DEVELOPING CONCEPTUAL MODELS FOR FLOW AND TRANSPORT IN BEDROCK AQUIFERS USING DEPTH-DISCRETE HYDRAULIC AND TRACER TRANSPORT MEASUREMENTS

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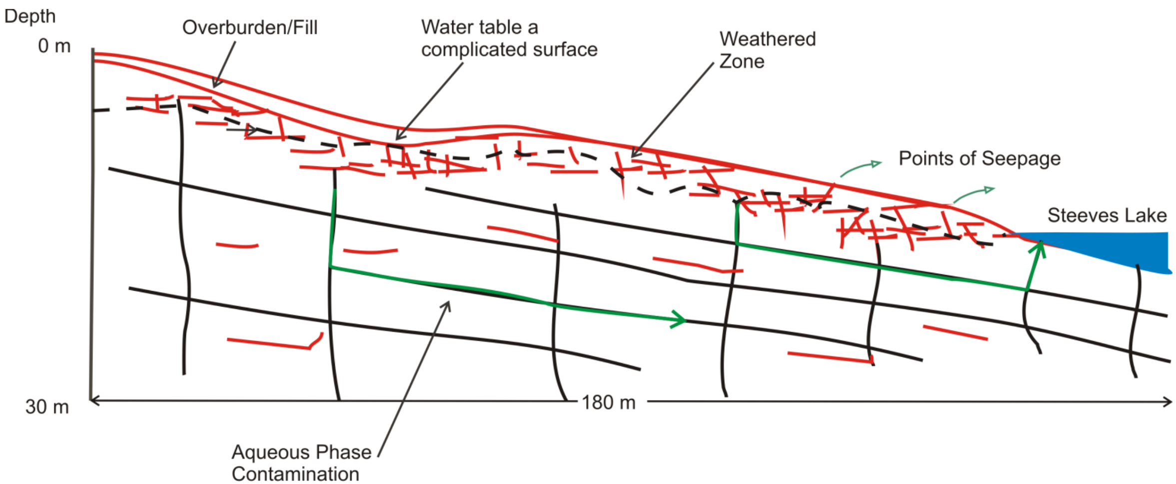
Attributes of Bedrock Aquifers

- Flow and transport are dominated by individual fracture features.
- Properties vary over many orders of magnitude, particularly fracture aperture, groundwater velocity, matrix porosity.

Characterization of Bedrock Sites

- Contaminated sites are particularly difficult as the use of bulk parameters does not work, and evaluation of discrete transport pathways is necessary.
- Tracking where contamination has gone is easy (now); predicting where it will go next, much more difficult.



Definition of a Conceptual Model

- Nuclear waste industry has struggled with meaning for years.

  "A depiction (schematic or verbal) of the defining features of the groundwater flow and transport system as understood at the time of formulation"

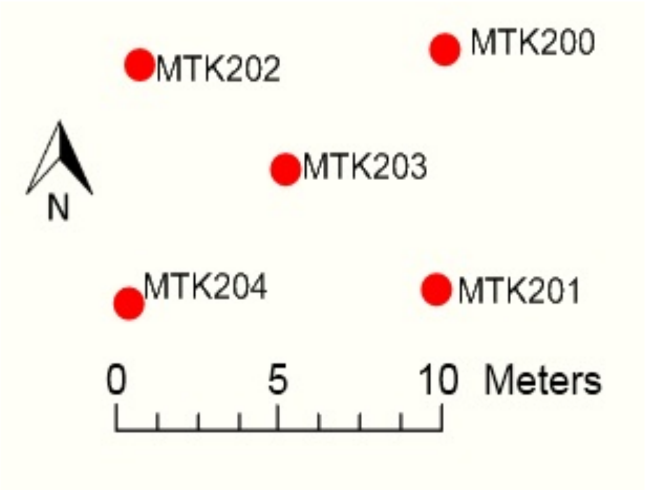
- Results in multiple, evolving conceptual models.
- Determine what the conceptual model will be used for.
  - ie. plume remediation, source remediation, litigation, predicting off-site migration, risk analysis

Objectives

- Can we use hydraulic methods to accurately predict contaminant transport pathways?
- Develop three distinct conceptual models. One based on single-well tests, one based on inter-well tests, and one based on inter-well tracer experiments.
- Students involved: Morgan Schauerte, Reid Smith, and Stephanie Demers.

Field Site

- The site is located in Kingston, Ontario, at a former industrial equipment store yard.
- The site is underlain by 4-6 metres of clay and approximately 22 metres of flat-lying Gull River limestone which overtops Precambrian granite.
  - 5 HQ sized wells were drilled using diamond coring to 30 m.
  - The wells were drilled in an "Five Star" formation down gradient from the estimated location of a TCE plume.



