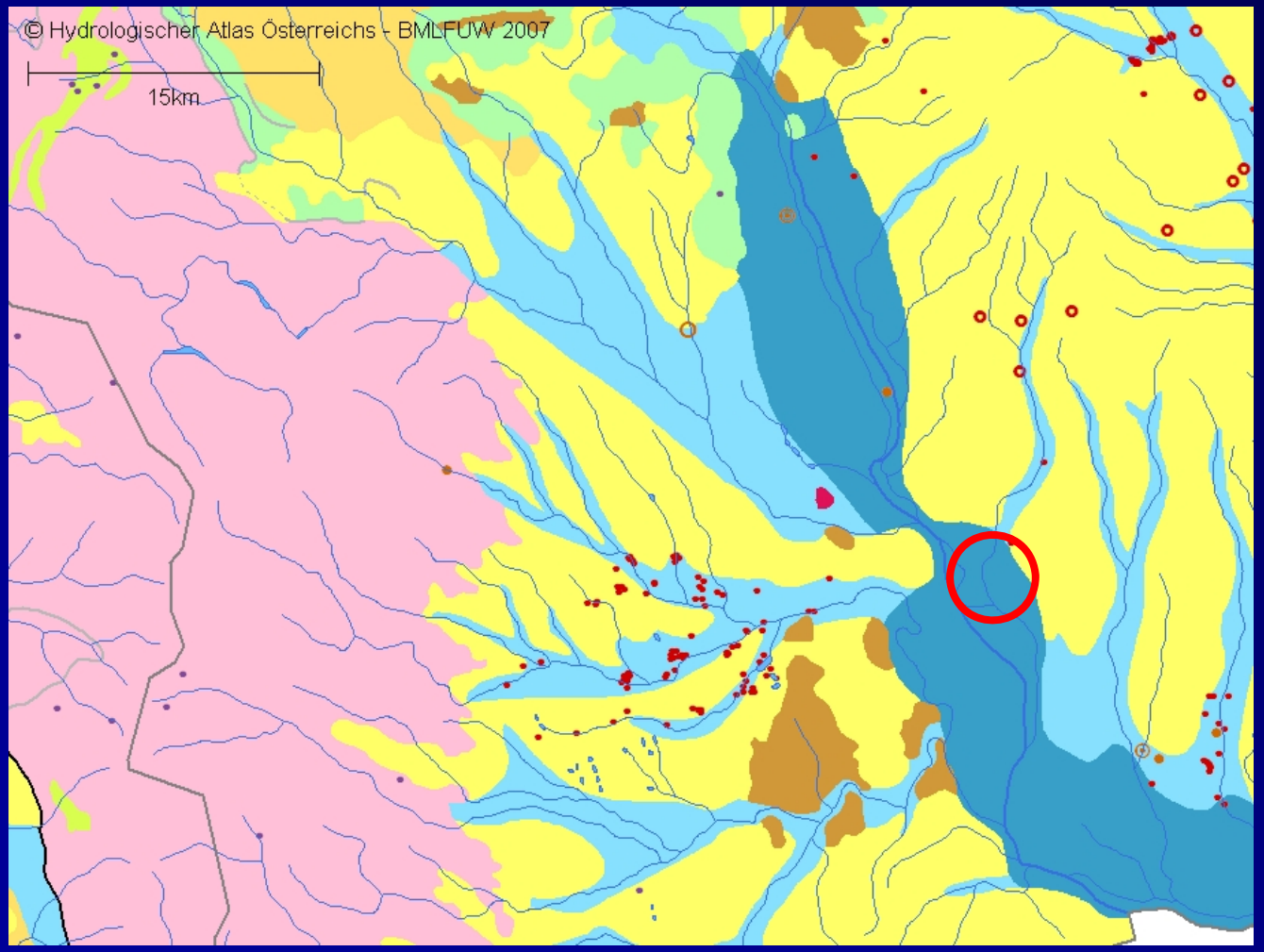
- A shallow alluvial aquifer along the river Mur is utilized for regional drinking water supply
- Intensive agricultural land use (corn, lifestock farming) has led to a continuous increase in nitrate loads and subsequently to an increase of nitrate concentrations of the groundwater
- The concentrations show a large spatio-temporal variabilty and the water managers would like to improve their knowledge about peaks in nitrate concentration

Tasks of the Study

- Origin of pollutants
- Flow of pollutants
- Uncertainty in estimates of nitrate concentratrions

Available Data

Hydrogeology of the Groundwater System



- Artesian wells
- Porous aquifer (gravel and sand)
- Porous aquifer (sand)
- Tertiary sediments (silt)

Land Use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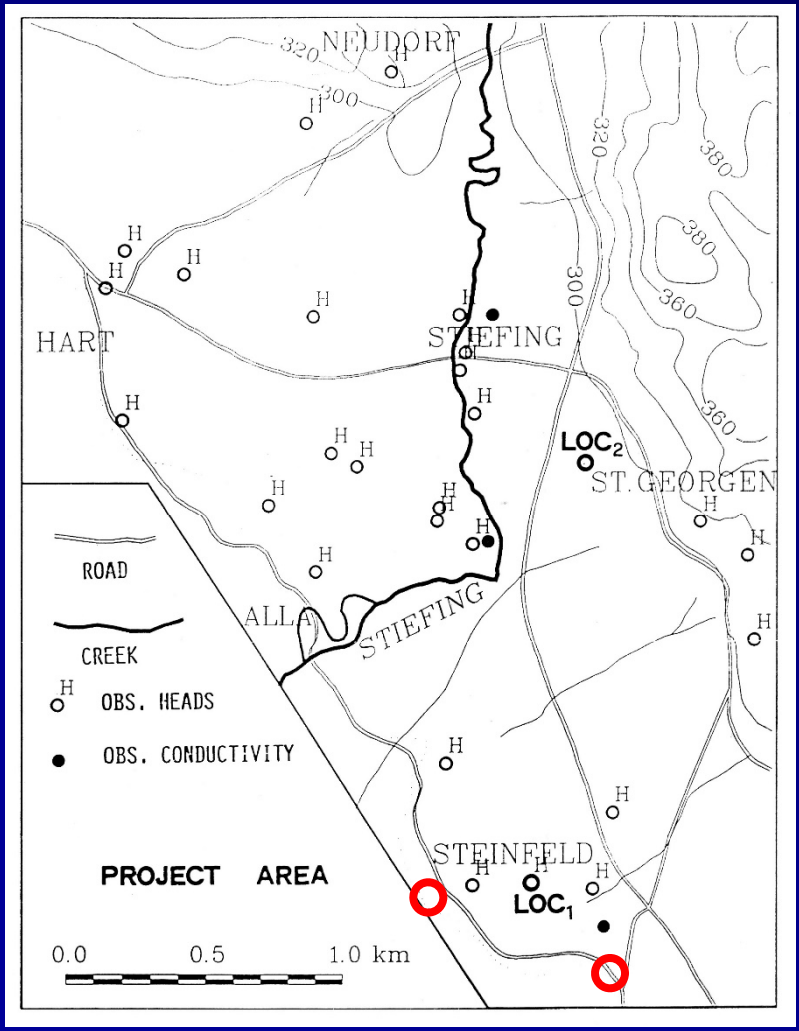
15km
Bodenbedeckung
Dicht bebaute Siedlu
Locker bebaute Siec
Weinbauflächen
Ackerland
Grünland
Nadelwälder
Laub- und Mischwälc
Feuchtflächen
Gletscherflächen
Vegetationsarme Flä
Offene Wasserfläche

