Research Lessons Learned by an Engineer Turned Hydrogeologist

Neil R. Thomson
Department of Civil and Environmental Engineering
University of Waterloo

University of Waterloo

XVII CONGRESSO BRASILEIRO DE ÁGUAS SUBTERRÂNEAS

Engineering

UNIVERSITY OF WATERLOO

- Currently an engineering professor
- 25+ years as a researcher
- Groundwater systems
- Contaminant fate and remediation
- Modelling
- Bench-scale experiments
- Field experiments

Engineering

UNIVERSITY OF WATERLOO

"…is the science, skill, and profession of acquiring and applying scientific, economic, social, and practical knowledge…

to design and also build structures, machines, devices, systems, materials and processes."

- ❑ **Professional**
- ❑ **Licensed**
- ❑ **Duty to ensure public safety**

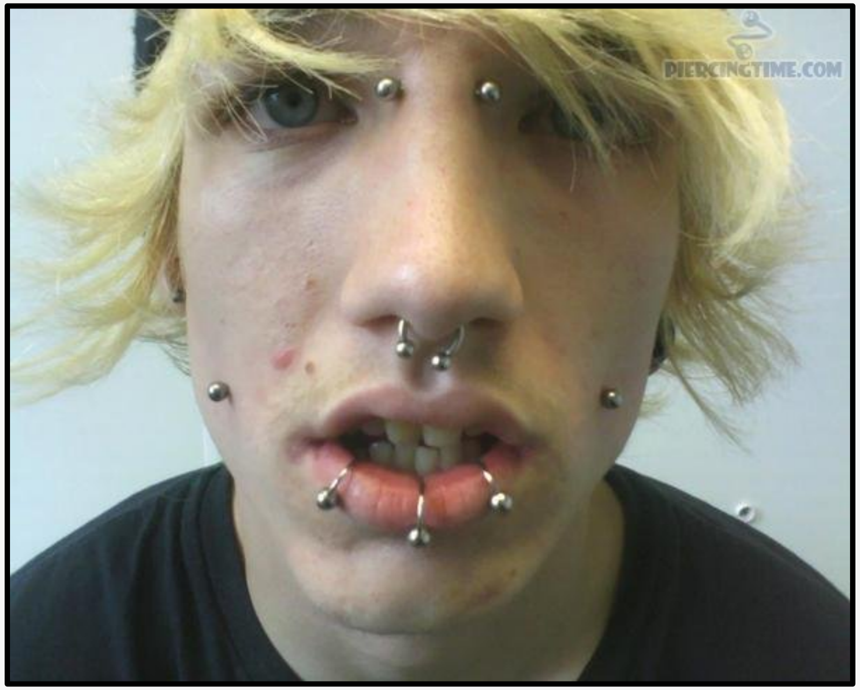
Training

UNIVERSITY OF WATERLOO

- ❑ Maths
- ❑ Basic science
- ❑ Engineering science
- ❑ Engineering design
- ❑ Economics
- ❑ Social impact

Training

UNIVERSITY OF
WATERLOO

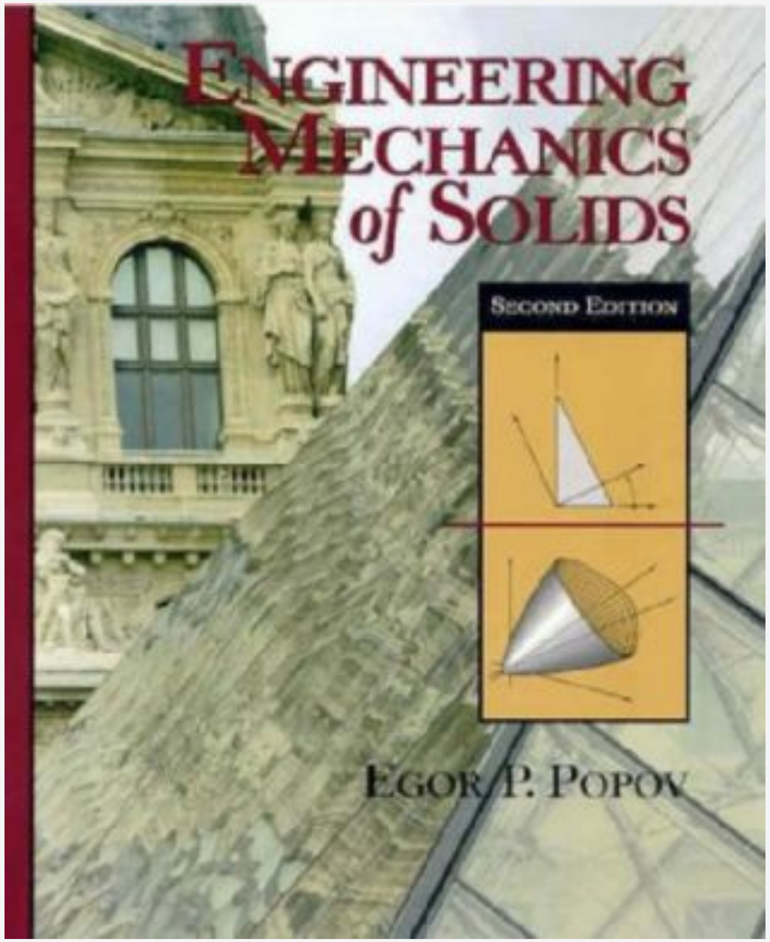


Training

UNIVERSITY OF WATERLOO

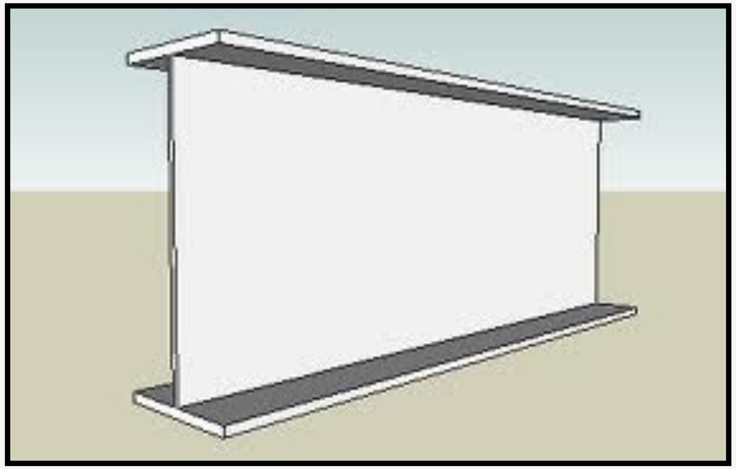
Civil engineering

- Materials
- Steel
- Concrete
- Transportation
- Structures
- Water treatment
- Soil mechanics



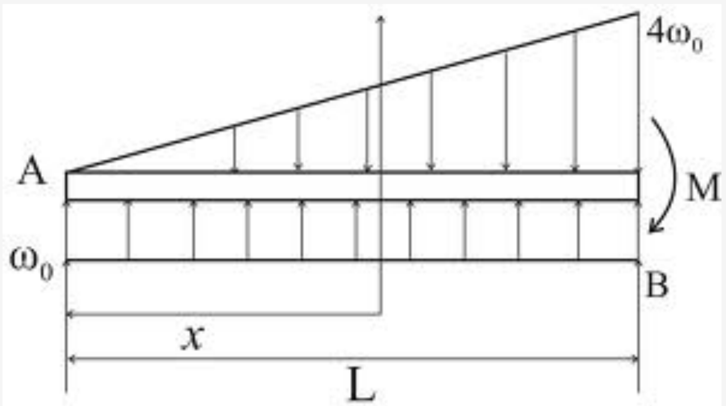
Engineering approach

UNIVERSITY OF WATERLOO



- All can be designed
- Control over most aspects
- Factor of safety

- Size beam to carry design load



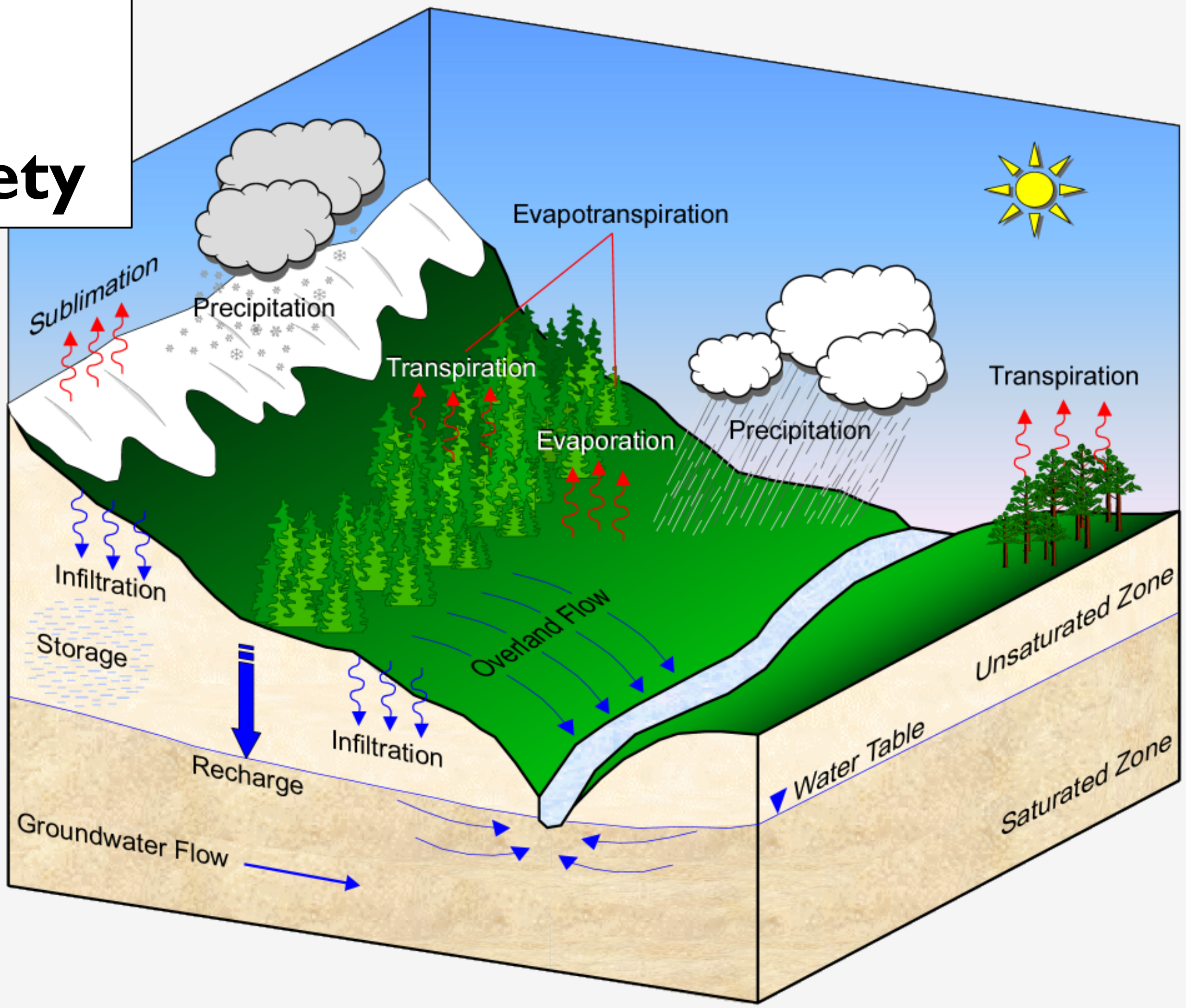
Environmental systems

UNIVERSITY OF WATERLOO

High variability

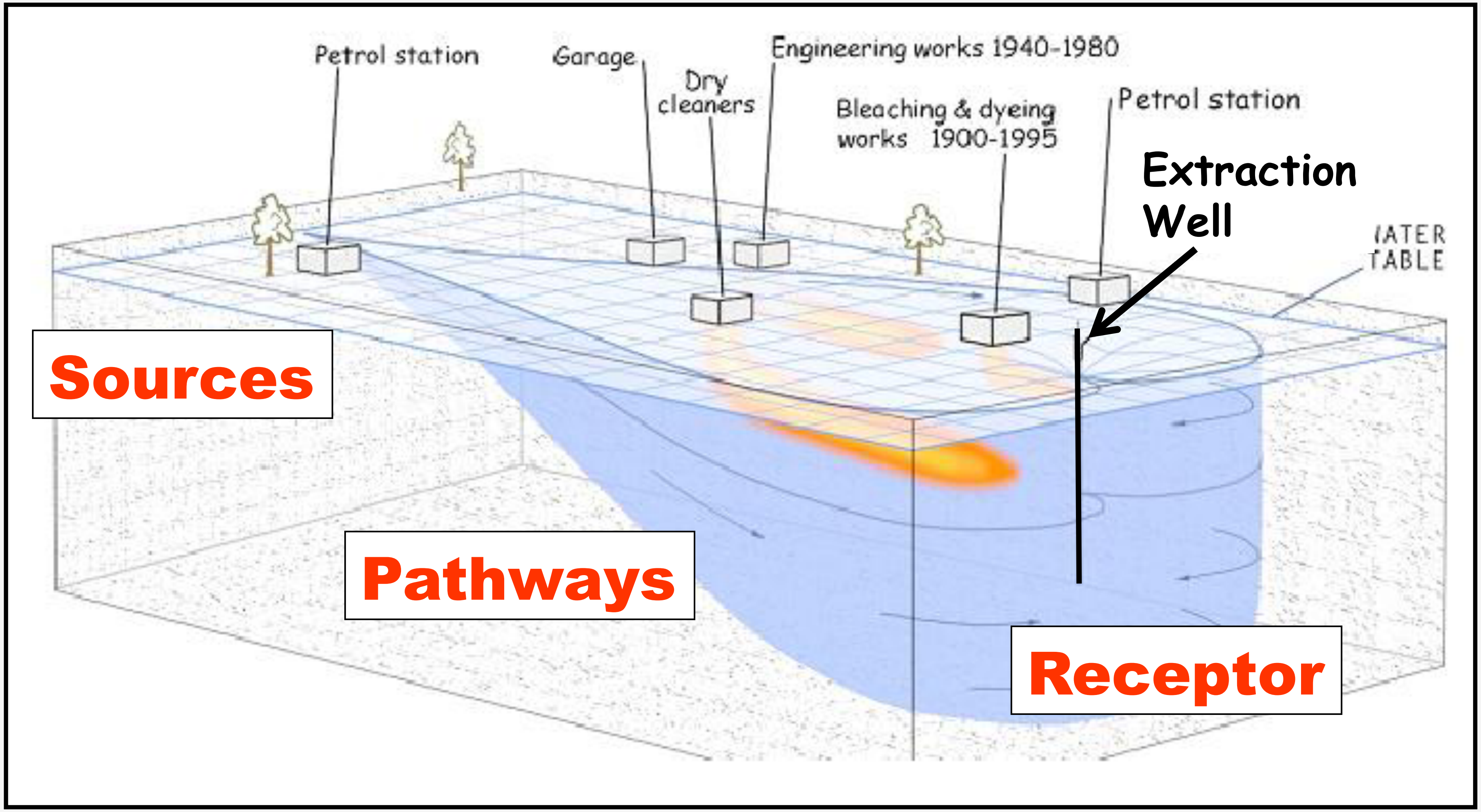
No control

No factor of safety



Contamination

UNIVERSITY OF WATERLOO



Pathway…

Some Lessons Learned

Perspective

"Success is not a good teacher, failure makes you humble"