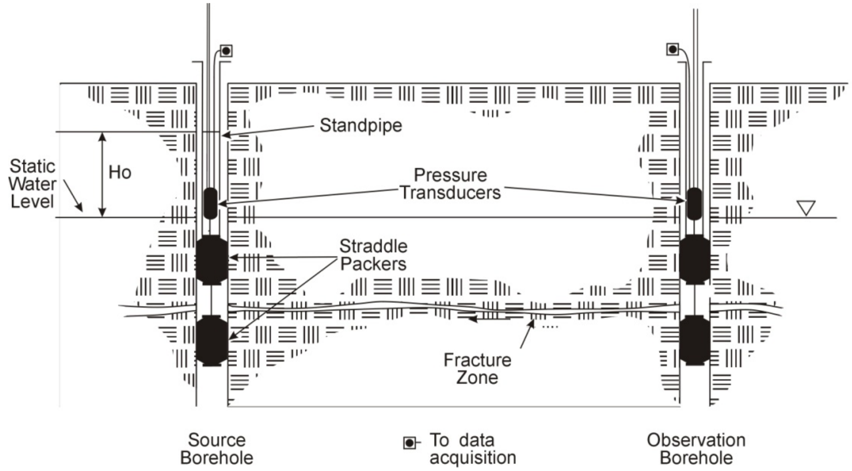
Tools

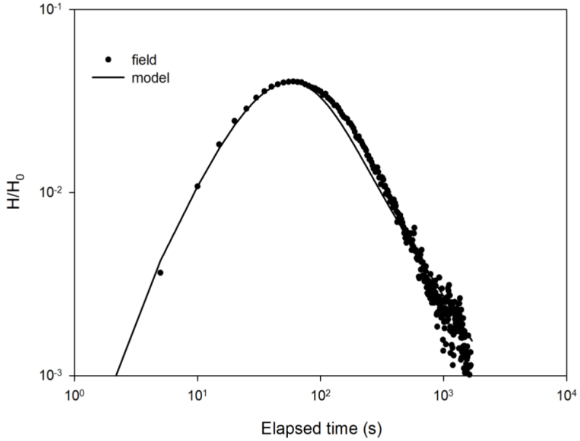
- Constant-head testing.
- Straddle packer system was used with a packer spacing of 0.85 m.
- In total, 87 contiguous intervals were tested using this approach amongst the five boreholes.
- Discrete fractures interpreted from borehole camera and core.


FIGURE 3.3.1: Straddle Packer System

Tools

- Pulse interference testing.
- straddle packer system was used in both source and observation wells, with an approximate packer spacing of 2.5 meters.
- 61 pulse interference tests were performed, using MTK 203 and MTK 201 as injection points.