Data Base

- Groundwater table is regularly monitored at 26 stations in a biweekly interval
- Groundwater quality at 22 locations monthly
  195 sampling points within the initial campaign
- Hydrogeological data
  3 pumping test locations in the project area
  8 from outside but near by
  12 boreholes and geoelectric data
- Soil map, land use data

The Project Area



2 of several water supply wells in the region

Methodology

- Analysis of sampling data to identify sources
- Geostatistical analysis of concentration data

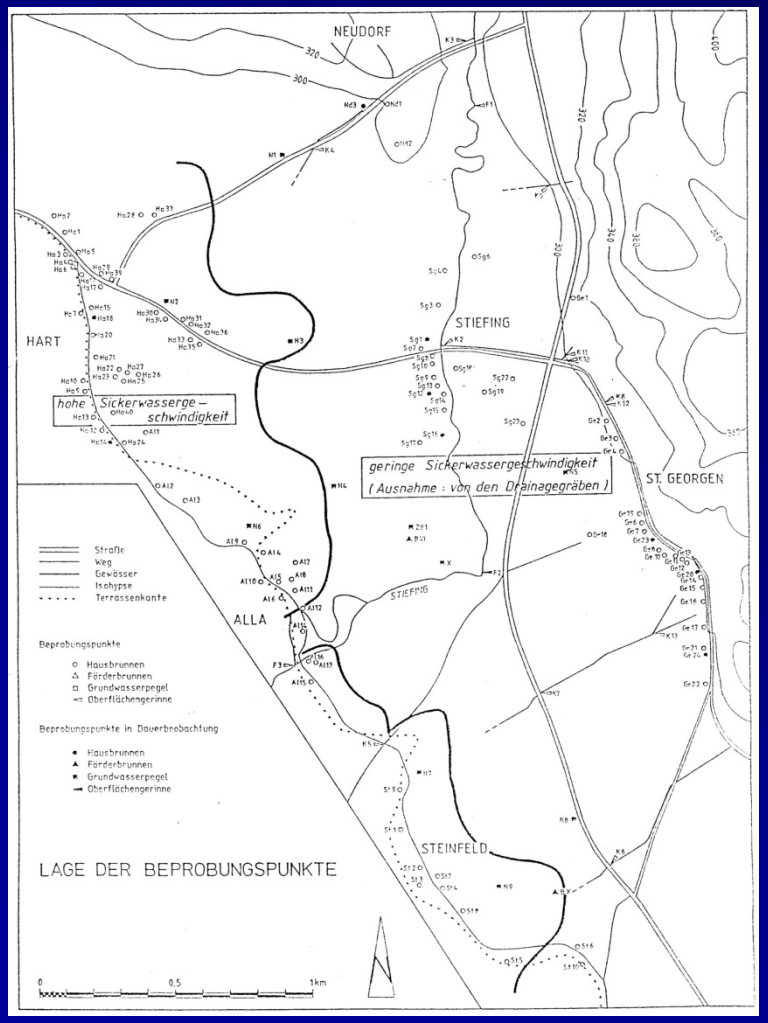
Methodology

- Analysis of sampling data to identify sources
- Geostatistical analysis of concentration data
- Application of a 2D-solute transport groundwater model
  What could it help ?
  Which additional conclusions can be drawn ?

Geostatistical analysis

- The nitrate concentrations vary in time and space
- The sampling points are quite irregularly distributed over the region
- The nitrate concentrations show a trend from North to South
- An extension of kriging „External Drift Kriging“ is applied

Detailed Monitoring Program



Within a monitoring campaign about 105 wells were sampled

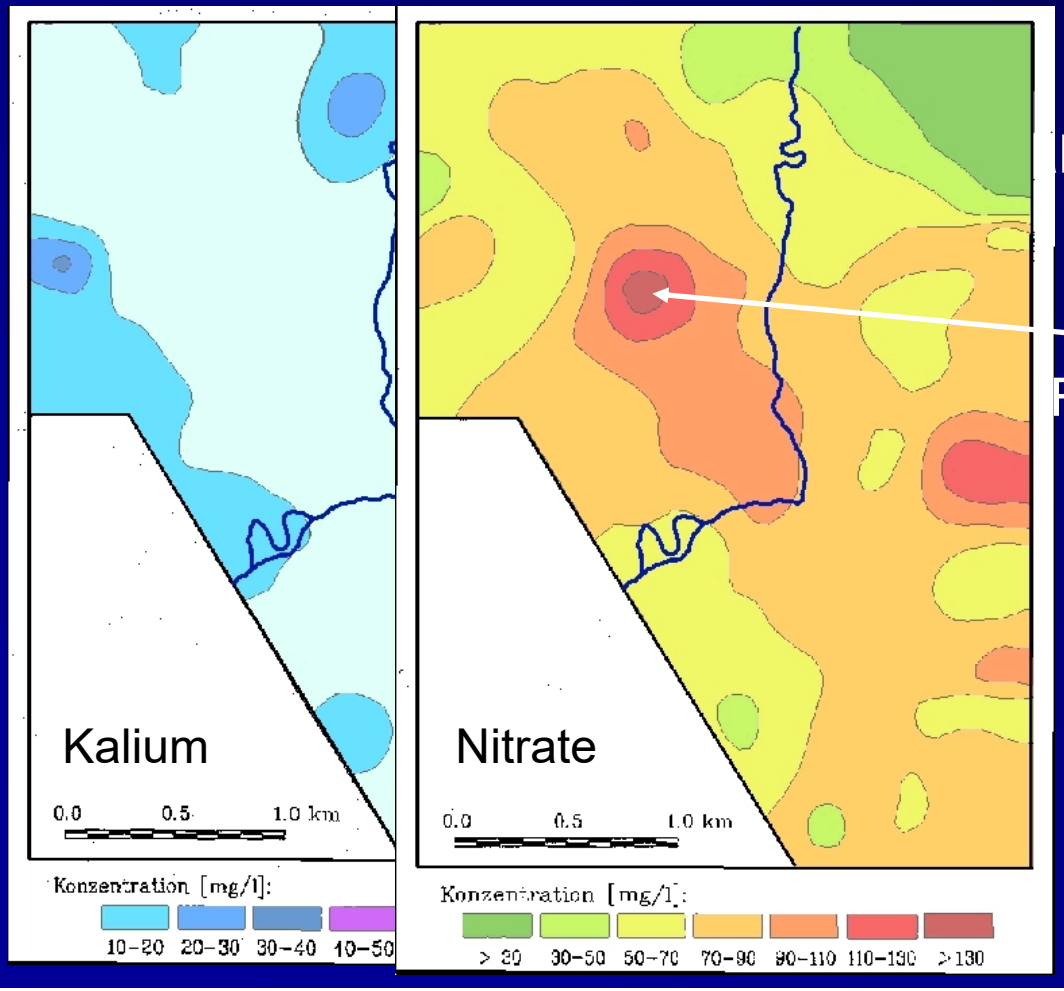
Irregularly distributed (clustering)