Shah Rukh Khan

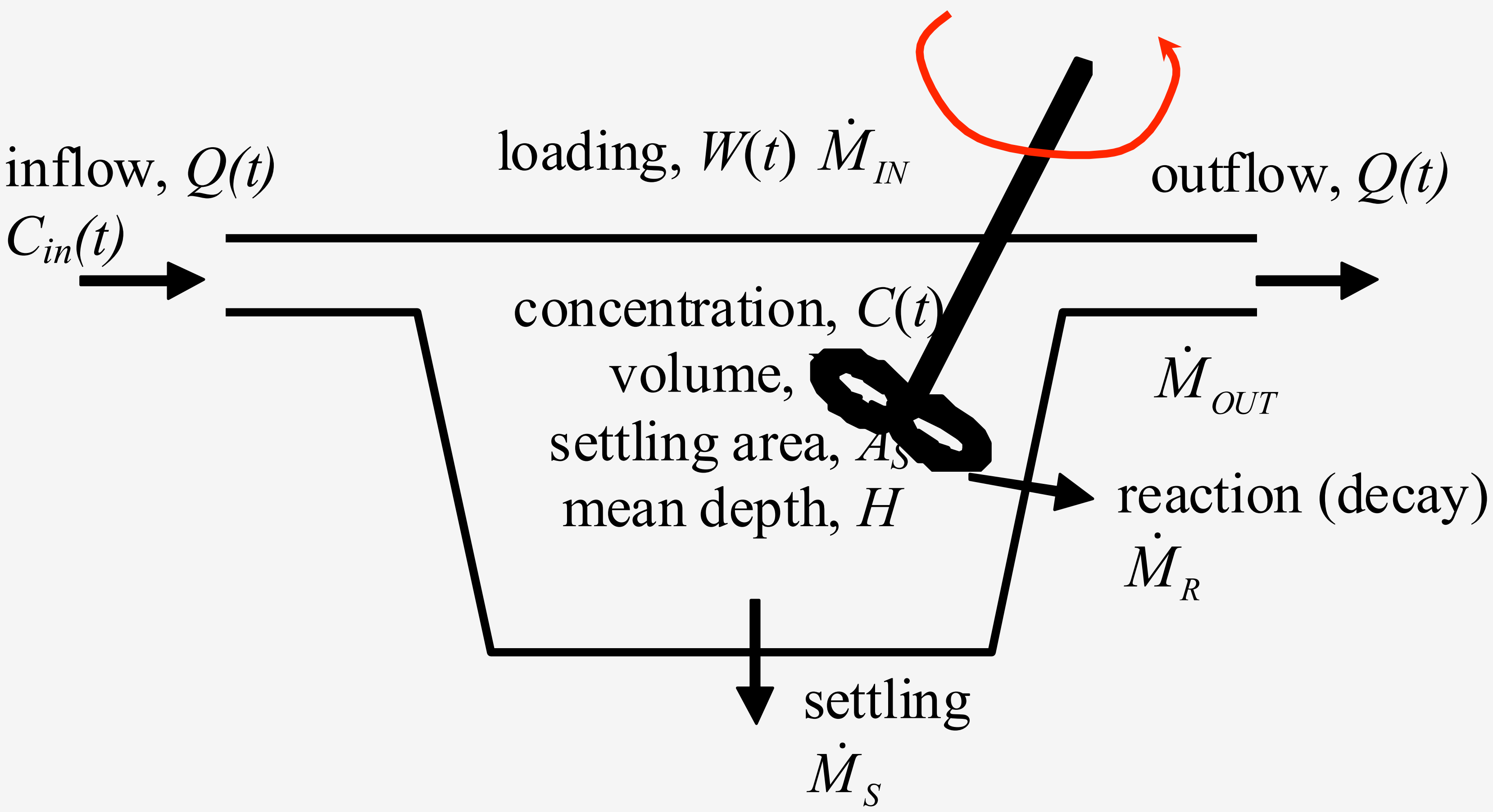
Example 1

UNIVERSITY OF WATERLOO

Modelling is fun…

Well-mixed systems

UNIVERSITY OF WATERLOO



Well-mixed systems

UNIVERSITY OF WATERLOO

$$V\frac{\mathrm{d}C_T}{\mathrm{d}t} = W(t) - QC_T - kVC_T - v_s f_s A_S C_T$$

mass input

mass output

mass decay

settling

rate of change of mass

Well-mixed systems

UNIVERSITY OF WATERLOO

$$\frac{\mathrm{d}\,C}{\mathrm{d}\,t} + \lambda(t)C = S(t)$$

which has the solution

$$C(t)e^{\int \lambda(t)dt} = \int S(t)e^{\int \lambda(t)dt}dt + K$$

$$C(t) = \int_{t_o}^{t} h(t,t')\left[S(t') + C_o\delta(t'-t_o)\right]\mathrm{d}t'$$

where

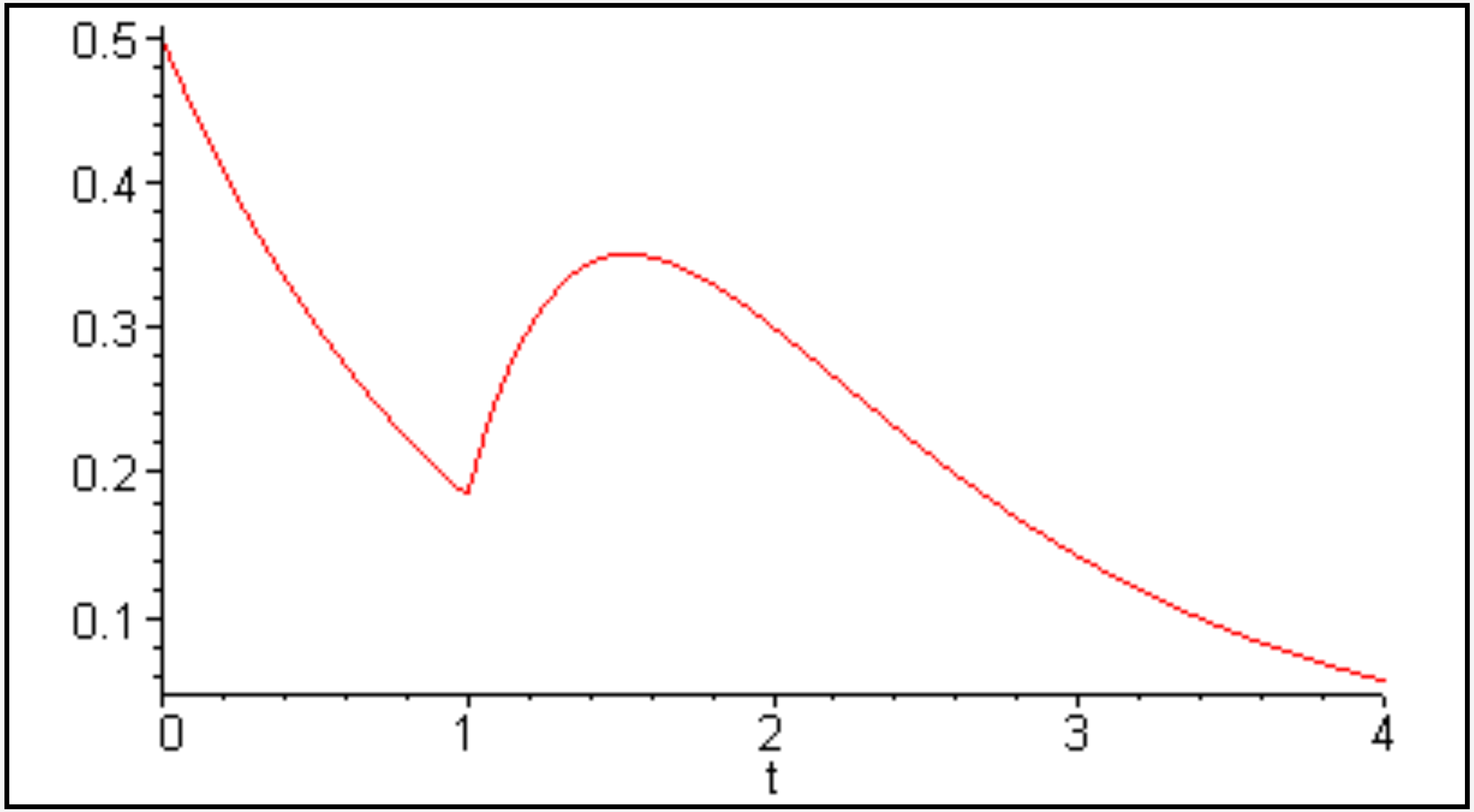
$$h(t,t') = e^{-\lambda(t-t')}$$

is the Green's function for the ODE

Well-mixed systems

UNIVERSITY OF WATERLOO

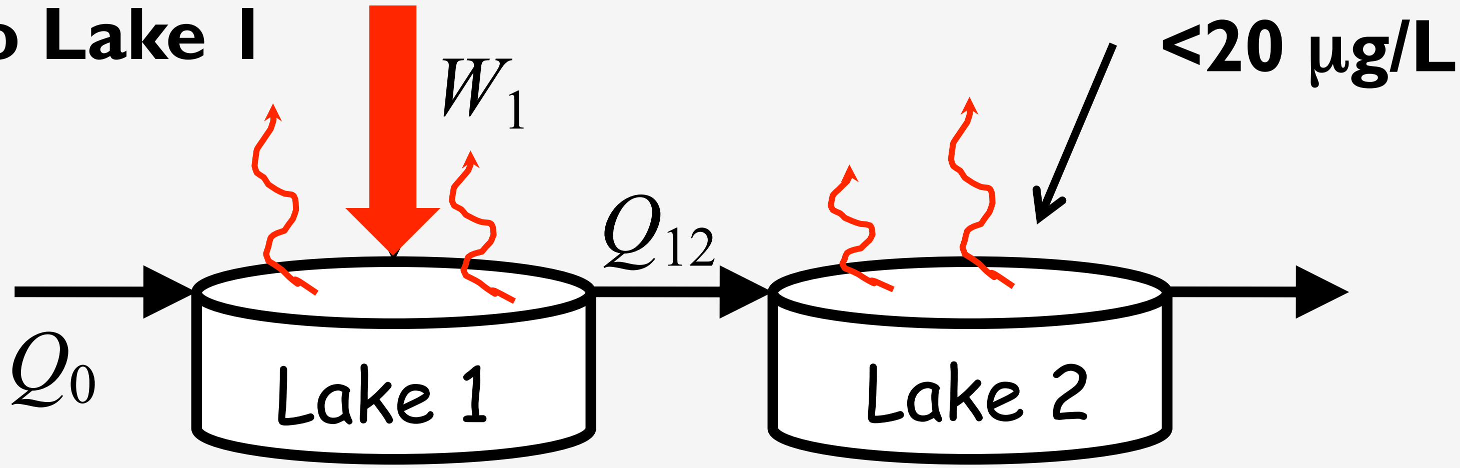
$$\frac{\mathrm{d}\,C}{\mathrm{d}\,t} + 1C = 1e^{-2(t-t_1)}H(t-t_1) \quad \text{with} \;\; C(0) = 0.5$$