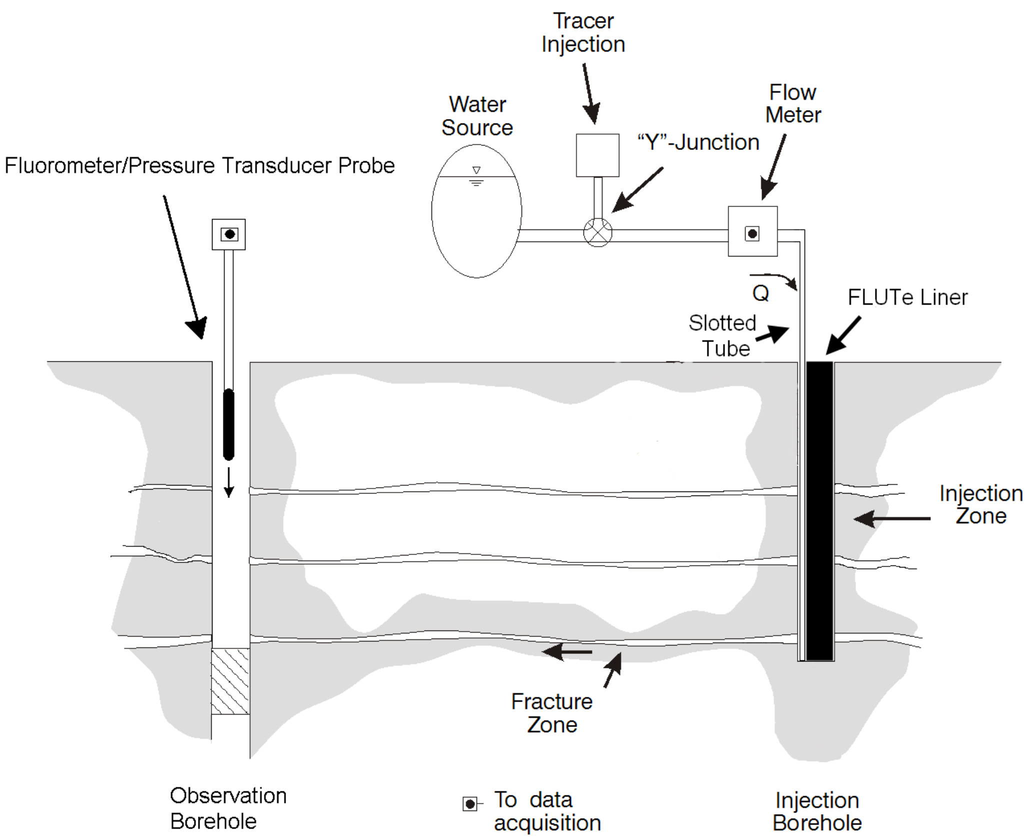




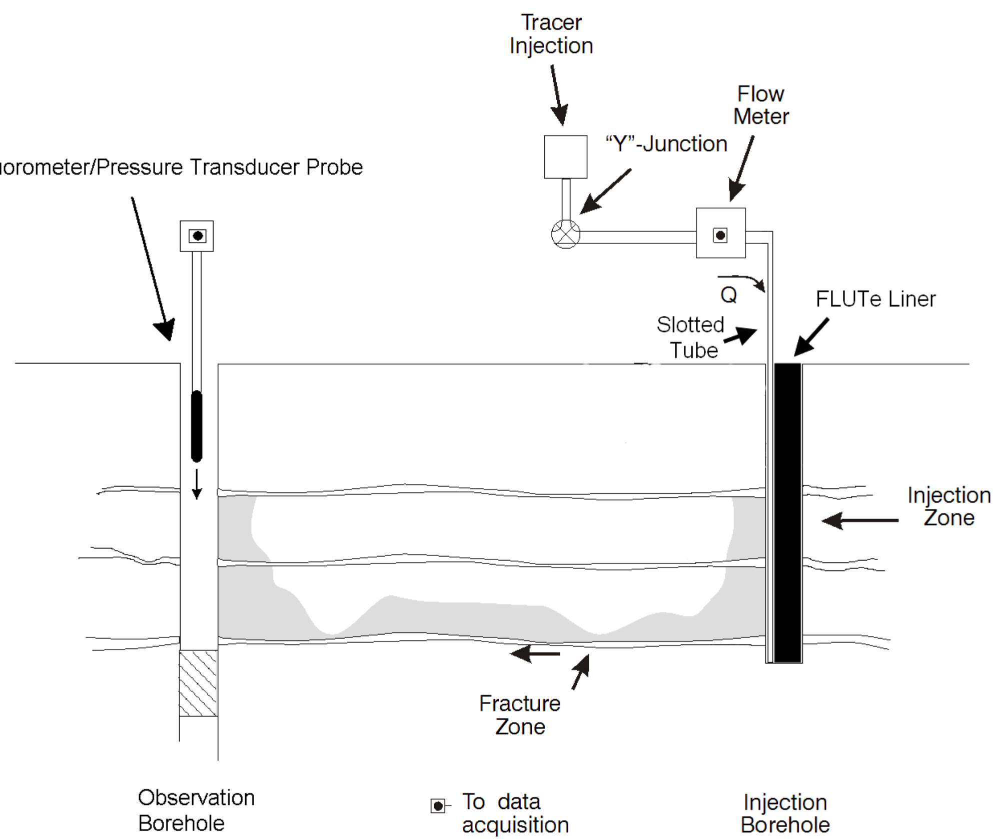
Tools

- Tracer experiments. Three methods employed:
  - Radial divergent
  - Natural gradient
  - Injection-withdrawal
- Sampling either conducted directly or using a submersible probe.
- Used a conservative fluorescein dye.
- Intent not to selectively isolate individual fracture features.
- Eleven experiments were conducted.