25 wells are regularly monitored

Water Quality Monitoring

- Temperature
- Electrical conductivity
- NH4
- NO3-Nitrate
- NO2-Nitrite
- Phosphorous (diss., particulate, Ortho)
- TOC
- Diss. Oxygen
- Hardness of water
- Carbonate, Ca, K, Mg, …..

Some Results from the Monitoring Program



king Septic Tank or Sewer

Fertilizer and manure application

Geostatistical analysis

- Nitrate data from first sampling campaign were statistically analysed
- Declustering (Journel, 1983) was applied due to irregular locations

Geostatistical analysis

$$\gamma^*(h) = \frac{1}{2n(h)} \cdot \sum W_{ij} \left(c(\underline{x}_i) - c(\underline{x}_j) \right)^2$$

$h = |\underline{x}_i - \underline{x}_j|$

$W_{ij} = 1$ for $h < 2\ ho$

$W_{ij} = \frac{1}{n_i \cdot n_j}$ else

For small distances a regular variogram estimation
For large distances an average is assumed

Geostatistical analysis

- Kriging is a BLUE estimator and it provides both

  estimation of the expectation value

  estimation of the uncertainty
  (estimation variance)

Geostatistical Analysis

- The data set may exhibit a spatial trend

  Universal or External Drift Kriging

- The data set may exhibit spatio-temporal features

Geostatistical Analysis

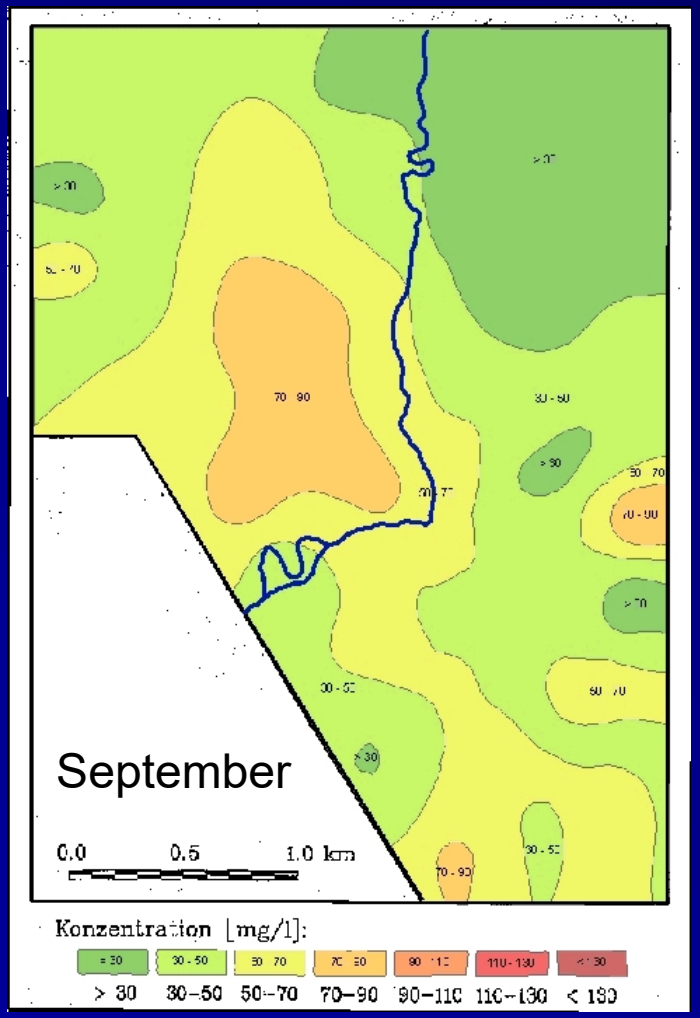
Spatial trend Random part

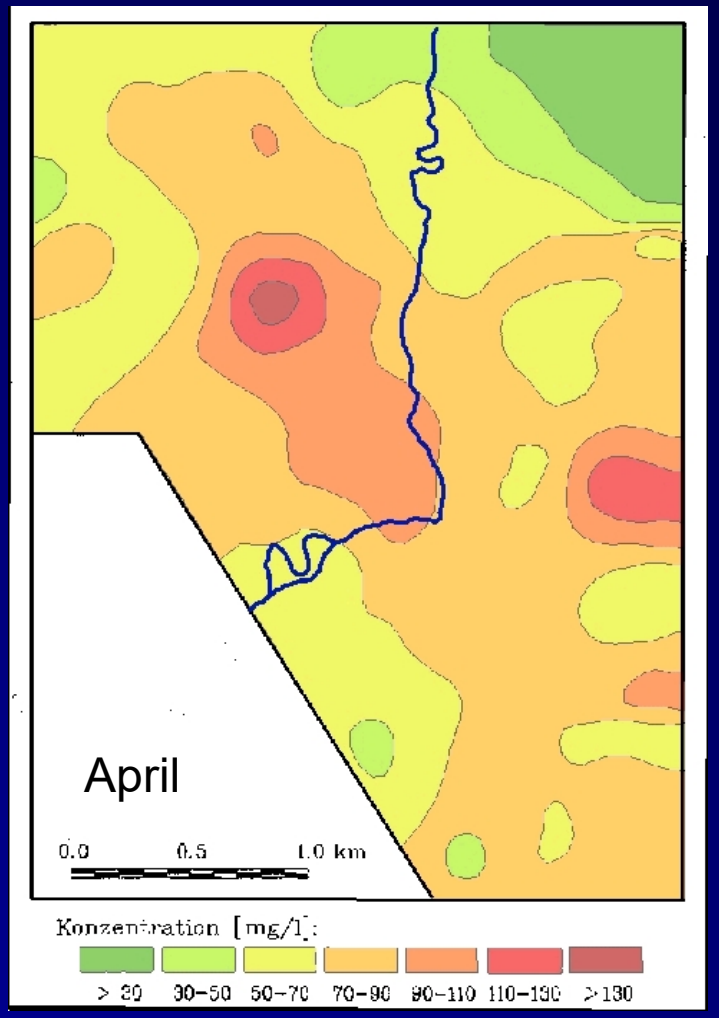
$$h_t(\underline{x}) = u_t(\underline{x}) + R_t(\underline{x})$$