Well-mixed systems

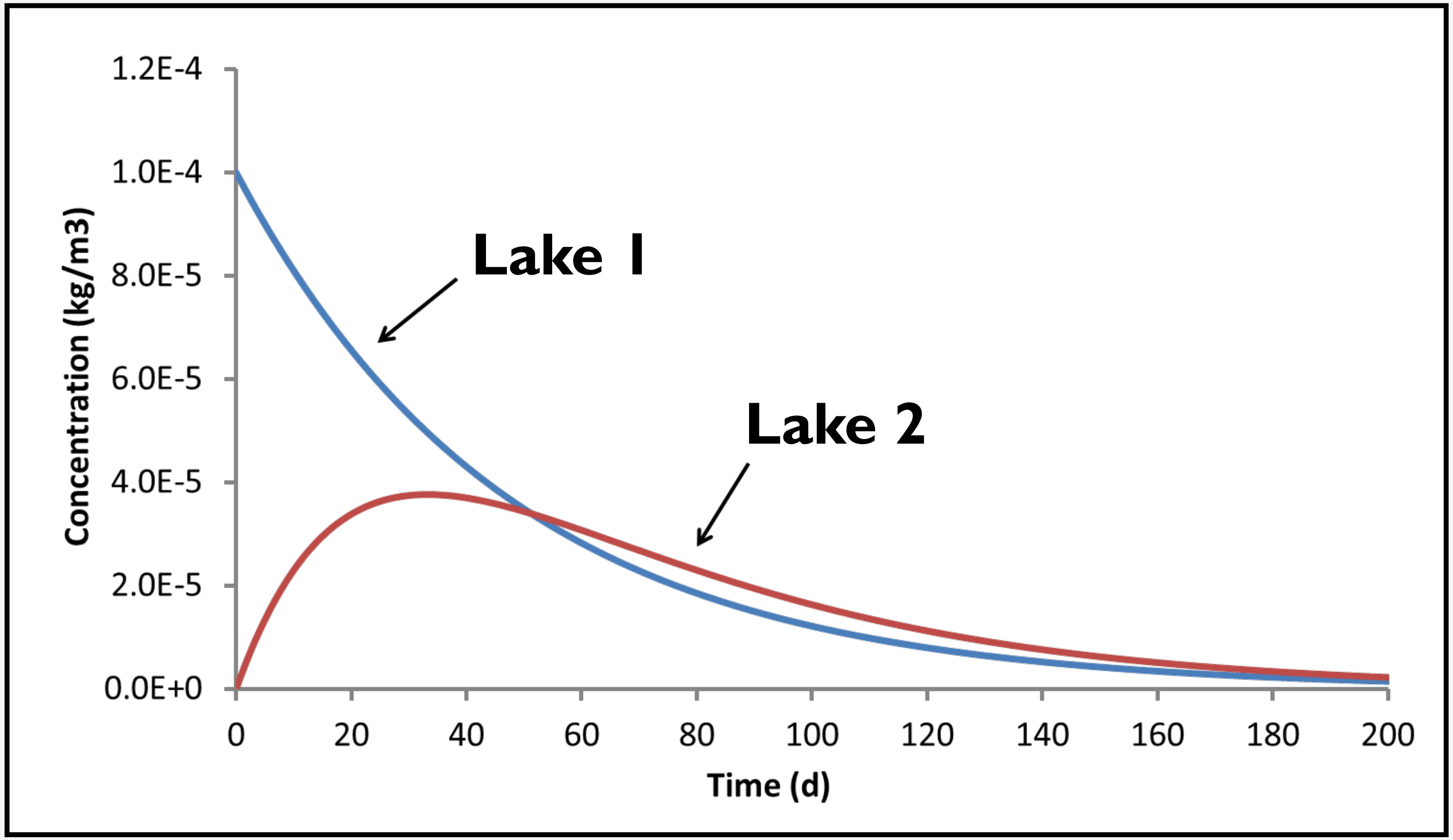
UNIVERSITY OF WATERLOO

Release of contaminant into Lake 1



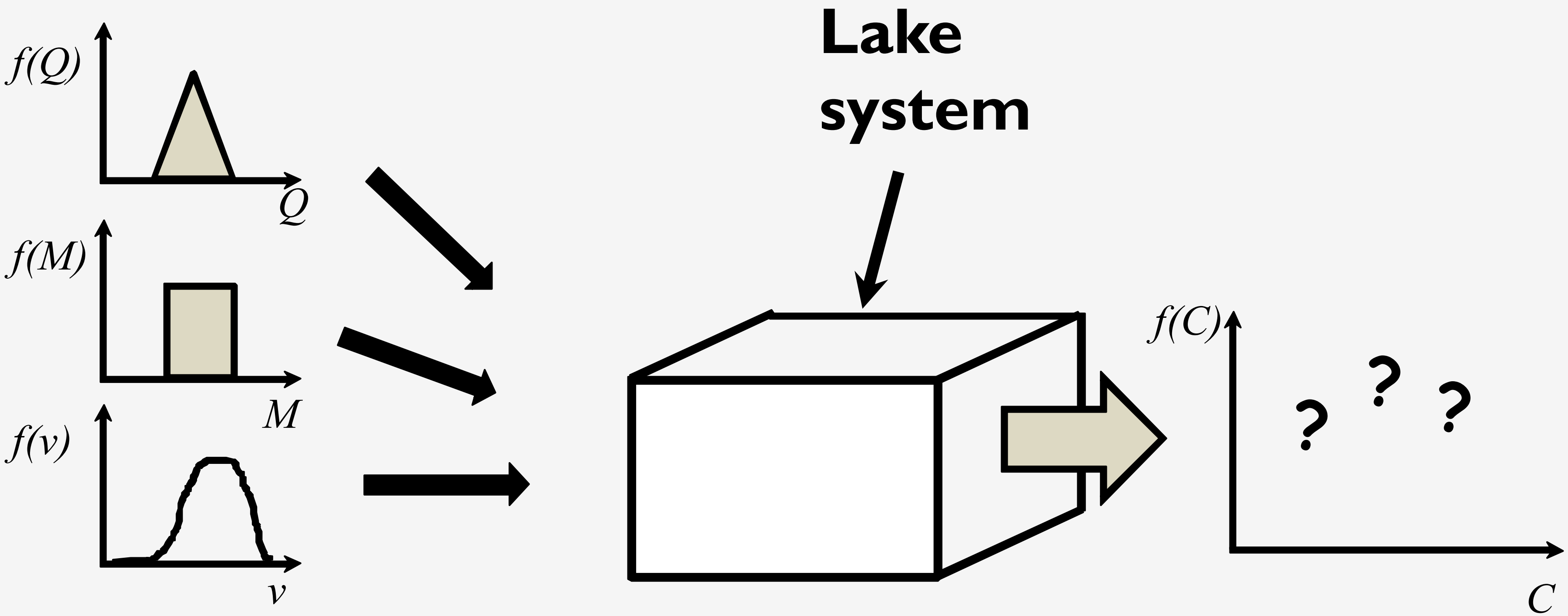
Well-mixed systems

UNIVERSITY OF WATERLOO



Well-mixed systems

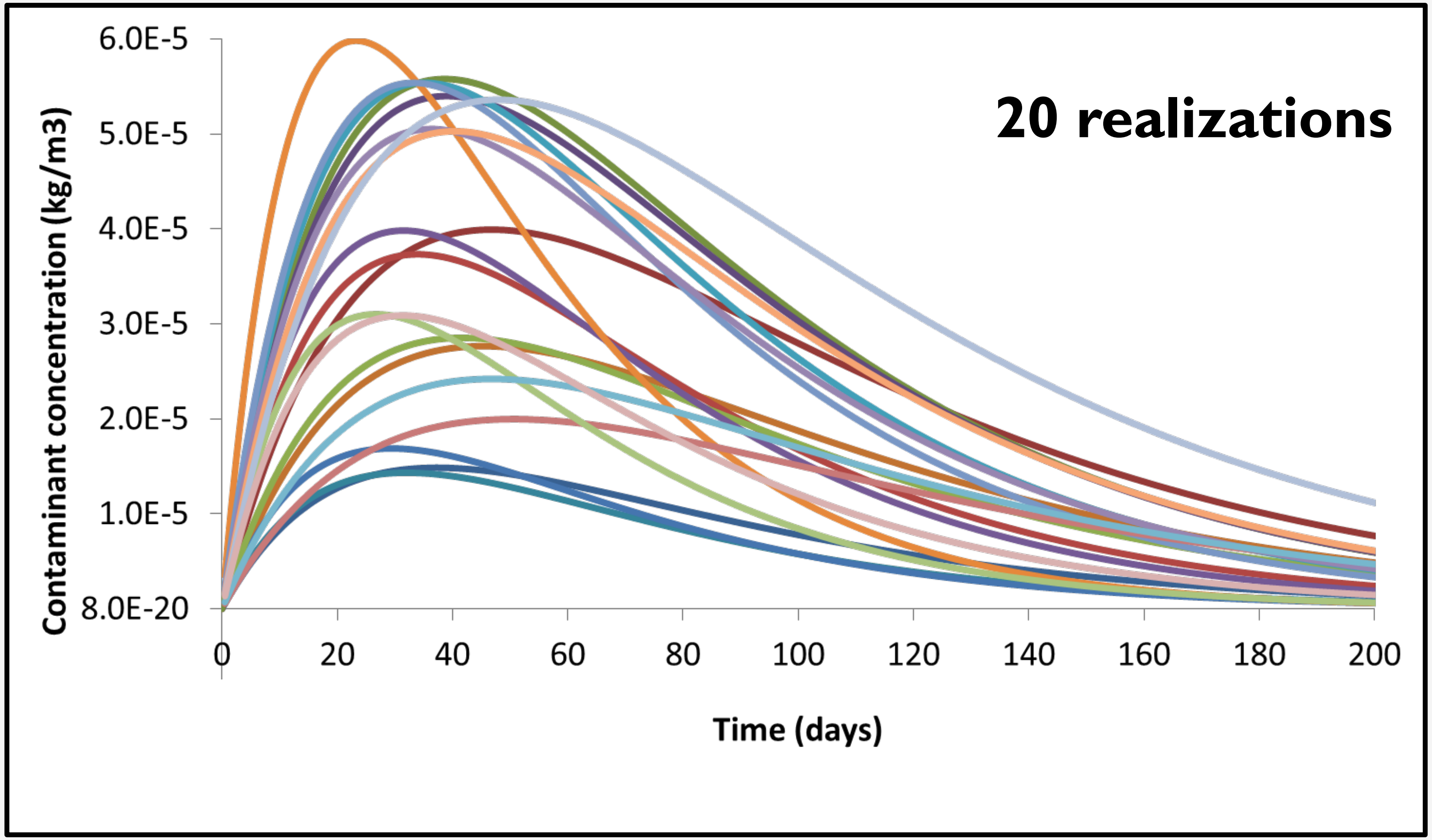
UNIVERSITY OF WATERLOO



Monte Carlo Method

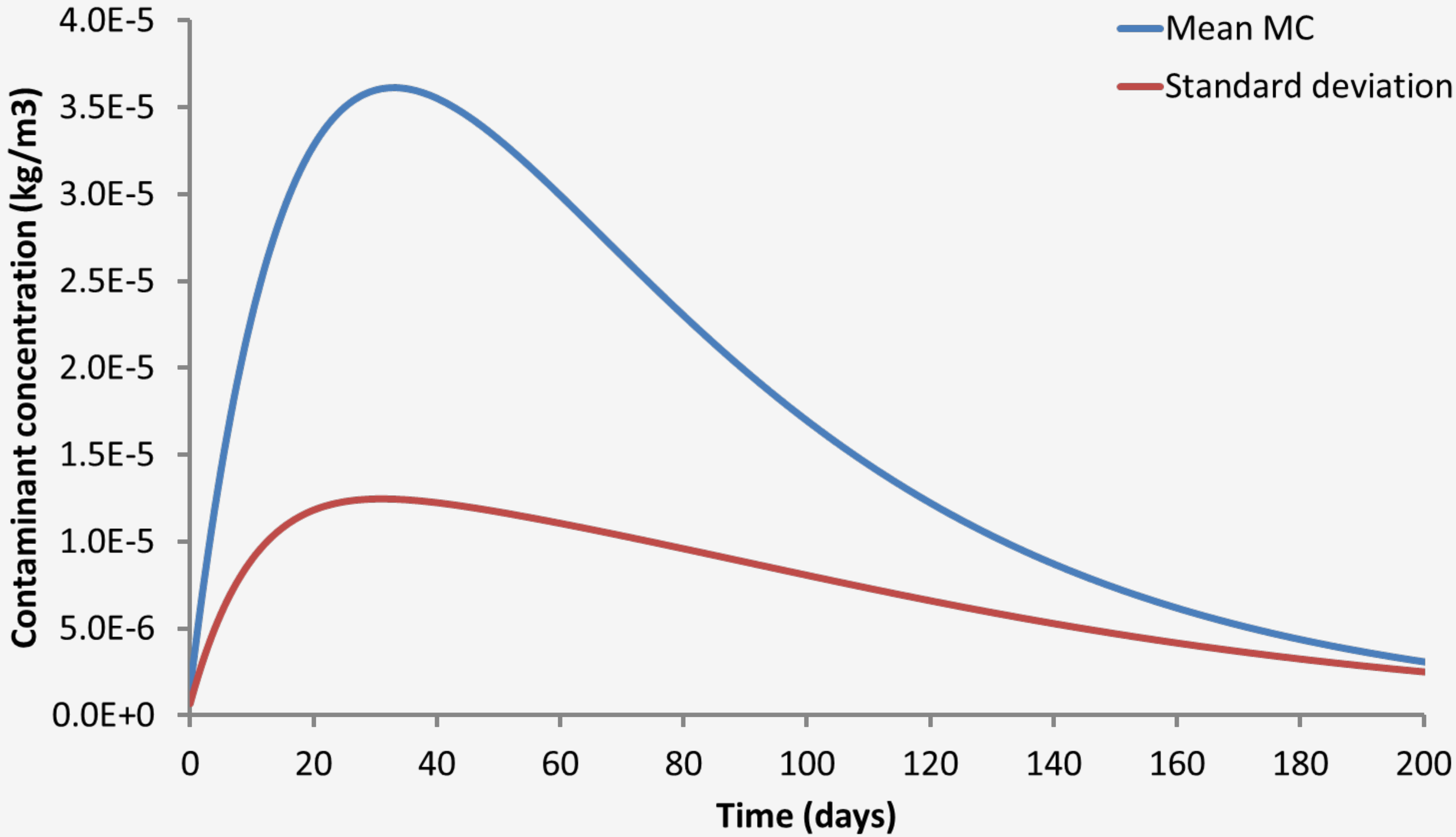
Well-mixed systems

UNIVERSITY OF WATERLOO



Well-mixed systems

UNIVERSITY OF WATERLOO



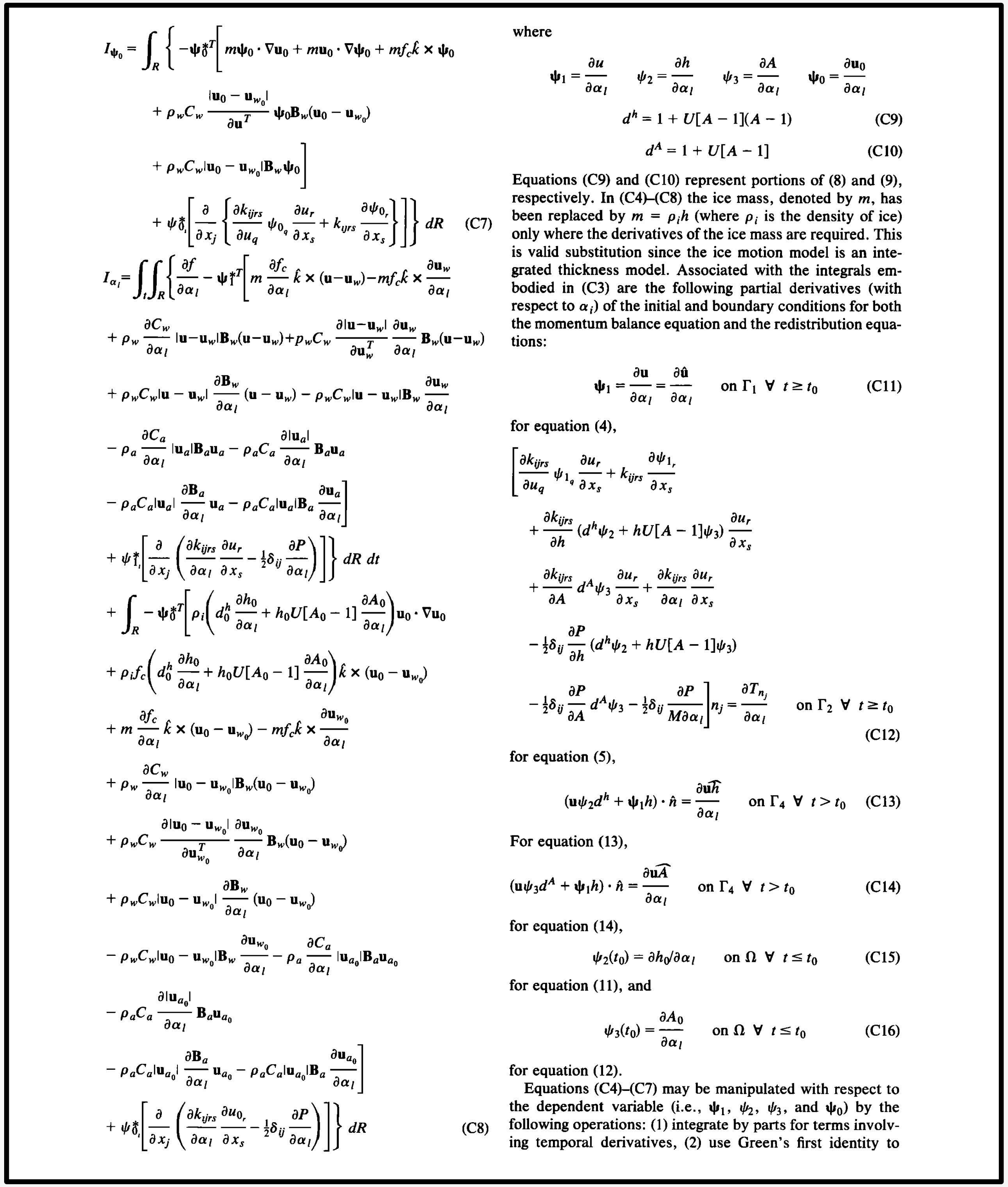
Well-mixed systems

UNIVERSITY OF WATERLOO

Advance complexity

+

Solve bigger problems



$$
\begin{aligned}
I_{\psi_0} = \int_R \Bigg\{ -\boldsymbol{\psi}_0^{*T}\Bigg[& m\boldsymbol{\psi}_0 \cdot \nabla \mathbf{u}_0 + m\mathbf{u}_0 \cdot \nabla \boldsymbol{\psi}_0 + m f_c \hat{k} \times \boldsymbol{\psi}_0 \\
& + \rho_w C_w \frac{|\mathbf{u}_0 - \mathbf{u}_{w_0}|}{\partial \mathbf{u}^T} \boldsymbol{\psi}_0 \mathbf{B}_w (\mathbf{u}_0 - \mathbf{u}_{w_0}) \\
& + \rho_w C_w |\mathbf{u}_0 - \mathbf{u}_{w_0}| \mathbf{B}_w \boldsymbol{\psi}_0 \Bigg] \\
& + \psi_{0_i}^{*}\left[\frac{\partial}{\partial x_j} \left\{ \frac{\partial k_{ijrs}}{\partial u_q} \psi_{0_q} \frac{\partial u_r}{\partial x_s} + k_{ijrs} \frac{\partial \psi_{0_r}}{\partial x_s} \right\} \right] \Bigg\} \, dR
\end{aligned}
\qquad \text{(C7)}
$$

$$
\begin{aligned}
I_{\alpha_l} = \int_t \int_R \Bigg\{ & \frac{\partial f}{\partial \alpha_l} - \boldsymbol{\psi}_1^{*T} \Bigg[m \frac{\partial f_c}{\partial \alpha_l} \hat{k} \times (\mathbf{u} - \mathbf{u}_w) - m f_c \hat{k} \times \frac{\partial \mathbf{u}_w}{\partial \alpha_l} \\
& + \rho_w \frac{\partial C_w}{\partial \alpha_l} |\mathbf{u} - \mathbf{u}_w| \mathbf{B}_w (\mathbf{u} - \mathbf{u}_w) + \rho_w C_w \frac{\partial |\mathbf{u} - \mathbf{u}_w|}{\partial \mathbf{u}_w^T} \frac{\partial \mathbf{u}_w}{\partial \alpha_l} \mathbf{B}_w (\mathbf{u} - \mathbf{u}_w) \\
& + \rho_w C_w |\mathbf{u} - \mathbf{u}_w| \frac{\partial \mathbf{B}_w}{\partial \alpha_l} (\mathbf{u} - \mathbf{u}_w) - \rho_w C_w |\mathbf{u} - \mathbf{u}_w| \mathbf{B}_w \frac{\partial \mathbf{u}_w}{\partial \alpha_l} \\
& - \rho_a \frac{\partial C_a}{\partial \alpha_l} |\mathbf{u}_a| \mathbf{B}_a \mathbf{u}_a - \rho_a C_a \frac{\partial |\mathbf{u}_a|}{\partial \alpha_l} \mathbf{B}_a \mathbf{u}_a \\
& - \rho_a C_a |\mathbf{u}_a| \frac{\partial \mathbf{B}_a}{\partial \alpha_l} \mathbf{u}_a - \rho_a C_a |\mathbf{u}_a| \mathbf{B}_a \frac{\partial \mathbf{u}_a}{\partial \alpha_l} \Bigg] \\
& + \psi_{1_i}^{*} \left[\frac{\partial}{\partial x_j} \left(\frac{\partial k_{ijrs}}{\partial \alpha_l} \frac{\partial u_r}{\partial x_s} - \tfrac{1}{2} \delta_{ij} \frac{\partial P}{\partial \alpha_l} \right) \right] \Bigg\} \, dR \, dt \\
& + \int_R - \boldsymbol{\psi}_0^{*T} \Bigg[\rho_i \left(d_0^h \frac{\partial h_0}{\partial \alpha_l} + h_0 U[A_0 - 1] \frac{\partial A_0}{\partial \alpha_l} \right) \mathbf{u}_0 \cdot \nabla \mathbf{u}_0 \\
& + \rho_i f_c \left(d_0^h \frac{\partial h_0}{\partial \alpha_l} + h_0 U[A_0 - 1] \frac{\partial A_0}{\partial \alpha_l} \right) \hat{k} \times (\mathbf{u}_0 - \mathbf{u}_{w_0}) \\
& + m \frac{\partial f_c}{\partial \alpha_l} \hat{k} \times (\mathbf{u}_0 - \mathbf{u}_{w_0}) - m f_c \hat{k} \times \frac{\partial \mathbf{u}_{w_0}}{\partial \alpha_l} \\
& + \rho_w \frac{\partial C_w}{\partial \alpha_l} |\mathbf{u}_0 - \mathbf{u}_{w_0}| \mathbf{B}_w (\mathbf{u}_0 - \mathbf{u}_{w_0}) \\
& + \rho_w C_w \frac{\partial |\mathbf{u}_0 - \mathbf{u}_{w_0}|}{\partial \mathbf{u}_{w_0}^T} \frac{\partial \mathbf{u}_{w_0}}{\partial \alpha_l} \mathbf{B}_w (\mathbf{u}_0 - \mathbf{u}_{w_0}) \\