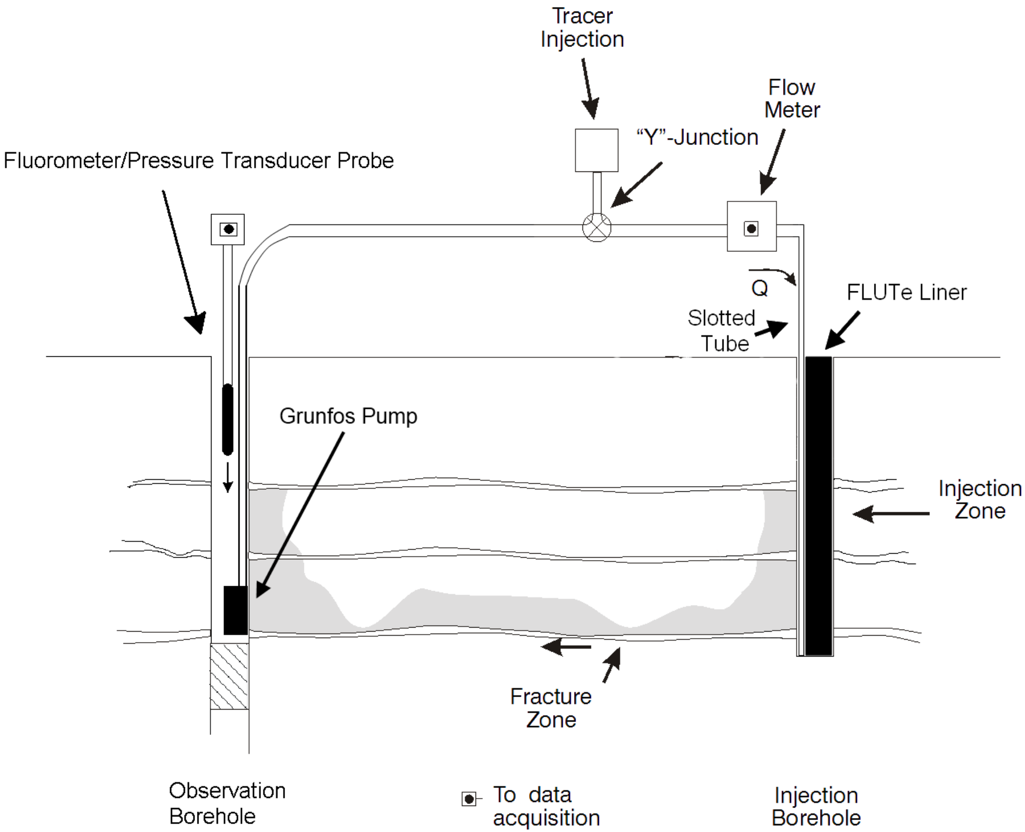
Radial Divergent



Natural Gradient



Injection-Withdrawal



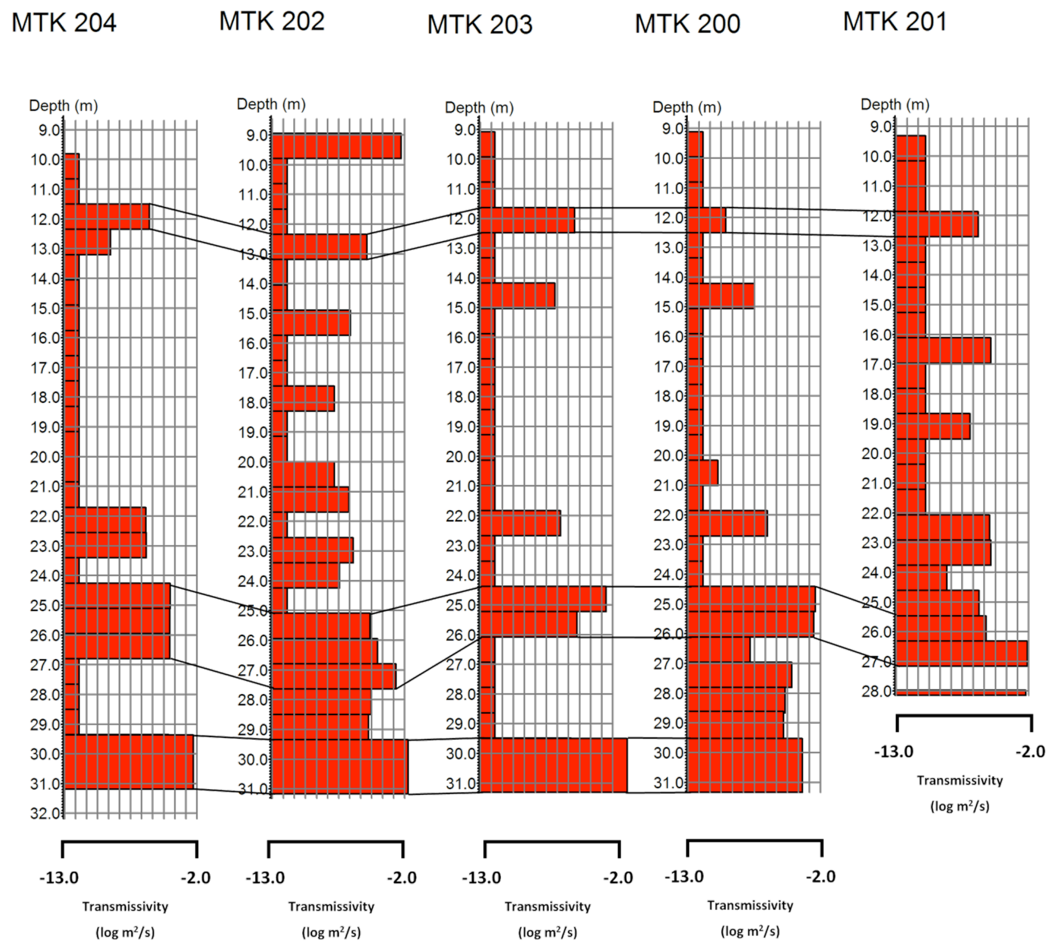
Results

- Identification of discrete features via core log and borehole camera.
- Used marker beds where appropriate.
- Linked these observations with constant head test results to develop the first conceptual model.
- The results of the pulse interference tests where 21 of 61 tests showed connection, were used to build the 2nd conceptual model.