Spatial trend $u_t(\underline{x}) = a_{j,t}\ f_j(\underline{x})$ Time dependent

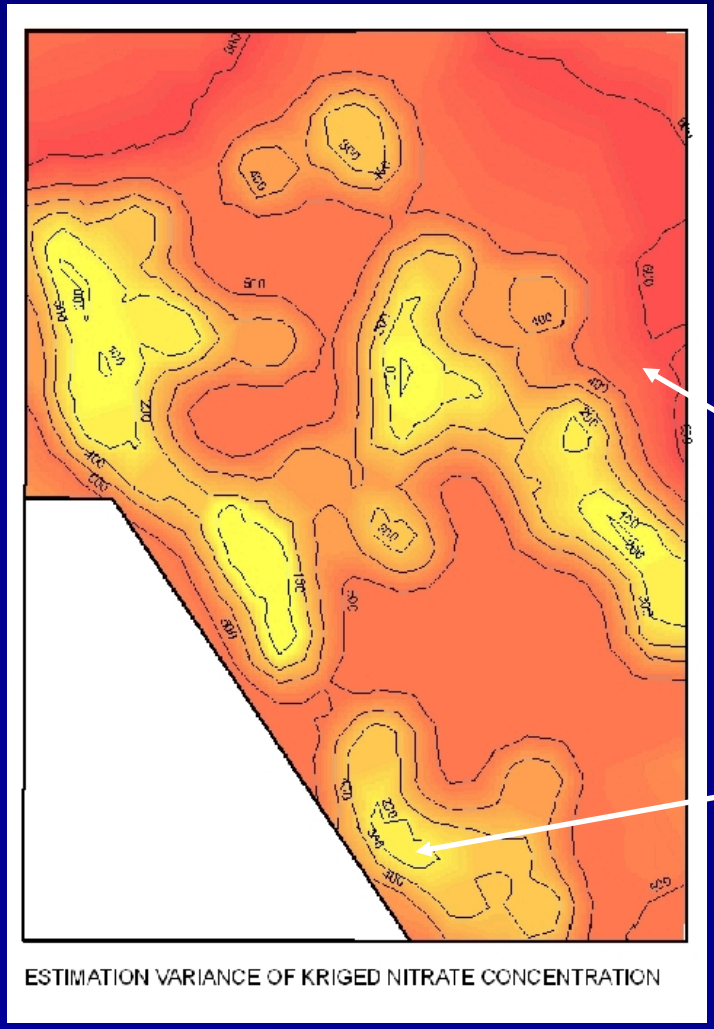
$$\gamma^*(h) = \frac{1}{2N(h)T} \Sigma\ \Sigma \left(R_r(\underline{x}_i) - R_t(\underline{x}_j)\right)^2$$

Spatial Distribution of Nitrate Concentration





Results from Geostatistical Analysis



ESTIMATION VARIANCE OF KRIGED NITRATE CONCENTRATION

High Uncertainty (22-26 mg/l)

Low Uncertainty (14 mg/l)

Conclusions from the Statistical Analysis

- Pollution sources could be identified
- Nitrate pollution is highly variable in space and time
- The estimation uncertainty is very large

- How could we improve our knowledge about the system ??

Application of a 2D Solute Transport Groundwater Model

L. F. Konikow and J. D. Bredehoeft, "Computer Model of Two-Dimensional Solute Transport and Dispersion in Groundwater," Techniques of Water-Resources Investigations of the USGS; Chapter C2, Book 7, 1978, p. 90.

- The Konikov-Bredehoeft model was used

Groundwater flow equation

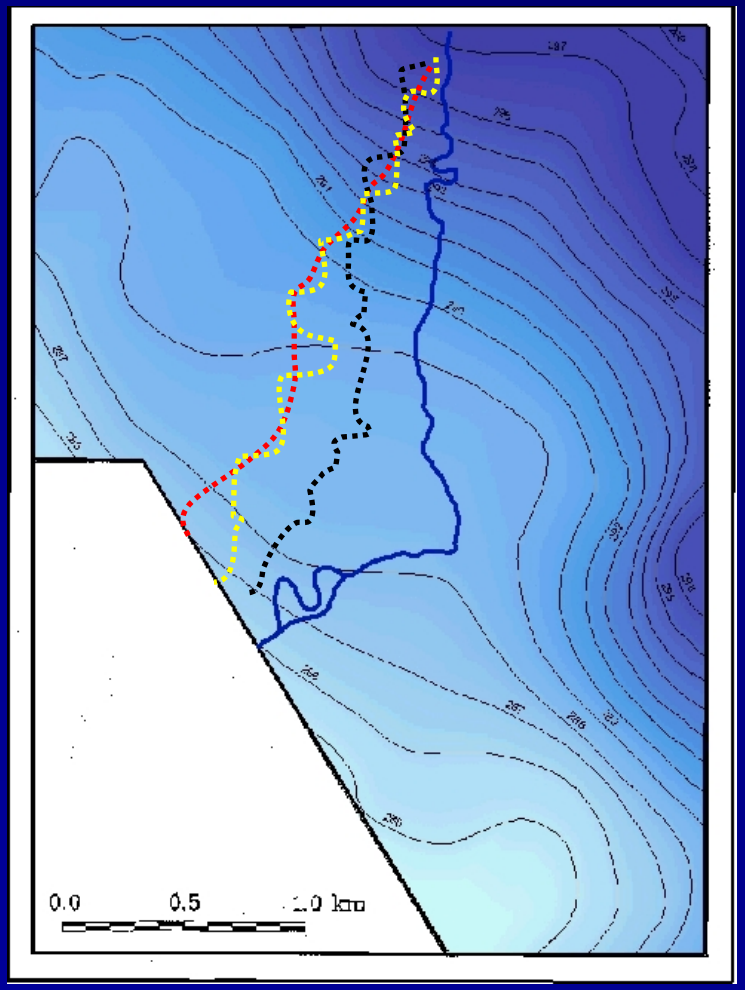
$$\frac{\partial}{\partial x_1}\left(bK_{11}\frac{\partial h}{\partial x_1}\right)+\frac{\partial}{\partial x_1}\left(bK_{12}\frac{\partial h}{\partial x_2}\right)+\frac{\partial}{\partial x_2}\left(bK_{21}\frac{\partial h}{\partial x_1}\right)+\frac{\partial}{\partial x_2}\left(bK_{22}\frac{\partial h}{\partial x_2}\right)=S\frac{\partial h}{\partial t}+W(x_1,x_2,t)$$