& + \rho_w C_w |\mathbf{u}_0 - \mathbf{u}_{w_0}| \frac{\partial \mathbf{B}_w}{\partial \alpha_l} (\mathbf{u}_0 - \mathbf{u}_{w_0}) \\
& - \rho_w C_w |\mathbf{u}_0 - \mathbf{u}_{w_0}| \mathbf{B}_w \frac{\partial \mathbf{u}_{w_0}}{\partial \alpha_l} - \rho_a \frac{\partial C_a}{\partial \alpha_l} |\mathbf{u}_{a_0}| \mathbf{B}_a \mathbf{u}_{a_0} \\
& - \rho_a C_a \frac{\partial |\mathbf{u}_{a_0}|}{\partial \alpha_l} \mathbf{B}_a \mathbf{u}_{a_0} \\
& - \rho_a C_a |\mathbf{u}_{a_0}| \frac{\partial \mathbf{B}_a}{\partial \alpha_l} \mathbf{u}_{a_0} - \rho_a C_a |\mathbf{u}_{a_0}| \mathbf{B}_a \frac{\partial \mathbf{u}_{a_0}}{\partial \alpha_l} \Bigg] \\
& + \psi_{0_i}^{*} \left[\frac{\partial}{\partial x_j} \left(\frac{\partial k_{ijrs}}{\partial \alpha_l} \frac{\partial u_{0_r}}{\partial x_s} - \tfrac{1}{2} \delta_{ij} \frac{\partial P}{\partial \alpha_l} \right) \right] \Bigg\} \, dR
\end{aligned}
\qquad \text{(C8)}
$$

where

$$
\boldsymbol{\psi}_1 = \frac{\partial u}{\partial \alpha_l} \qquad \psi_2 = \frac{\partial h}{\partial \alpha_l} \qquad \psi_3 = \frac{\partial A}{\partial \alpha_l} \qquad \boldsymbol{\psi}_0 = \frac{\partial \mathbf{u}_0}{\partial \alpha_l}
$$

$$
d^h = 1 + U[A - 1](A - 1) \qquad \text{(C9)}
$$

$$
d^A = 1 + U[A - 1] \qquad \text{(C10)}
$$

Equations (C9) and (C10) represent portions of (8) and (9), respectively. In (C4)–(C8) the ice mass, denoted by m, has been replaced by $m = \rho_i h$ (where ρ_i is the density of ice) only where the derivatives of the ice mass are required. This is valid substitution since the ice motion model is an integrated thickness model. Associated with the integrals embodied in (C3) are the following partial derivatives (with respect to α_i) of the initial and boundary conditions for both the momentum balance equation and the redistribution equations:

$$
\boldsymbol{\psi}_1 = \frac{\partial \mathbf{u}}{\partial \alpha_l} = \frac{\partial \hat{\mathbf{u}}}{\partial \alpha_l} \qquad \text{on } \Gamma_1 \ \forall \ t \geq t_0 \qquad \text{(C11)}
$$

for equation (4),

$$
\begin{aligned}
\Bigg[& \frac{\partial k_{ijrs}}{\partial u_q} \psi_{1_q} \frac{\partial u_r}{\partial x_s} + k_{ijrs} \frac{\partial \psi_{1_r}}{\partial x_s} \\
& + \frac{\partial k_{ijrs}}{\partial h} (d^h \psi_2 + hU[A - 1]\psi_3) \frac{\partial u_r}{\partial x_s} \\
& + \frac{\partial k_{ijrs}}{\partial A} d^A \psi_3 \frac{\partial u_r}{\partial x_s} + \frac{\partial k_{ijrs}}{\partial \alpha_l} \frac{\partial u_r}{\partial x_s} \\
& - \tfrac{1}{2} \delta_{ij} \frac{\partial P}{\partial h} (d^h \psi_2 + hU[A - 1]\psi_3) \\
& - \tfrac{1}{2} \delta_{ij} \frac{\partial P}{\partial A} d^A \psi_3 - \tfrac{1}{2} \delta_{ij} \frac{\partial P}{M \partial \alpha_l} \Bigg] n_j = \frac{\partial T_{n_j}}{\partial \alpha_l} \qquad \text{on } \Gamma_2 \ \forall \ t \geq t_0
\end{aligned}
\qquad \text{(C12)}
$$

for equation (5),

$$
(\mathbf{u}\psi_2 d^h + \boldsymbol{\psi}_1 h) \cdot \hat{n} = \frac{\partial \widehat{\mathbf{u}h}}{\partial \alpha_l} \qquad \text{on } \Gamma_4 \ \forall \ t > t_0 \qquad \text{(C13)}
$$

For equation (13),

$$
(\mathbf{u}\psi_3 d^A + \boldsymbol{\psi}_1 h) \cdot \hat{n} = \frac{\partial \widehat{\mathbf{u}A}}{\partial \alpha_l} \qquad \text{on } \Gamma_4 \ \forall \ t > t_0 \qquad \text{(C14)}
$$

for equation (14),

$$
\psi_2(t_0) = \partial h_0 / \partial \alpha_l \qquad \text{on } \Omega \ \forall \ t \leq t_0 \qquad \text{(C15)}
$$

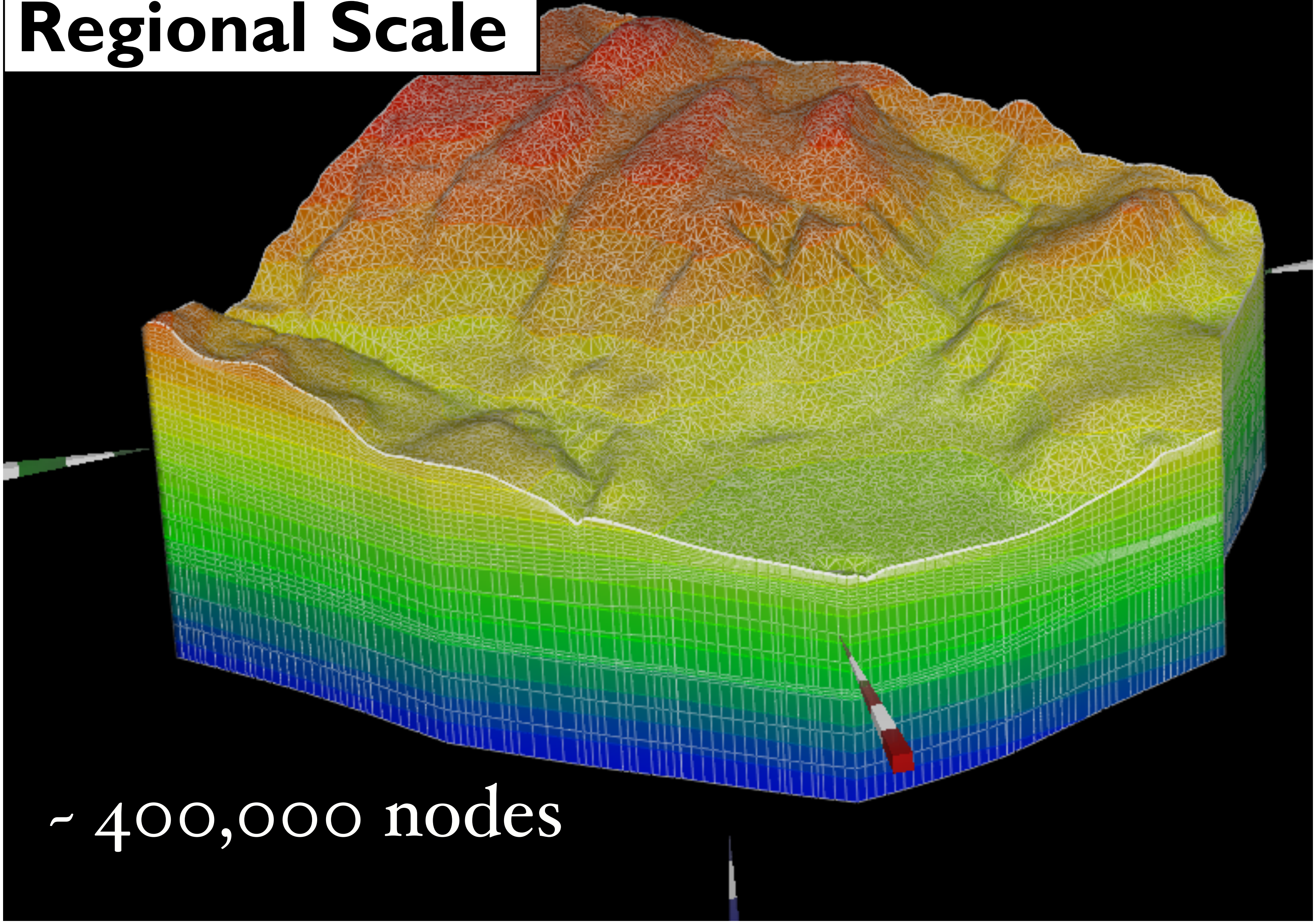
for equation (11), and

$$
\psi_3(t_0) = \frac{\partial A_0}{\partial \alpha_l} \qquad \text{on } \Omega \ \forall \ t \leq t_0 \qquad \text{(C16)}
$$

for equation (12).