- Analysis of the tracer experiments was conducted based on first arrival time and full numerical simulation using *HydroGeoSphere* for the injection-withdrawal experiments.
- Formed the 3rd conceptual model.

Core

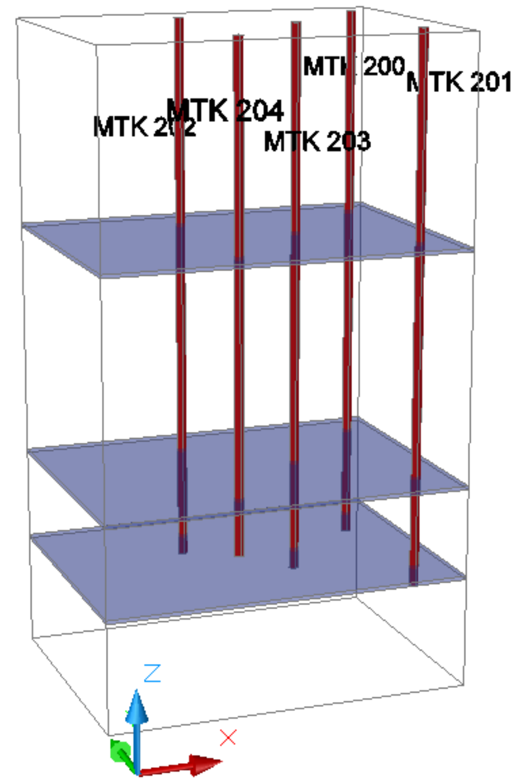
- Limestone more sparsely fractured than the granite.
- Many core runs intact.
- Contact between limestone and granite is welded.