Transport equation

$$\frac{\partial}{\partial x_1}\left(bD_{11}\frac{\partial C}{\partial x_1}\right)+\frac{\partial}{\partial x_1}\left(bD_{12}\frac{\partial C}{\partial x_2}\right)+\frac{\partial}{\partial x_2}\left(bD_{21}\frac{\partial C}{\partial x_1}\right)+\frac{\partial}{\partial x_2}\left(bD_{22}\frac{\partial C}{\partial x_2}\right)$$
$$=\frac{\partial}{\partial x_1}\left(bCV_{x_1}\right)+\frac{\partial}{\partial x_2}\left(bCV_{x_2}\right)+\frac{\partial(Cb)}{\partial t}+\frac{C'W}{\in}$$

Dispersion introduces additional uncertainty

Flow and Dispersion



Groundwater flow
(perpendicular to iso-lines)

Particle movement (yellow and black)
(plus a random component)

Parameter Estimation

- Based on the few local data plus from outside data variograms were estimated for
  - hydraulic conductivity,
  - bottom layer,
  - heads (initial and boundary conditions)

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- Based on the few local data plus from outside data variograms were estimated for
  - hydraulic conductivity,
  - bottom layer,
  - heads (initial and boundary conditions)

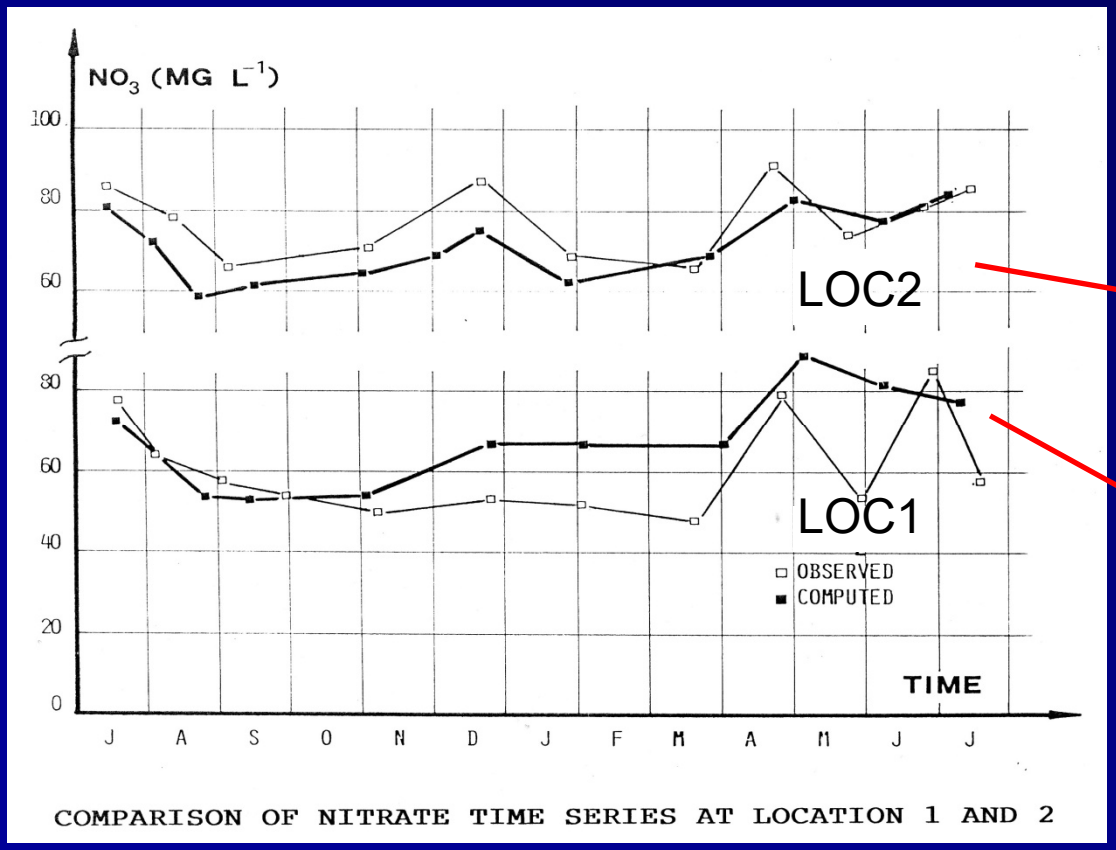
- Due to limited data there is a large uncertainty in these parameters

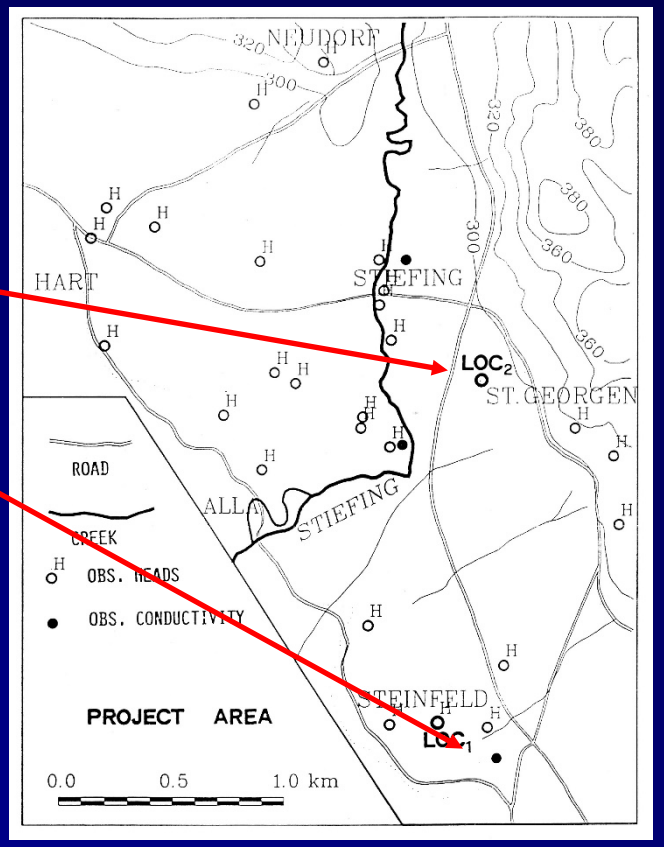
Model Calibration

- Time series of heads and concentrations should be well reproduced
- The spatial pattern should be well reflected