Equations (C4)–(C7) may be manipulated with respect to the dependent variable (i.e., $\boldsymbol{\psi}_1$, ψ_2, ψ_3, and $\boldsymbol{\psi}_0$) by the following operations: (1) integrate by parts for terms involving temporal derivatives, (2) use Green's first identity to

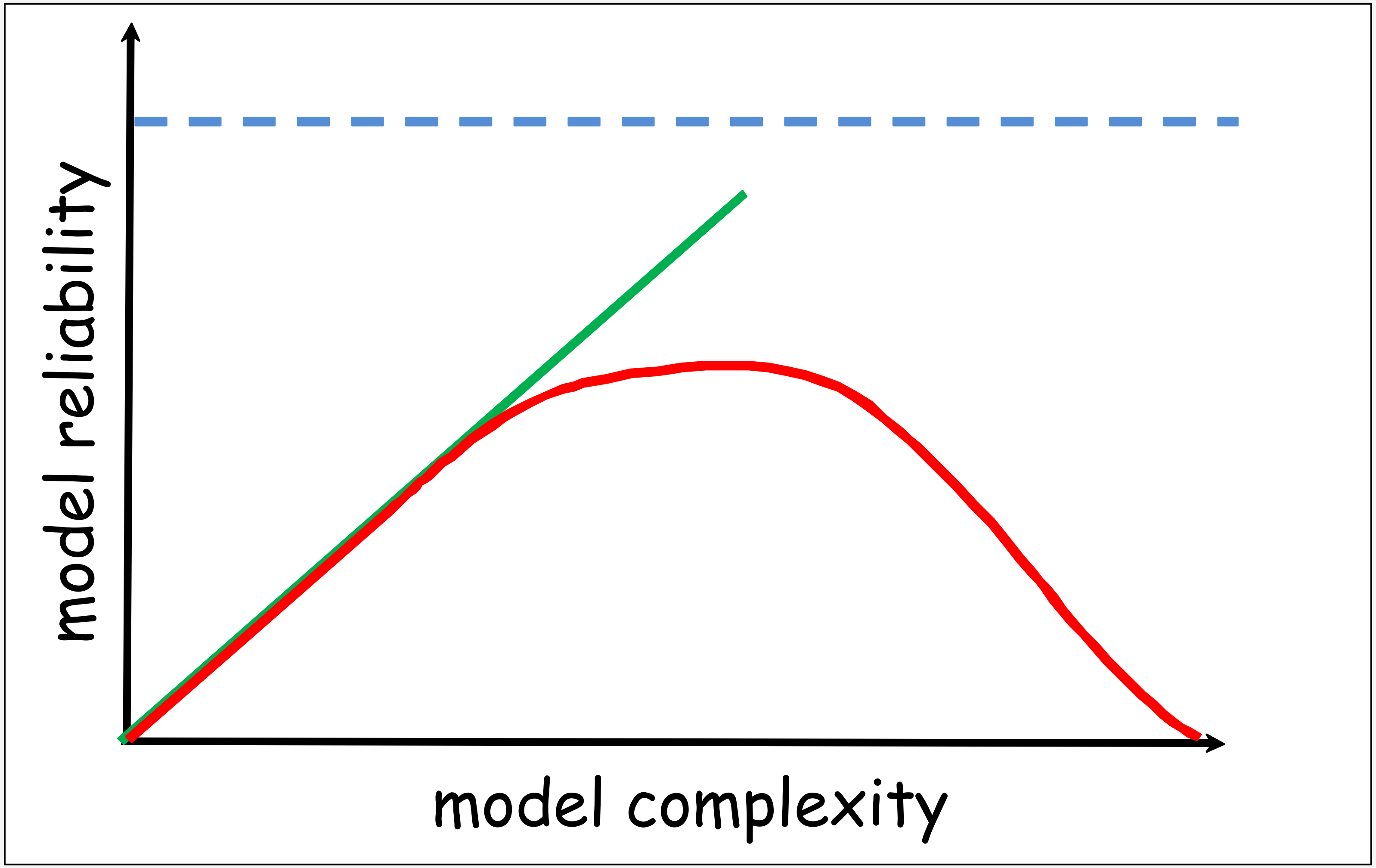
Regional Scale



~ 400,000 nodes

Model complexity

UNIVERSITY OF WATERLOO



Lesson learned - 1

UNIVERSITY OF WATERLOO

“the natural world is a complex system and we cannot predict its behaviour

nor should we behave as we can with any certainty”

Lesson learned - 2

UNIVERSITY OF WATERLOO

- Models can be very complex
- Demand more input than available
- Need to be grounded in observational data to appreciate the complexity of groundwater systems

Moving time…

Example 2

UNIVERSITY OF WATERLOO

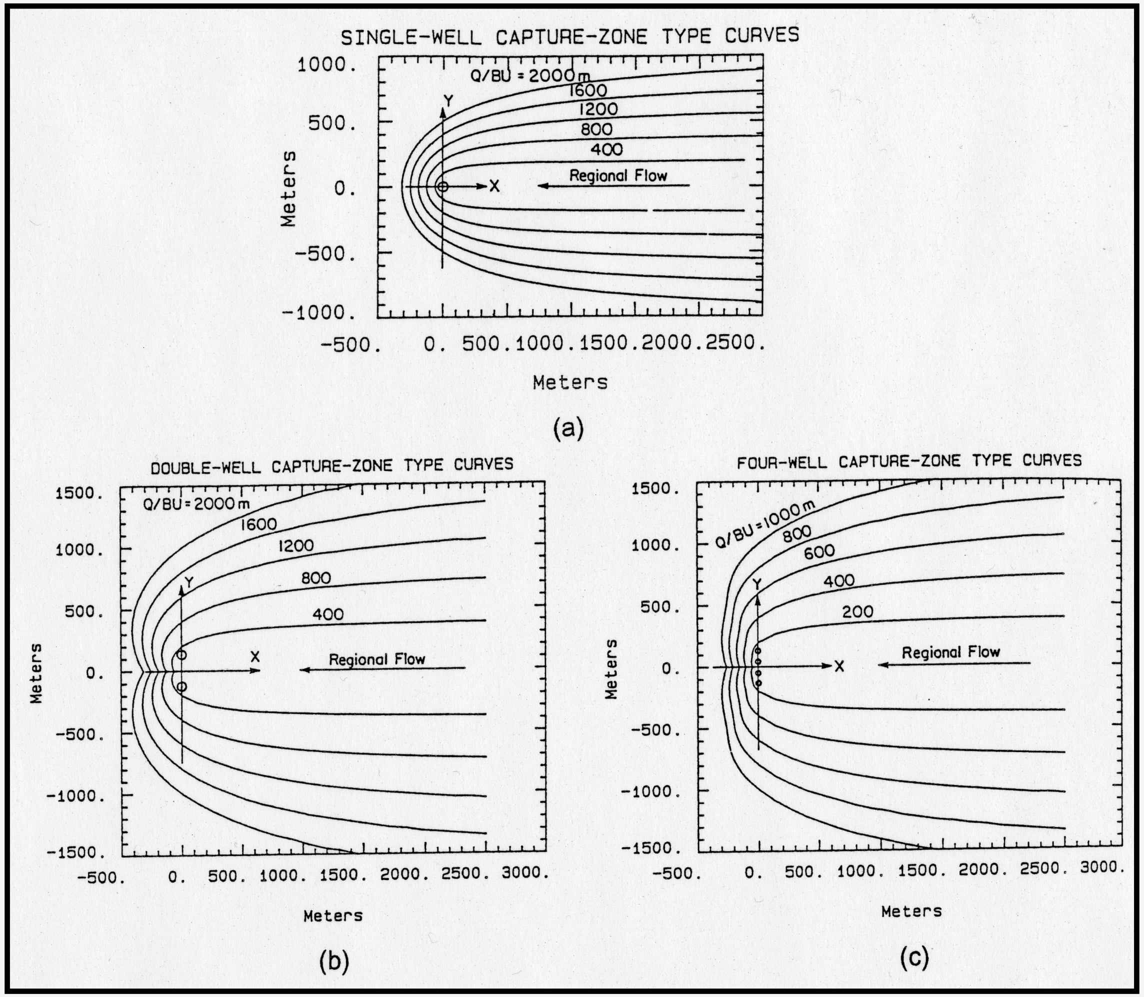
Some things just confuse…

Capture zones

UNIVERSITY OF WATERLOO

Capture Zones...

capture zone type curves & other tools exist to help design & optimize wells



(from Bedient et al., 1999)