Constant Head Tests

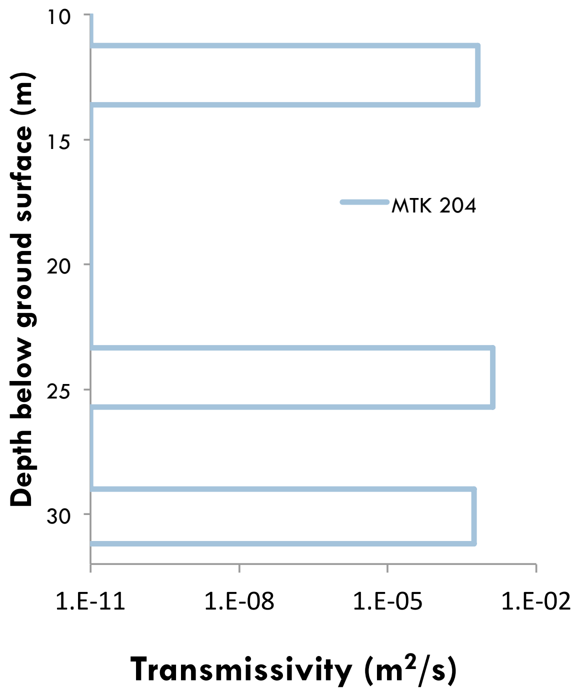


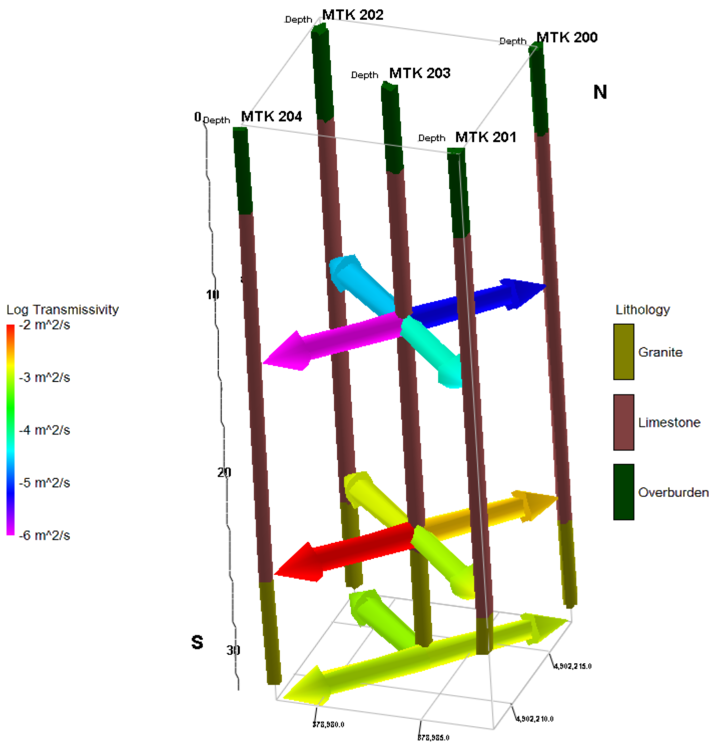
Constant Head Conceptual Model

- Three pervasive horizontal fractures were identified at 14.5 m BGS, 24.3 m BGS and 29.7m BGS.
- The fractures range in aperture from 250 µm to 700 µm.



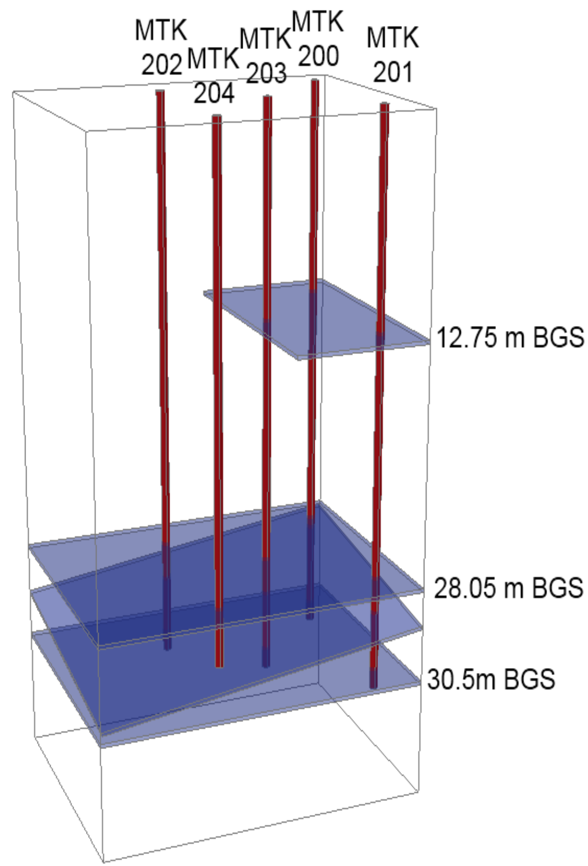
Pulse Interference Tests





Pulse Interference Conceptual Model

- Three pervasive horizontal fractures were identified at 14.5 m BGS, 24.3 m BGS and 29.7m BGS.
- One subhorizontal fracture feature was identified, sloping from a depth approximately 27.5 m.
- Apertures slightly smaller than what was determined from constant head.

