Quantifying Risk for Groundwater Modelling
From Deterministic to Stochastic Geo-models

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Objective

• Discuss the role for stochastic geo-models in hydrogeologic studies
Background

- From reservoir modelling...

- Great well control
- Seismic data (3D)
Background

• From reservoir modelling...
  • Grana and Dvorkin (2011): Geostatistical simulations in seismic reservoir characterization studies
Background

• ... to hydrogeology studies

• Scale of the problem
  • Regional study: 10’s to 1000’s km (water supply)
  • Local study: 10’s to 100’s m (solute transport, wastewater)

• Level of heterogeneity

• Well control
  • Hydraulic parameters availability

• Time / economic incentive
Background

• ... to hydrogeology studies
• Heterogeneity vs Data / Model Resolution

(Singh and Srinivasan, 2014)

(Vanessa et al., 2009)
Regional Models

- Interpolation of 2D horizons from well picks, constrained by knowledge of geology
  - Build 3D grid model by filling between the surfaces (Gocad)
- Model is the “most-likely” representation of stratigraphy / hydrostratigraphy at regional scale
  - Averaging local groundwater flow pattern
Definition of geo-model

- 3D model representation of facies representing:
  - geology
  - petrophysics
  - hydrostratigraphy

- Assignment of facies to all cells of the 3D model representation
  - How to assign facies?
Definition of geo-model

1. Deterministic Approach:
   - 1 facies per unit
   - Assume homogeneous parameters for each unit / layer
   - No uncertainty
   - Kriging
   - 1 best-fit model (least error)
   - Uncertainty evaluated but not considered

2. Stochastic Approach:
   - Multiple realizations
   - Uncertainty considered
# Deterministic Geo-models vs Stochastic Geo-models

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<td>Honors wells</td>
<td>Honors wells Honors histogram and probability</td>
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<td>One unique “best-fit” geo-model</td>
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<td>Mapping Regional-scale geo-models</td>
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Modified from Dubrule (2003)
Stochastic Geo-models

- Objective: Build several “equally-probable” geo-models

- All realizations are equally probable, even if one “looks” better
- Probabilistic approach of uncertainty and risk analysis for:
  - groundwater modelling
  - Solute transport problems

Doliguez et al. (2014)

Jablonski (2012)

AAPG Memoir 31

NNEL PATTERNS
rearward and braided river channels
3 Case Studies
Stochastic Geo-models

• Quantify risk for groundwater modelling in 3 different contexts:
  • Site 1: Water Quality Impacts to a residential well
  • Site 2: Thermal plume migration and potential surface water/groundwater interaction from a Steam-Assisted Gravity Drainage (SAGD) Project
  • Site 3: Wastewater migration away from disposal wells toward nearby source well in same aquifer
Site 1: Project Area

- for confidentiality purposes:
Site 1: Project Area

- **Regional Model**
  - 2.0 km x 2.5 km

- **Local Model**
  - 400 m x 300 m
  - Assess risk of near-surface water quality impacts
Layered model with sandstone domestic use aquifer (DUA) at base

Structure intended to capture presence of sand lenses
  • critical in characterizing groundwater travel and migration of chloride plume concentrations

Some heterogeneity
  • random Kzone assignments to upper Till unit
  • K value of each zone tuned by PEST (Model Independent Parameter Estimation)
Site 1: Model Conceptualization

- Hydrogeologic units interpreted along NS (top) and EW (bottom) sections
  - Clay
  - Clay Till
  - Sand, silty sand
  - Sandstone
  - Siltstone

2D cross-sections
What in 3D? out of 2D plane?
Site 1: Objectives

- Build probable representations of hydrofacies distribution
  - Integrate “hard” knowledge at boreholes with “soft” knowledge of geology (trends, regional geology...)
  - Heterogeneous models of geology
    - Sand vs Till facies

- Quantify uncertainty:
  - Geology
  - Hydraulic parameters
Site 1: Initial Parameters

- 3D Cartesian Grid 40 x 30 x 80 cells
- Use boreholes to develop layer structure and units thickness

- Clay
- Silt
- Sand
Site 1: Initial Parameters

- Proportions of hydrofacies: Histograms
- Geometrical trend: Indicator Variograms
  - vertical
  - horizontal
Site 1: Initial Parameters

- Data at local scale, not good to determine larger scale structures
- Knowledge of geology: sand bodies with trend in EW direction
  - Discussions with the project’s geologist
  - To replace parameters for horizontal variograms
Site 1: Hydrofacies Modelling

- Sequential Indicator Simulations (SIS)
  - Simulate many realistic geo-models based on statistics from borehole logs and knowledge of geology
Site 1: Hydraulic Parameters

• Simulate the initial spatial distribution of hydraulic parameters within each hydrofacies
  • For input in FeFlow (PEST calibration)
  • Optimization of hydraulic conductivity parameters: K or a proxy to K (soil saturation %)
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3 selected realizations (cross-section)
Site 1: Hydraulic Parameters

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From 1 realization...
Site 1: Hydraulic Parameters

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Site 1: Conclusions

- Ability to assess different probable scenarios of contamination at local scale
  - Evaluate possible volumes of contaminant
  - Quantify risk by evaluating the whole range of possible outcomes

- Conduct risk analysis by simulating different scenarios of propagation of contaminant in the near-surface geology
  - Evaluate probable paths of propagation
Site 2: SAGD Project

- Phase 1
- Phase 2
- Phase 3
- Heat migration across the wellbore
- Water well
- Aquifer
- Aquitard
- Surface water body

from N. Molina Giraldo
Site 2: Stochastic Geo-modelling

- Multiple-Point Statistics simulations (MPS)
  - Training Image: Knowledge of depositional trends to guide simulations (can be hand-drawn image, seismic-derived image...)
    - Channel-type structure
    - Not regionally correlatable - limited length and width
    - Maximum thickness 25m (based on well logs)
    - 10% sand (based on well logs)

[Diagram of 3D Training Image]
Site 2: Connectivity of Sand Hydrofacies

- Simulate 100 probable scenarios of sand facies distribution

Horizontal slice of 3 realizations
Site 2: Connectivity of Sand Hydrofacies

- Probability of connectivity to surface water body

![Graph showing connectivity probabilities for Steaming Pad A and B](image)

**Steaming Pad A**
- Probability of Sand (blue)
- Probability Connectivity to Surface Water Body (pink)

**Steaming Pad B**
- Probability of Sand (blue)
- Probability Connectivity to Surface Water Body (pink)
Site 3

- Evaluate rate and extent of wastewater migration away from disposal wells toward nearby source well in same aquifer.
  - Assess differences in disposal fluid arrival time and concentration at source well
Site 3: Variability of Geo-models

Blue = clay
Red = sand
Green = transition
Black = below Pre-Cretaceous Unc.
Site 3: Variability of flow models

- Simulated Concentration of disposal fluid at source well
- Stochastic geo-modelling allows computing the range of concentrations likely to be sourced
To conclude...

- Find best way to integrate available data
  - Deterministic or Stochastic Approach
  - Honor hard data
  - Hydrofacies (sand vs clay)
  - Respect geological knowledge from geologist

- Stochastic Geo-models allow to run Connectivity Analysis
  - Probability of:
    - Facies occurrence
    - Connectivity between Source/Receptor
To conclude...

- Quantify risk by considering the uncertainty and evaluating the variability of stochastic geo-models

- Compute range of possible outcomes
  - minimum - mean - maximum volumes
  - P10 - P50 - P90
Any Questions?

Please ask...

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