Dewatering systems

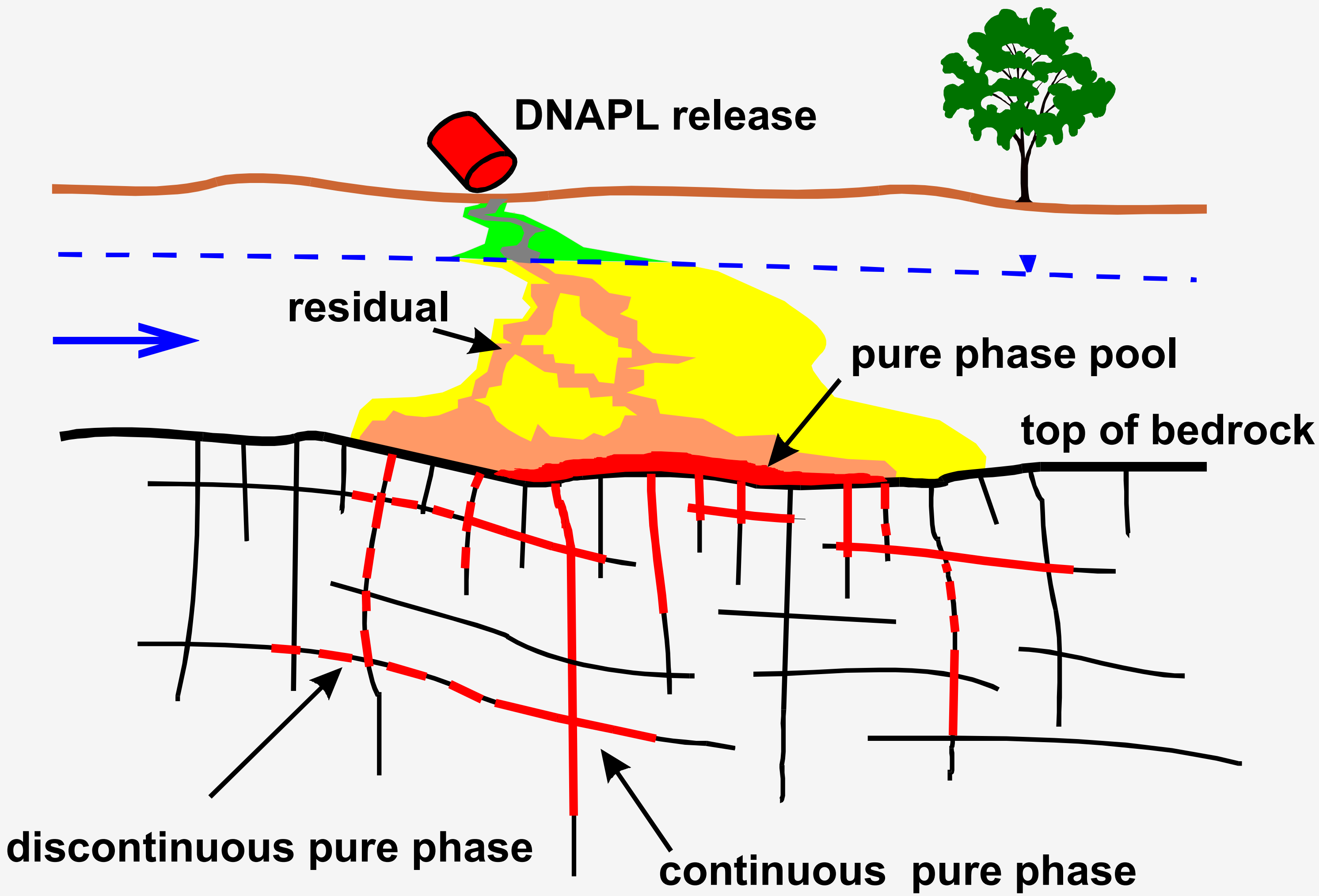
UNIVERSITY OF WATERLOO

Dewatering System

Dewatering System

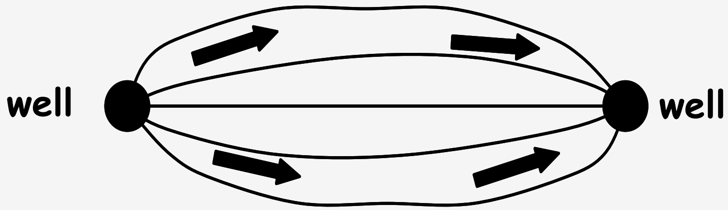
Organic compounds

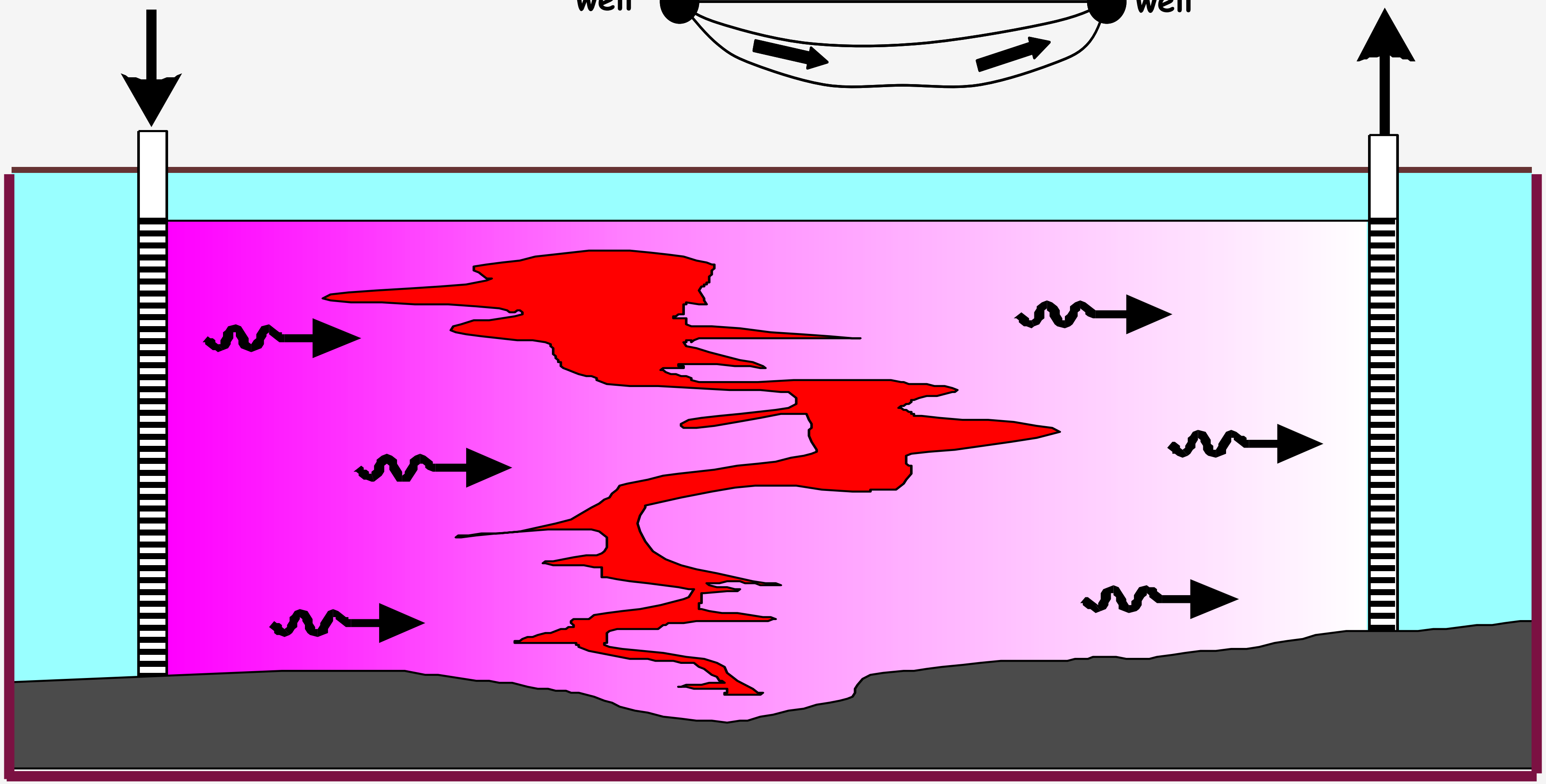
UNIVERSITY OF WATERLOO



GW Recycling

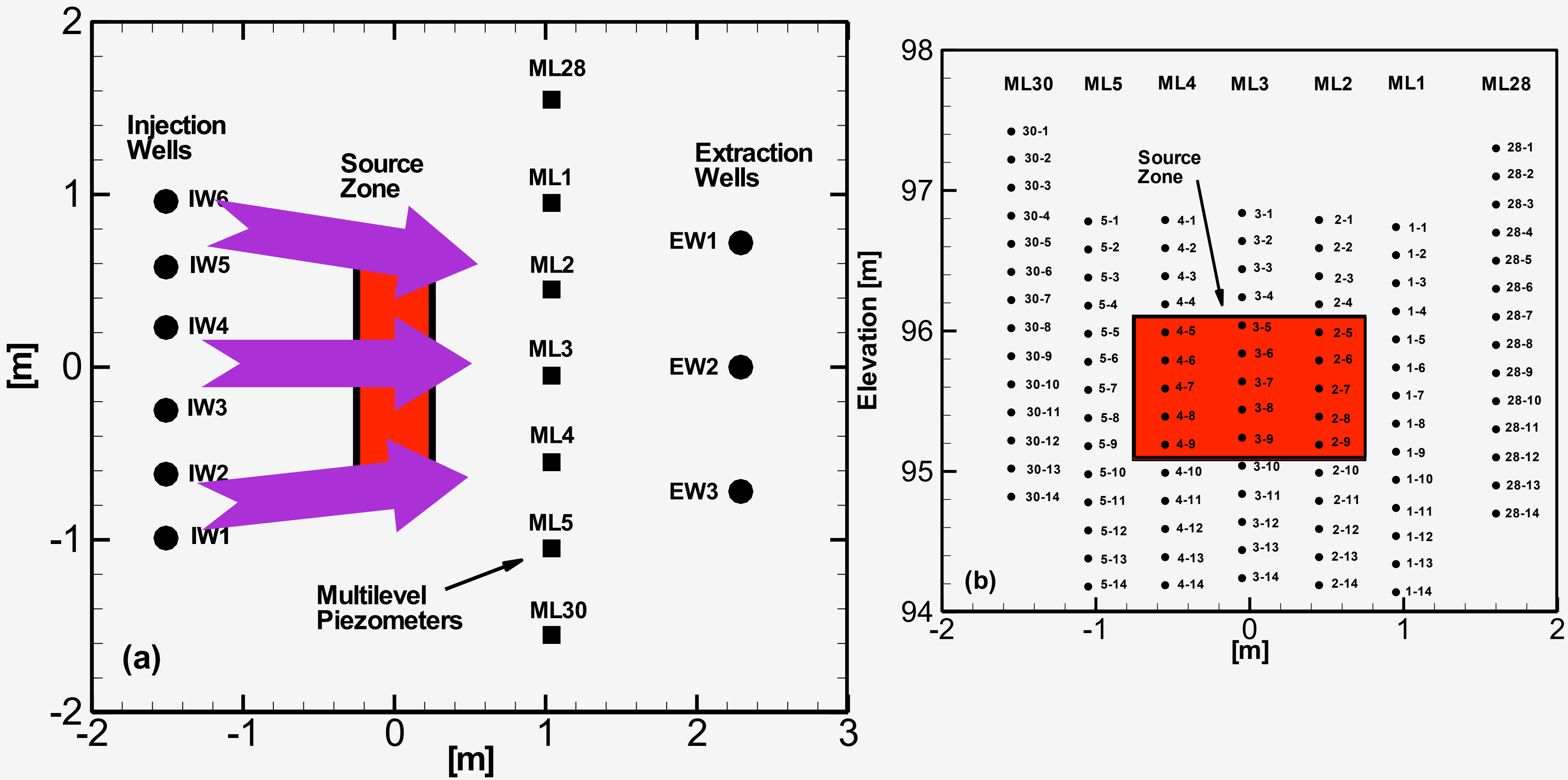
UNIVERSITY OF WATERLOO





GW Recycling

UNIVERSITY OF WATERLOO



from Thomson et al., 2007

Mass Balance

UNIVERSITY OF WATERLOO

40% of the injected mass (+ by products) was recovered….

Lesson learned - 3

UNIVERSITY OF WATERLOO

- ❑ Hard to engineer simple flow systems
- ❑ Understanding groundwater flow is the key!
- ❑ Transcends the practice

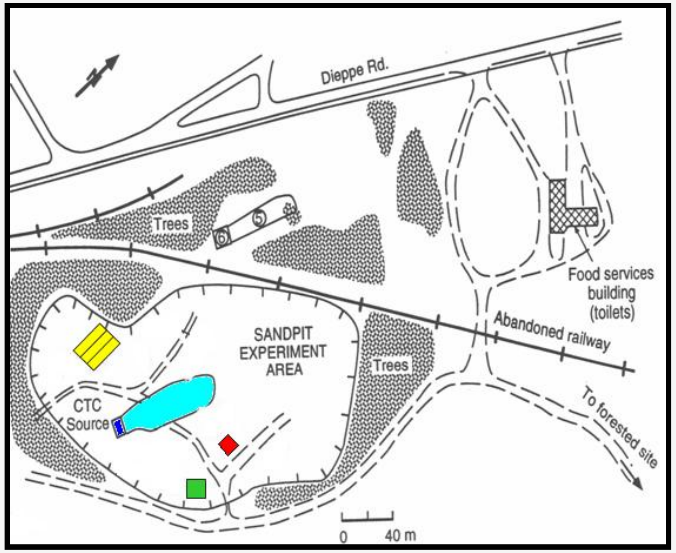
Example 3

UNIVERSITY OF WATERLOO

Geology controls…

CFB Borden

UNIVERSITY OF WATERLOO



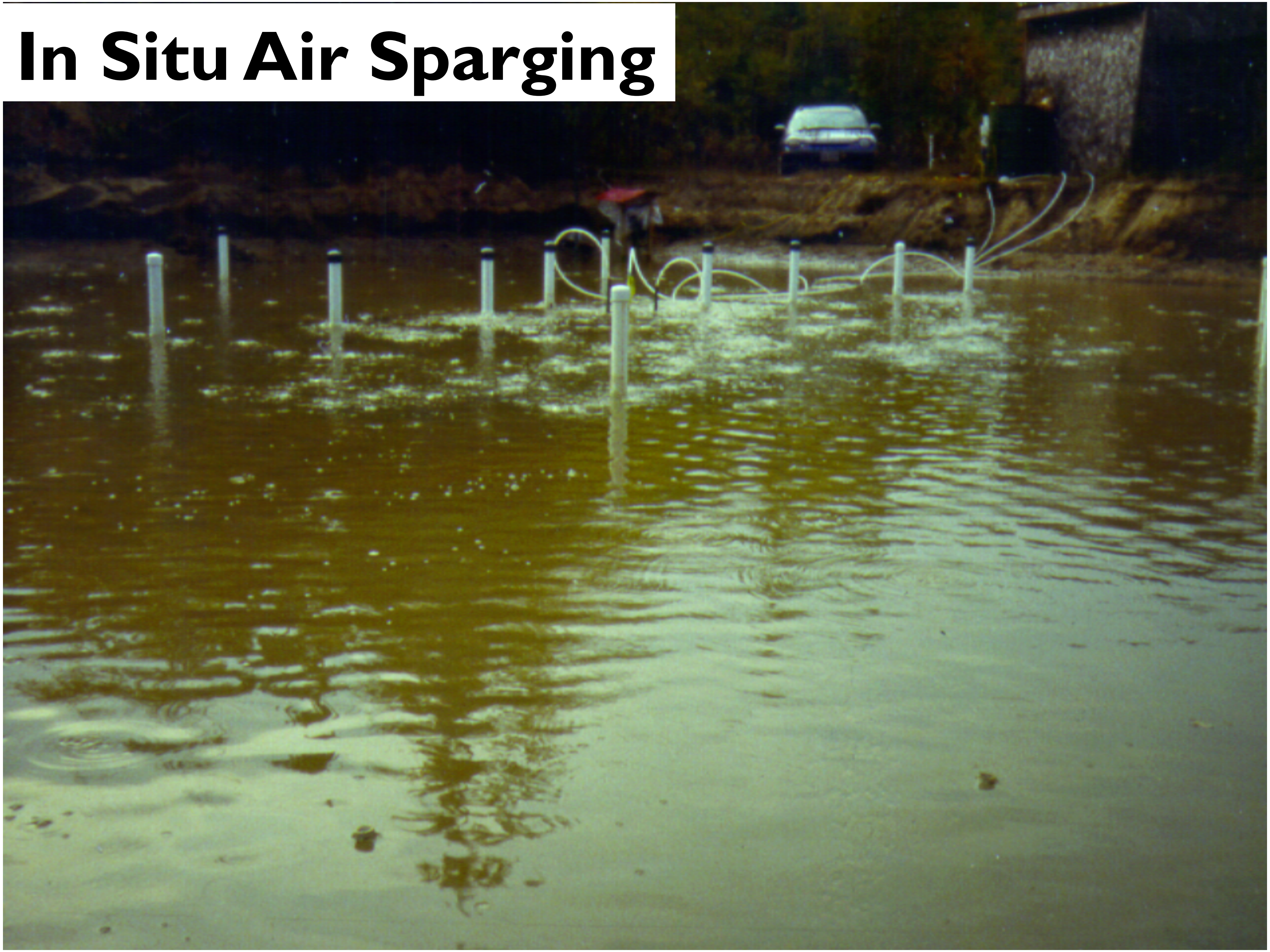
Porosity:	0.33
Bulk Density:	1.81 g/cm^3
Hydraulic Conductivity:	$7x10^{-5}$ m/s
Depth to Water Table:	varies, 0 - 1.5 mbgs
Hydraulic Gradient:	mean 0.0039
Groundwater Velocity:	0.091 m/day