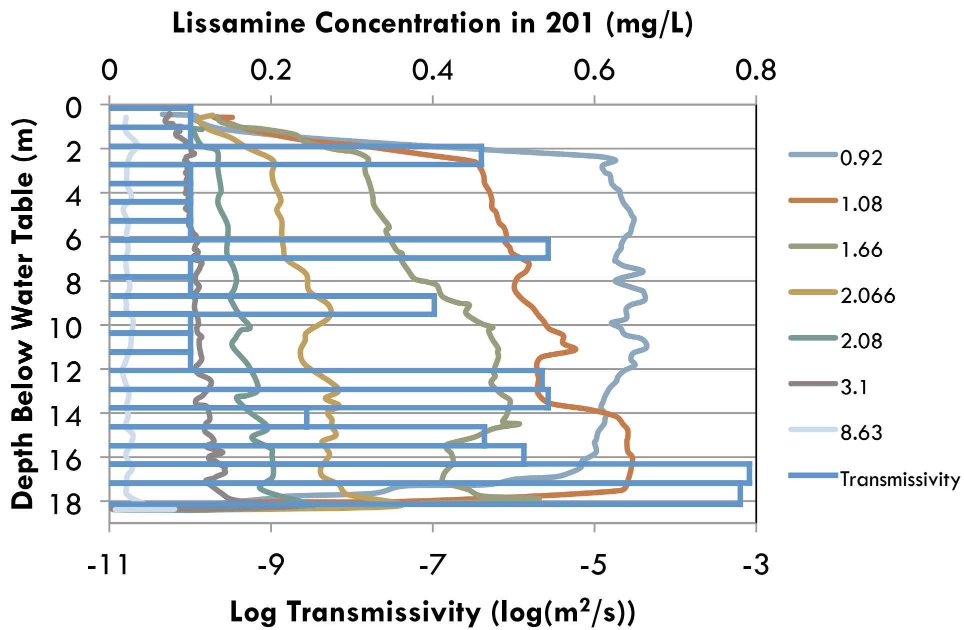


Summary of Tracer Experiments

Experiment Type	Source Well	Pumped Well	Boreholes with Breakthrough
Radial Divergent	204	N/A	Negative Result
Radial Divergent	204	N/A	Negative Result
Radial Divergent	204	N/A	Negative Result
Radial Divergent	203	N/A	MTK 201 MTK 204
Radial Divergent	202	N/A	Negative Result
Radial Divergent	201	N/A	MTK 203 MTK 204
Natural Gradient	203	N/A	MTK 201 MTK 204
Injection-Withdrawal	MTK 201	MTK 202	Negative Result
Injection-Withdrawal	MTK 202	MTK 201	Negative Result
Injection-Withdrawal	MTK 202	MTK 203	Positive Result
Injection-Withdrawal	MTK 200	MTK 203	Positive Result

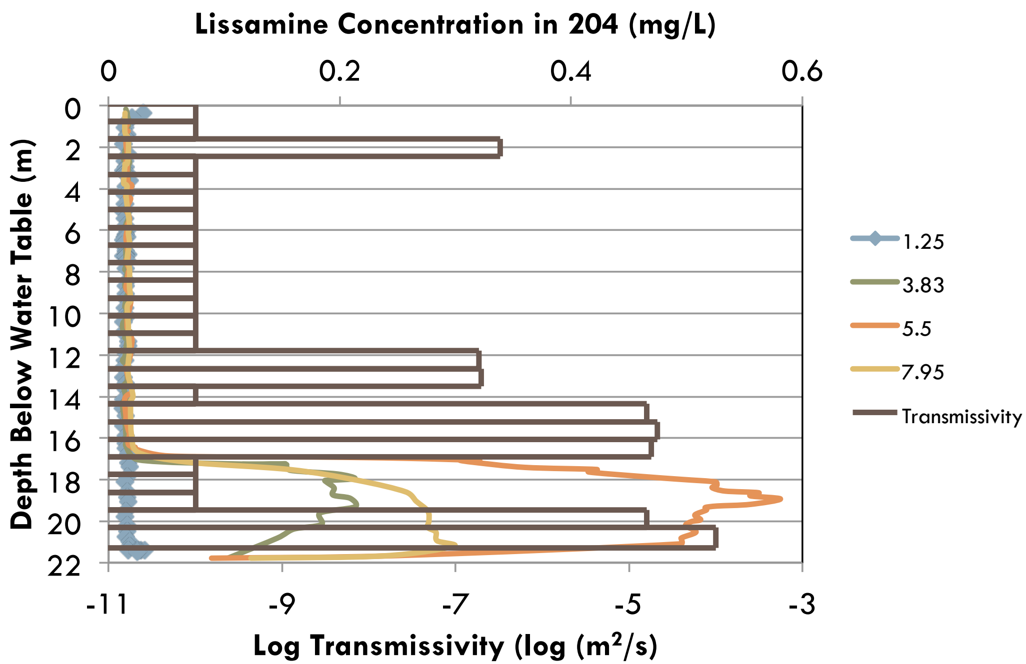
Tracer Experiments

- Experiment #4 - radial divergent (203 source, 201 obs.).
- Injection rate of 4.2 L/min.
- Distribution of tracer arrival at specific times (hrs).
- Distribution of T overlain.