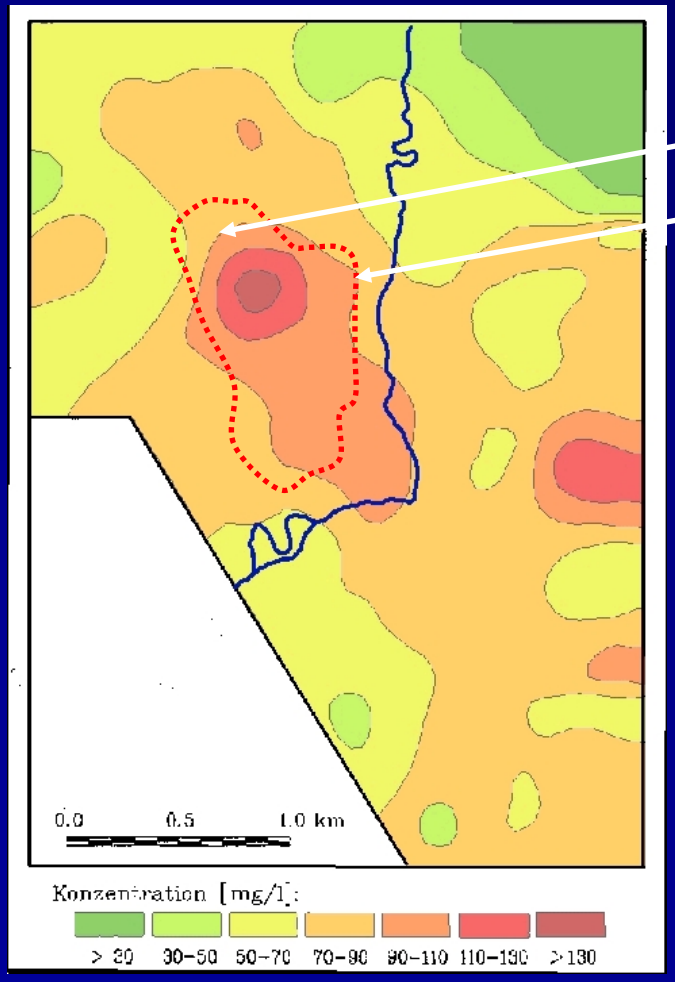
Model Calibration

- Observed heads and concentrations in time





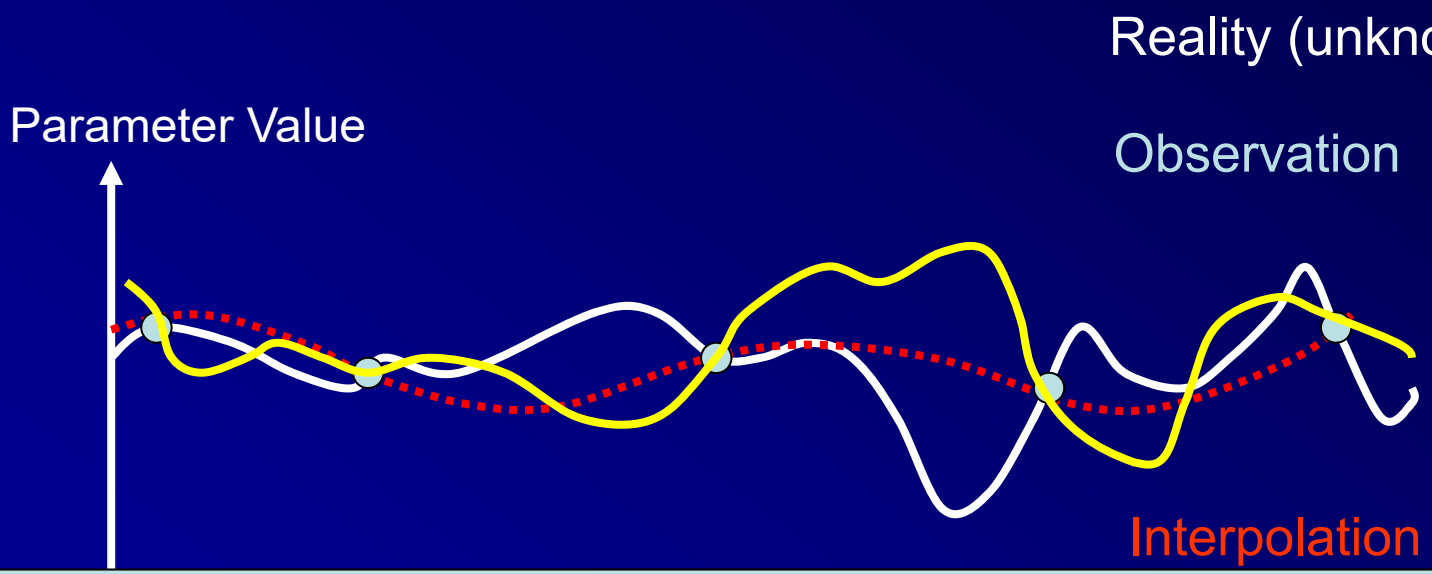
Model Calibration with Respect to Pattern



Contour lines of same concentration level
From model
From observation (interpolation)