CFB Borden

UNIVERSITY OF WATERLOO

cm scale variations in hydraulic conductivity

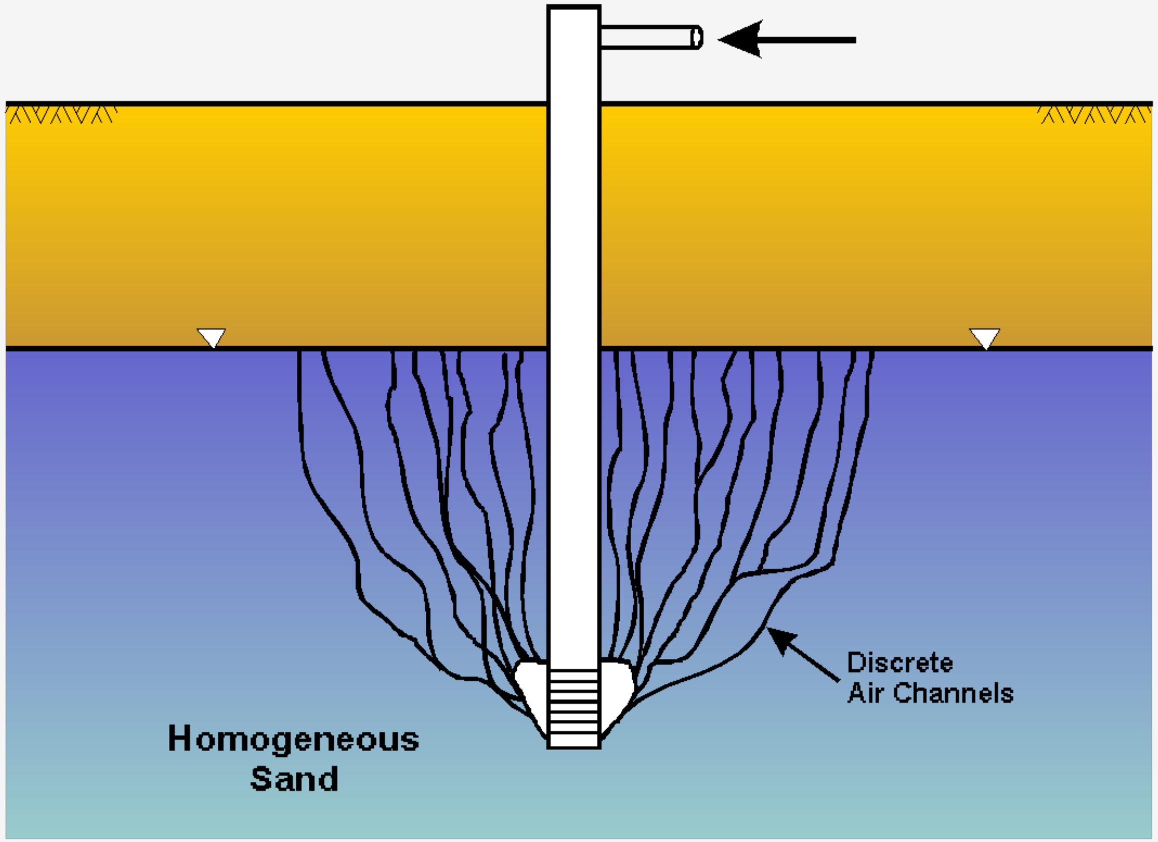
In Situ Air Sparging



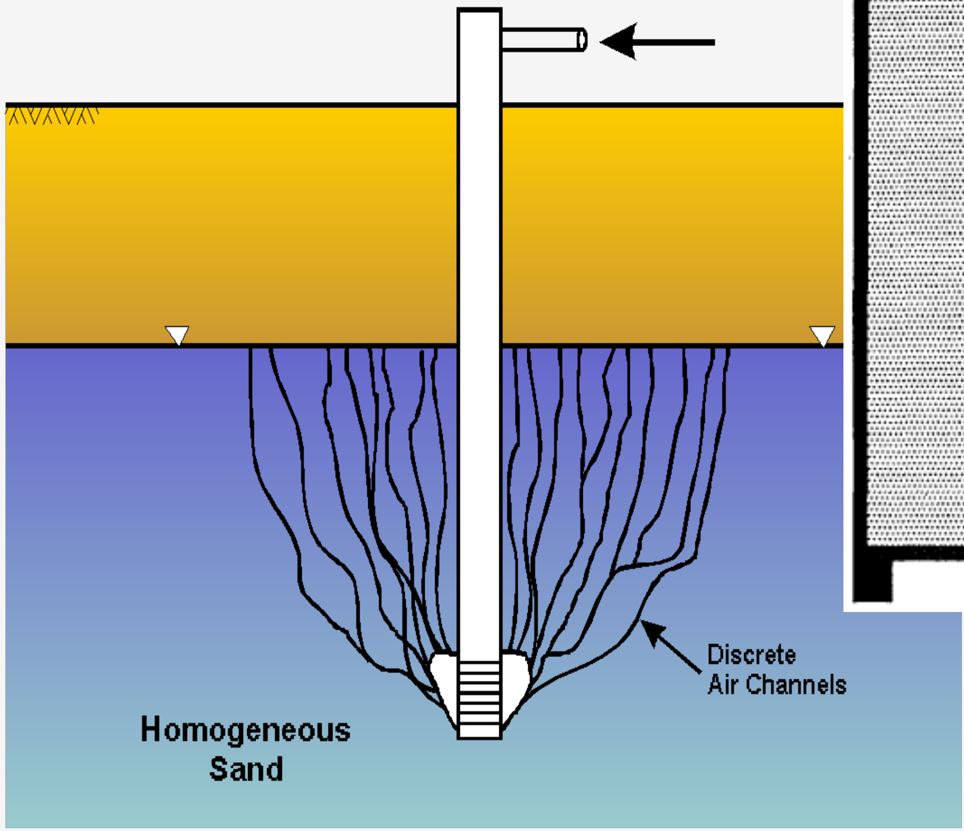
Injection of air

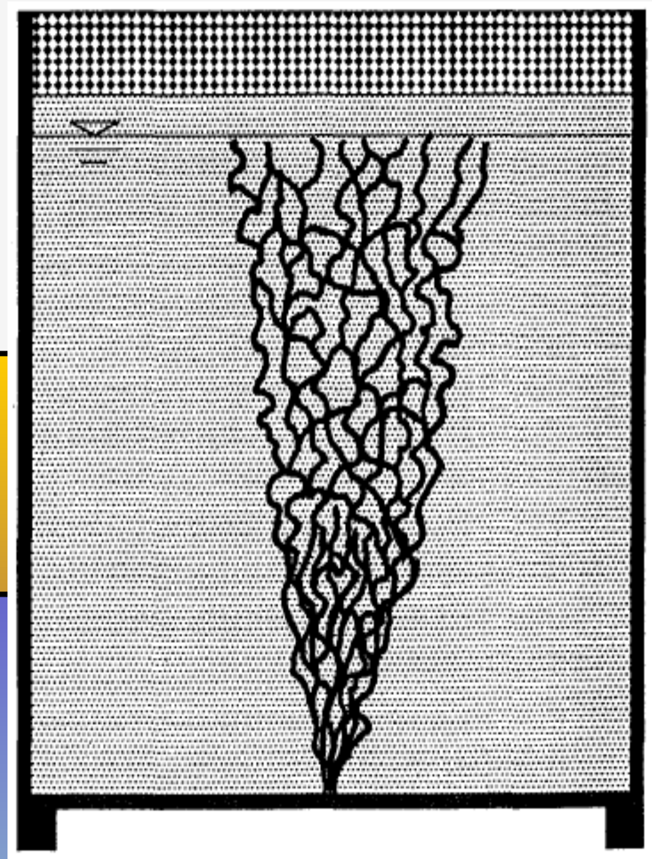
UNIVERSITY OF WATERLOO

In situ air sparging



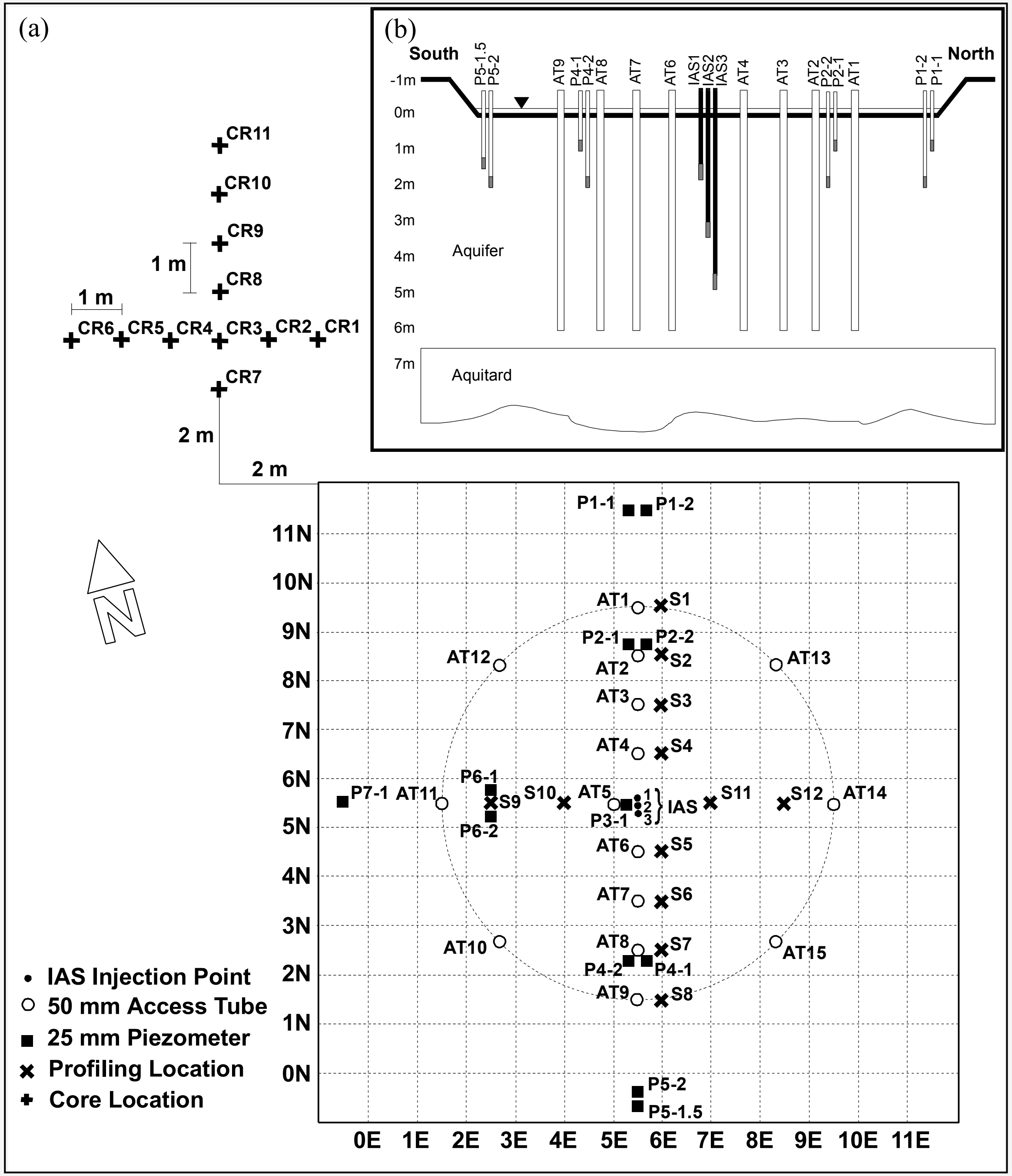
Air channel distribution





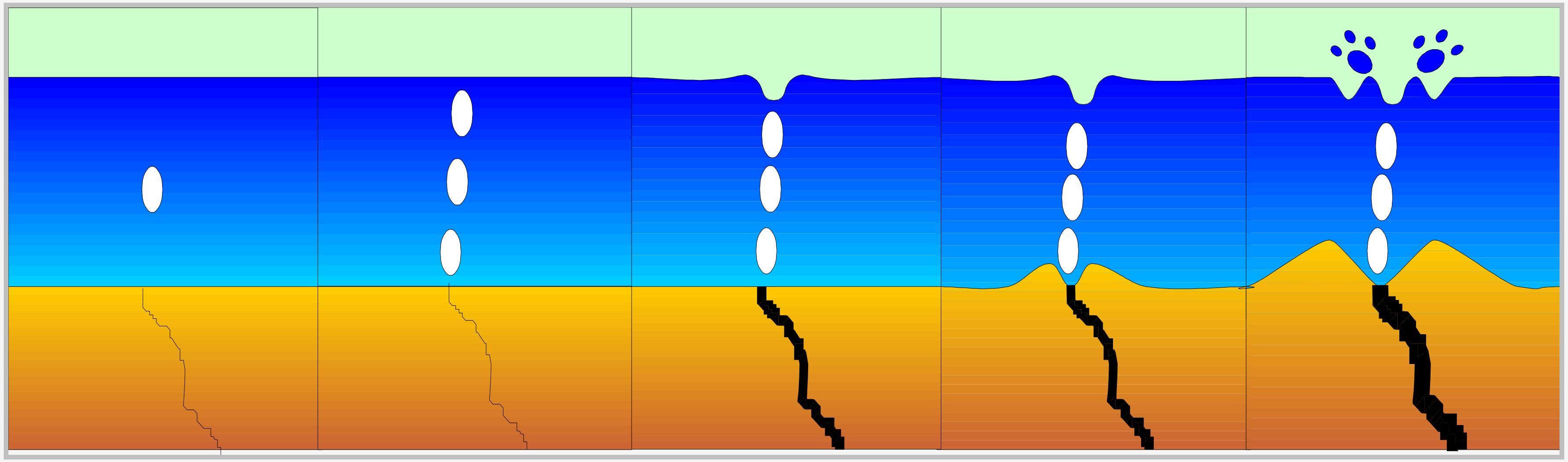
Ji et al., GWMR, 13(4): 115-126

Field Setup


(a)
(b)
South
North
Aquifer
Aquitard
CR1
CR2
CR3
CR4
CR5
CR6
CR7
CR8
CR9
CR10
CR11
1 m
2 m
N
IAS Injection Point
50 mm Access Tube
25 mm Piezometer
Profiling Location
Core Location