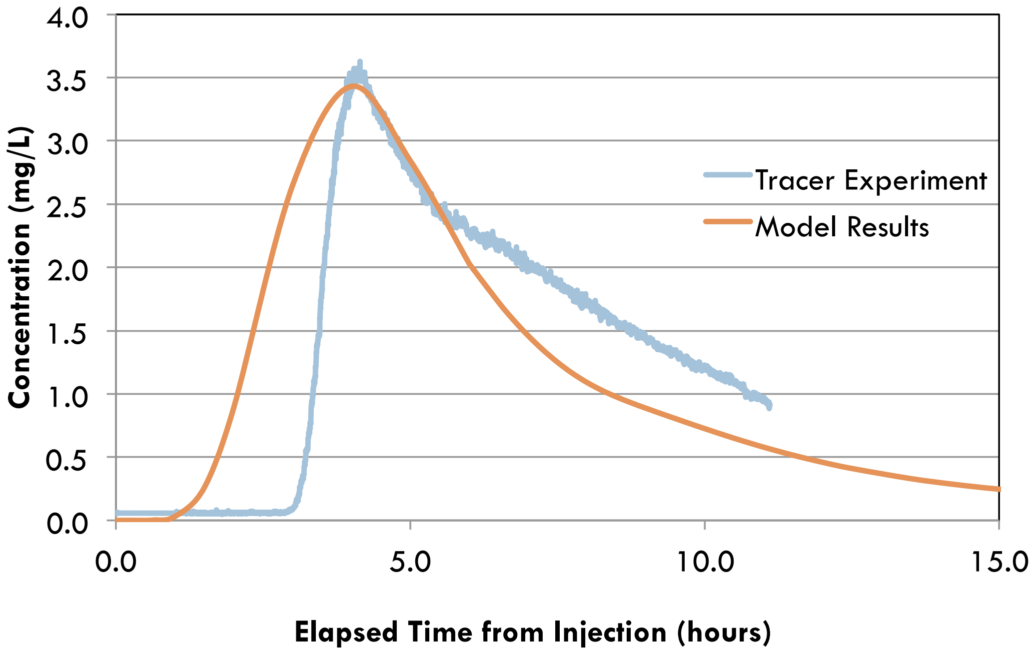
Tracer Experiments

- Experiment #6 – radial divergent (201 source, 204 obs.).
- Injection rate of 6.5 L/min.



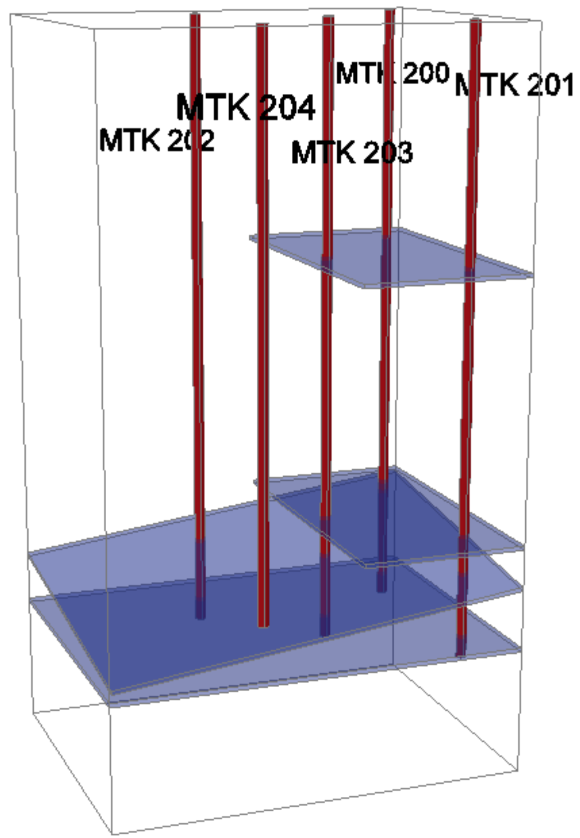
Tracer Experiments

- Experiment #9 – injection-withdrawal (202 injection, 203 withdrawal).
- Injection-withdrawal rate of 4.0 L/min.
- Impossible to fit to the rising limb. Suggests linear connection.
- Inflection in field data due to recirculation.



Solute Transport Conceptual Model

- One pervasive horizontal fracture located at 29.7m BGS.
- One subhorizontal fracture feature was identified, sloping from a depth approximately 27.5 m in 204 to 24.8 m in 202, 203 and 200.
- Two horizontal fractures connecting 200, 203 and 201 located at 14.5 m BGS and 24.3 m BGS.



Conceptual Model Comparison

Characterization Method	Summary of Conceptual Model
Constant Head	Three pervasive horizontal sheeting fractures. Highest hydraulic conductivity was estimated using this method.
Pulse Interference	Three pervasive horizontal sheeting fractures and one subhorizontal fracture feature. Lower hydraulic conductivity predicted vs. constant head for similar features.
Tracer Experiments	Three discontinuous horizontal sheeting fractures, one subhorizontal fracture feature. The fracture features are not connected between all boreholes.

Conclusions

- Constant head characterization will over-predict the potential connections and effective permeability available for transport.
- Pulse interference is a better estimate of solute transport pathways than constant head characterization, but also over-predicts connections.
- Complex fracture heterogeneity can result in pathways that will transmit pressure between boreholes, but not necessarily solute.
- Study is limited by lack of inclined boreholes. Should be repeated at another site with more detail on the vertical connections.