Ratio of overlapping area to outside areas

Uncertainty in Model Parameters



We assume that measurements are perfect

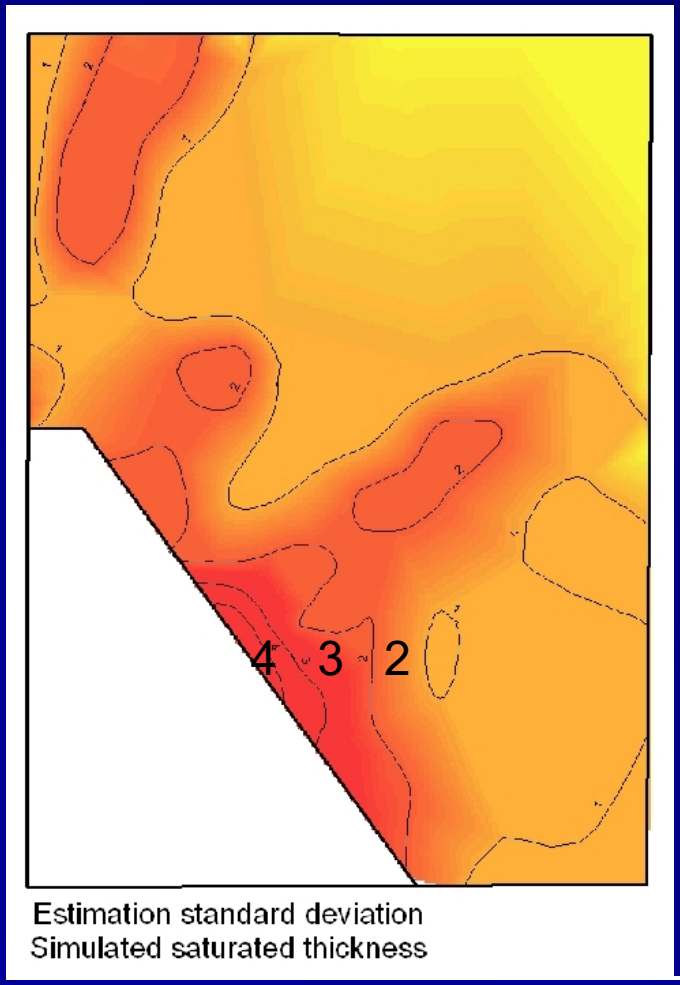
Conditional Simulation

- Hundreds of different bottom layers, hydraulic conductivity fields, initial conditions are generated
- All of them have the same probability and fit the observations
- Each input results in a different GW model output
  (flow field and concentration pattern)

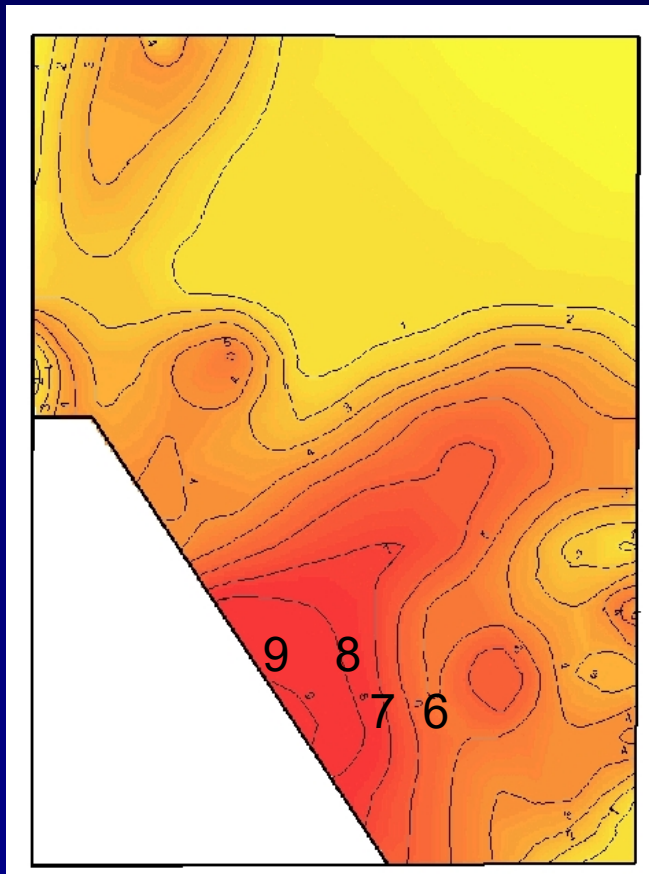
Results from Simulation

- For each grid point we get hundreds of NO3 time series
- We can estimate the uncertainty in the model output
- We can see the importance (significance) of an input parameter for the output (sensitivity)

Estimation Uncertainty of Nitrate (mg/l)

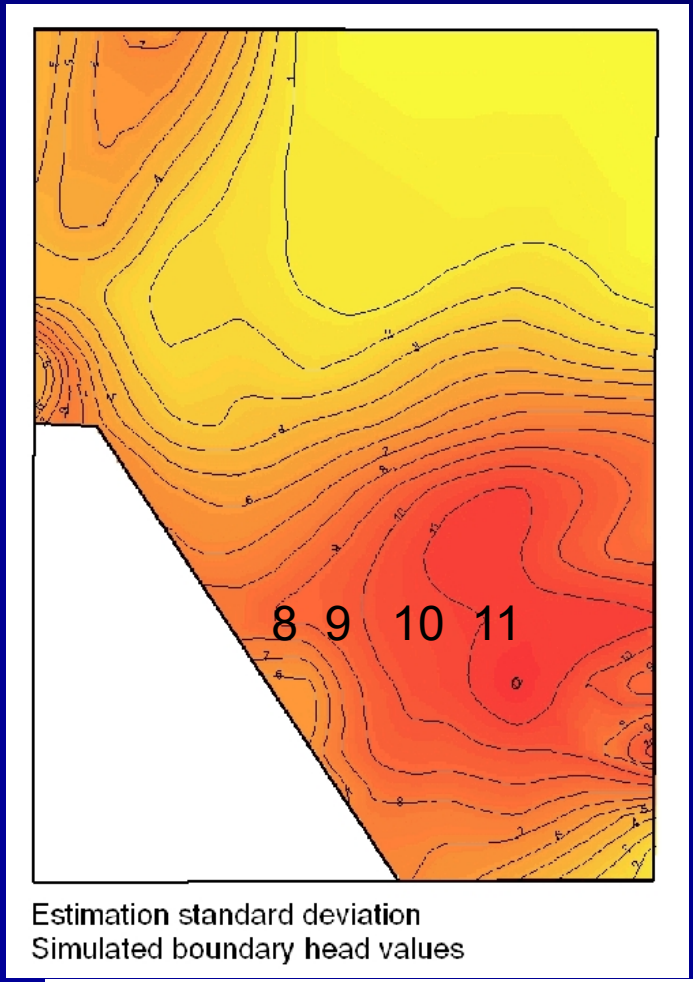


Estimation standard deviation
Simulated saturated thickness

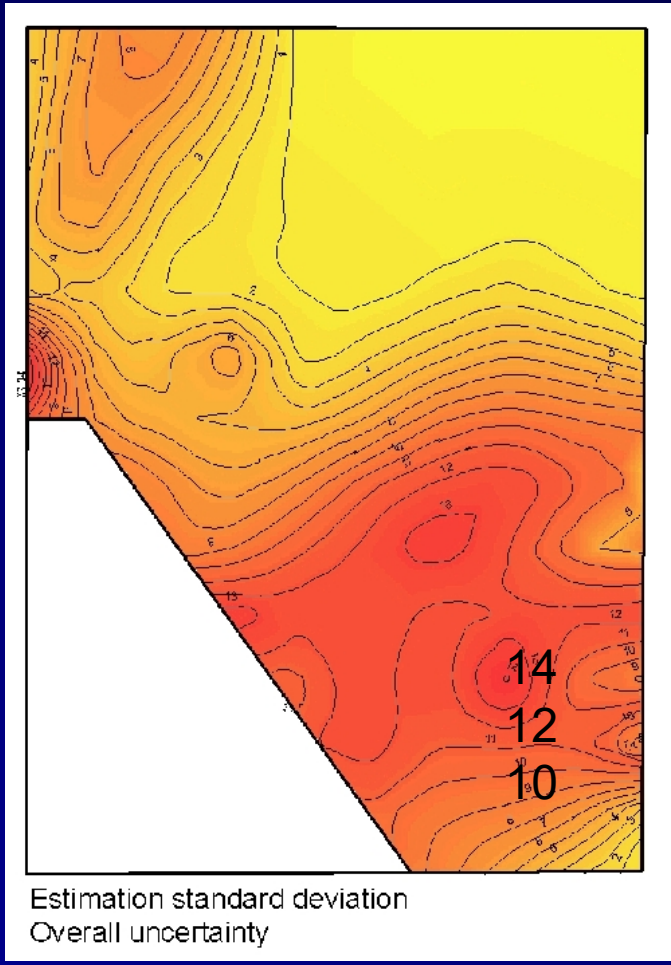


Estimation standard deviation
Simulated K values

Estimation Uncertainty of Nitrate (mg/l)

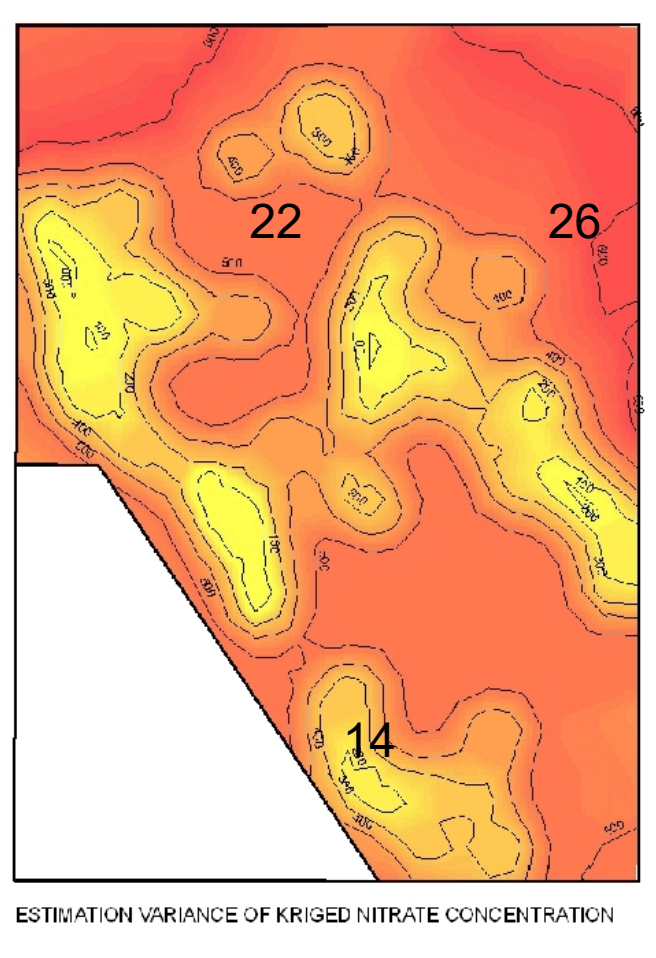


Estimation standard deviation
Simulated boundary head values



Estimation standard deviation
Overall uncertainty

Comparison of Geostatistics with Model



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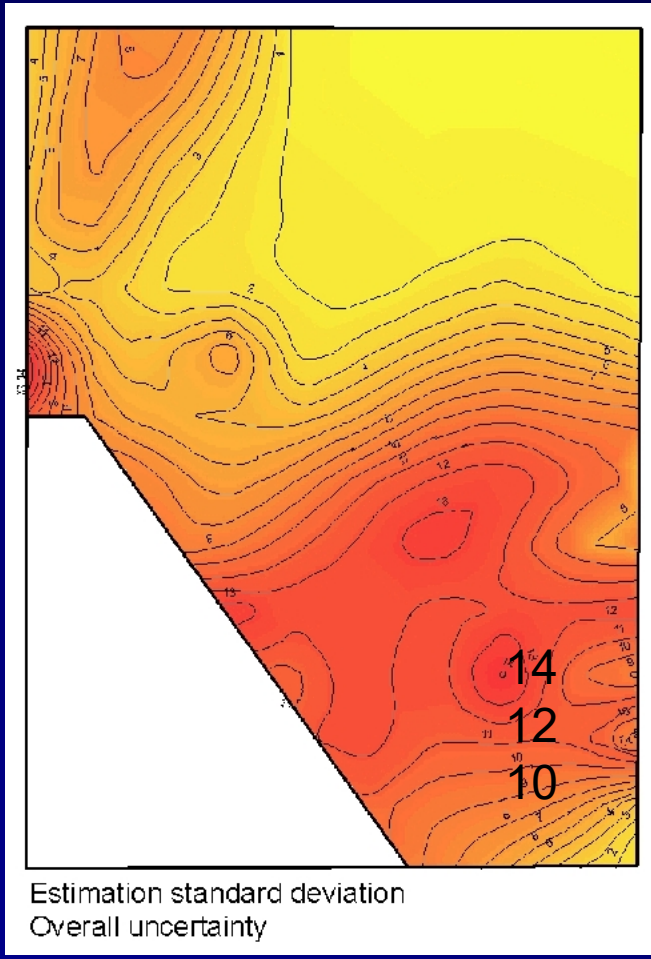

Estimation standard deviation
Overall uncertainty

Conclusions

- The overall uncertainty in Nitrate concentrations is larger in the geostatistical analysis than in the GW-model output
- Why ?

Conclusions

- The overall uncertainty in Nitrate concentrations is larger in the geostatistical analysis than in the GW-model output
- Why ?
- We have included additional information (data and knowledge e.g. flow and transport model)

Conclusions

- Here, heads (initial and boundary conditions) are the largest source of uncertainty
- Then hydraulic conductivity
- Bottom layer information is not so relevant

Assesing the impacts

- Until now the probability of exceeding a pollution level has been estimated
- Possible consequences:
  - New wells have to be drilled
  - Water purification systems have to be developed
  - Water transfer from another region
  - ….

Summary

- A groundwater pollution problem was analysed by geostatistical methods and by a physically based approach
- Estimates of pollution level as well as the respective uncertainties are available
- The incorporation of a model had reduced the overall uncertainty

Thank you for your attention