Air channel descriptions

UNIVERSITY OF WATERLOO

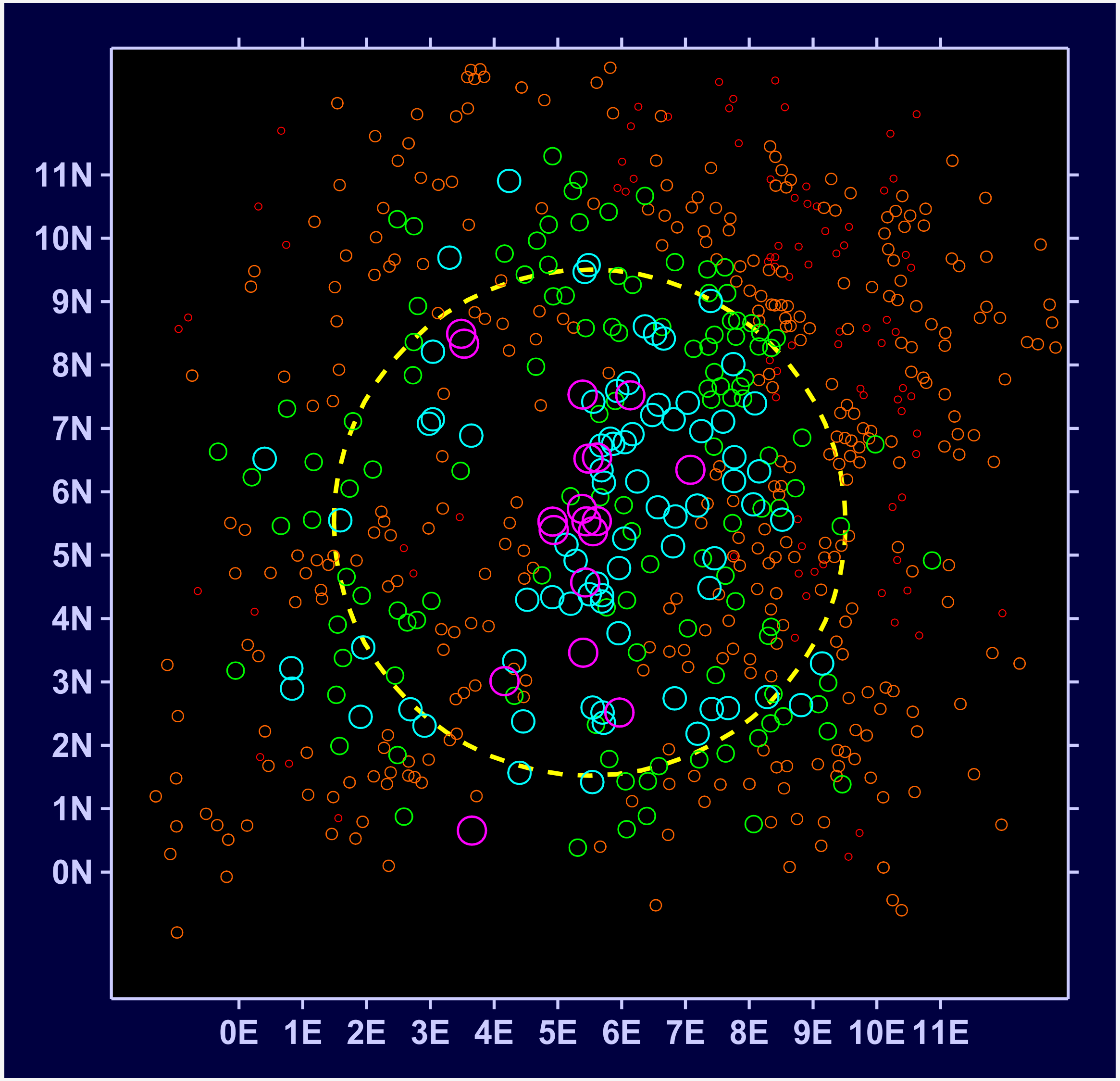


(a) Low/Periodic (b) Medium (c) High (d) Extreme (e) Volatile

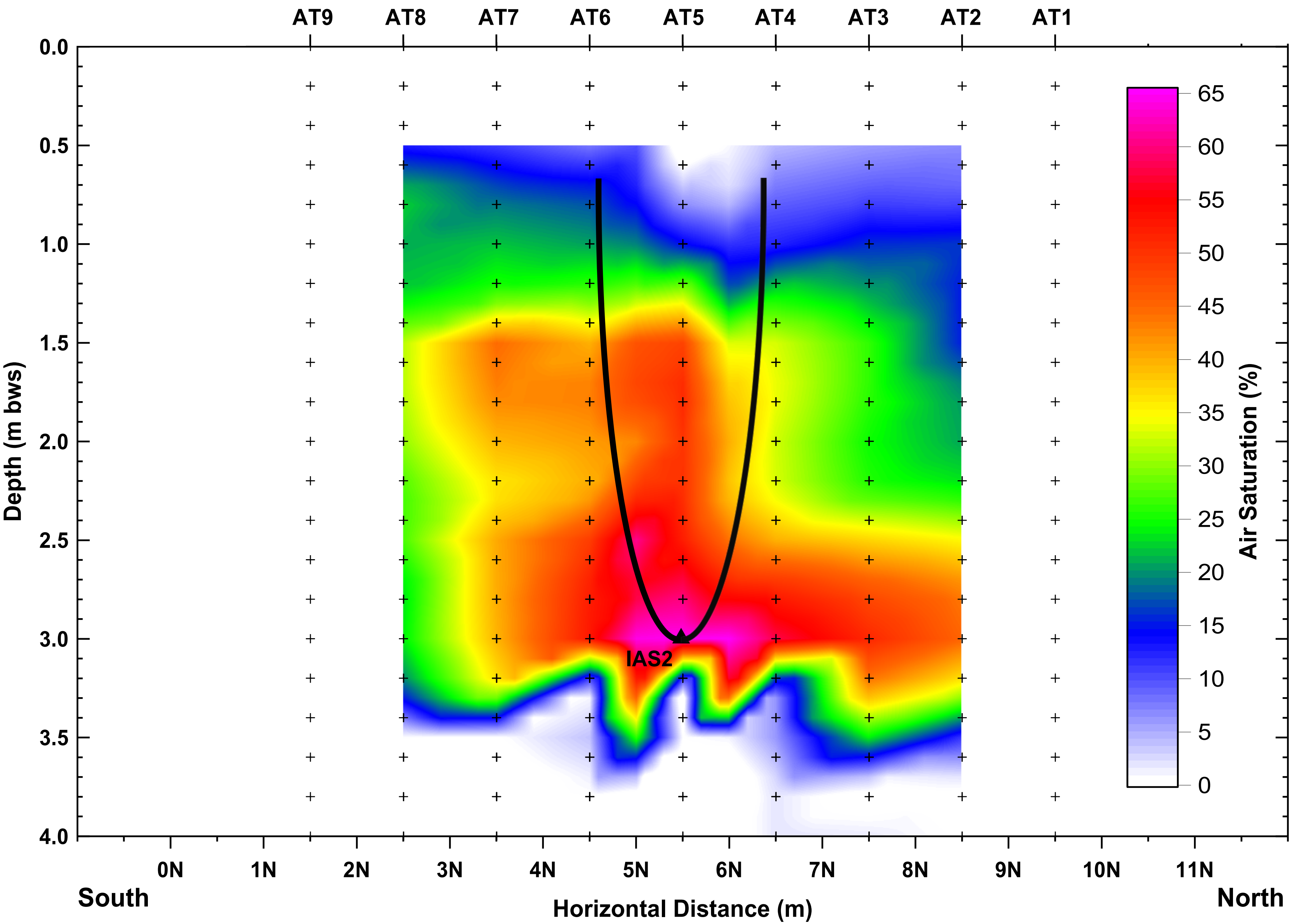
Surface air channels

UNIVERSITY OF WATERLOO

Air channeling evident throughout



Air Saturation: Cross-Borehole Ground Penetrating Radar



Lesson learned - 4

UNIVERSITY OF WATERLOO

- Subtle changes in sediment structure control many important processes
- Be prepared for the unexpected & don’t be surprised

Example 4

UNIVERSITY OF WATERLOO

Good ideas can stall…

DFRTT

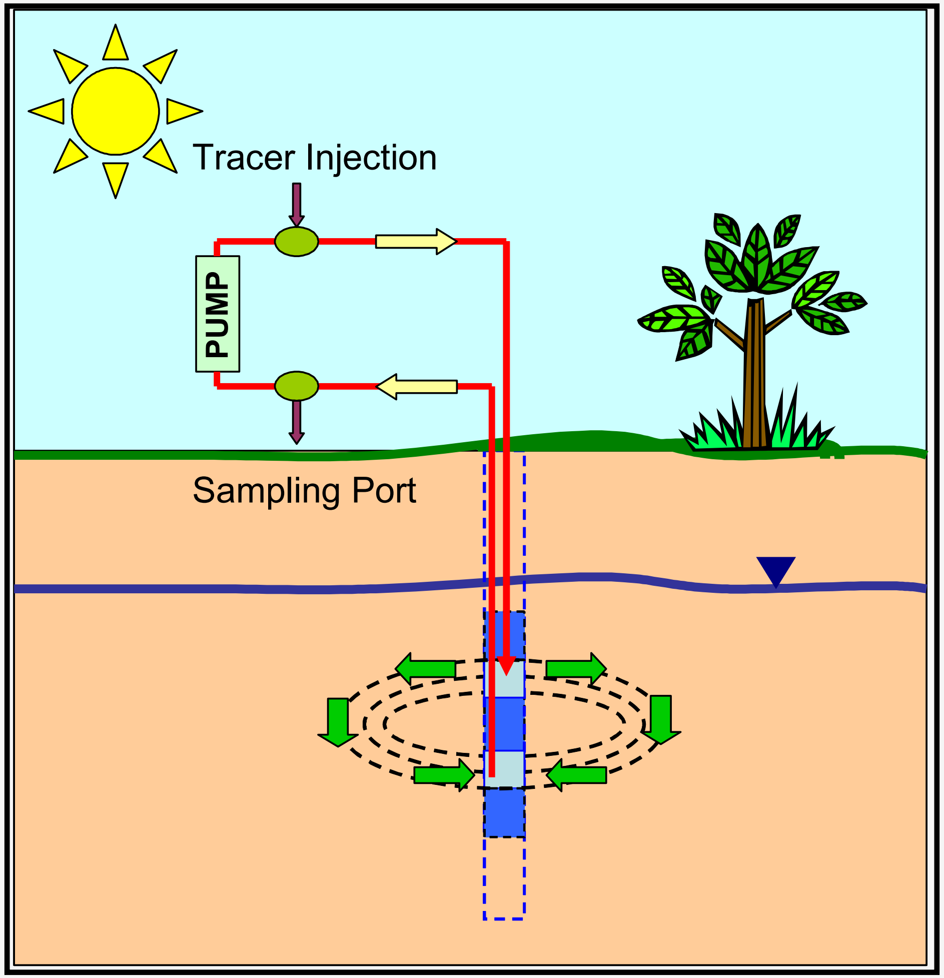
UNIVERSITY OF WATERLOO

Dipole Flow and Reactive Tracer Test (DFRTT) for Aquifer Parameter Estimation

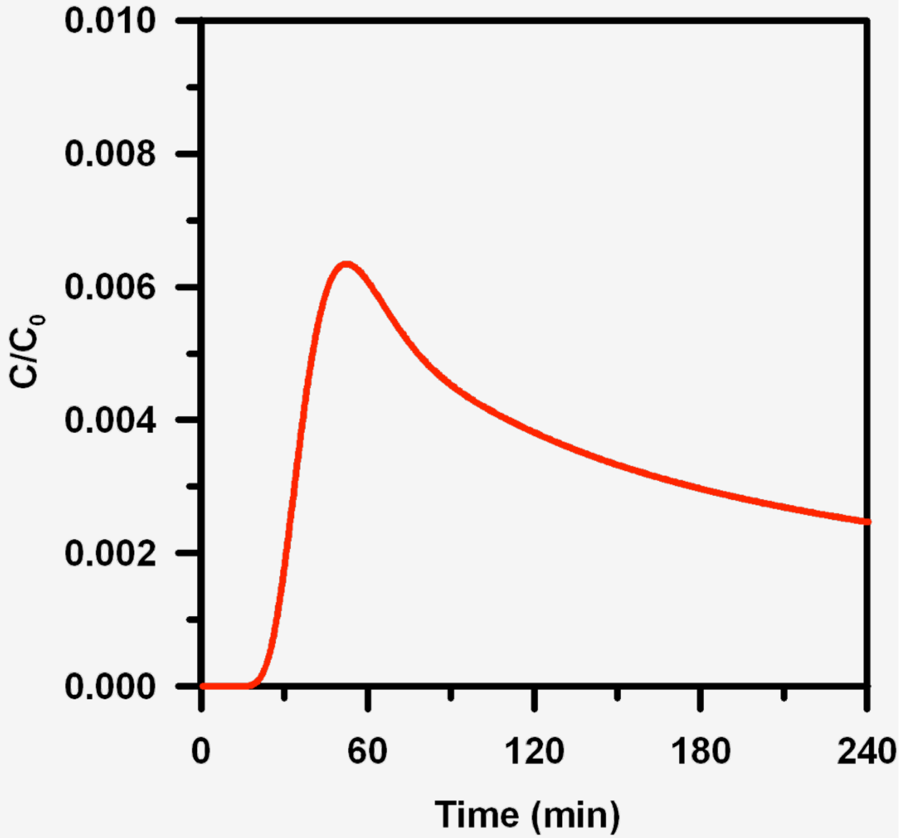
Adaption of some early work by
from Kabala and co-workers

DFRTT

UNIVERSITY OF WATERLOO



Breakthrough curve at sampling port



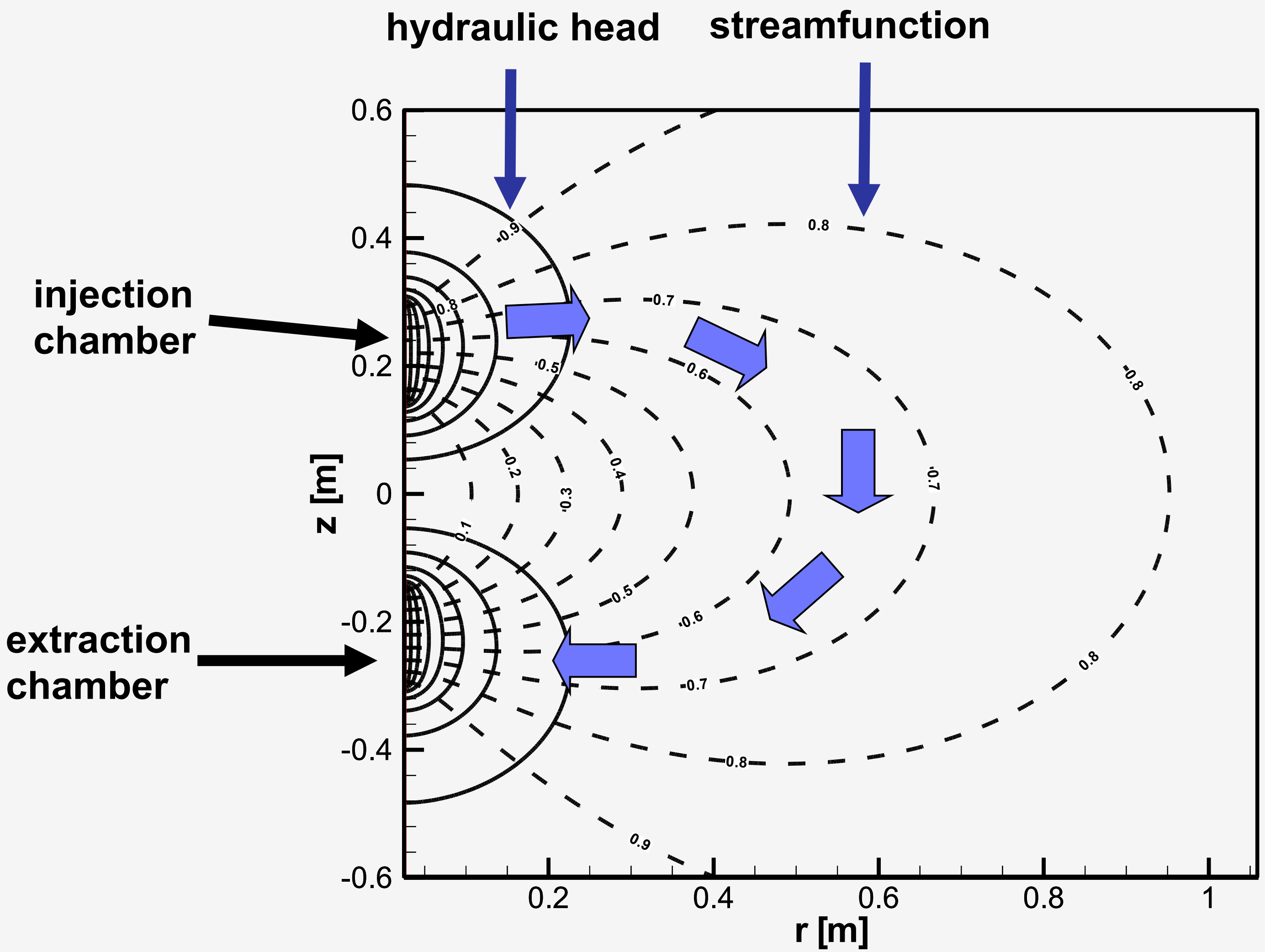
DFRTT

UNIVERSITY OF WATERLOO

- ❑ **Hydraulic conductivity (K)**
- ❑ **Biodegradation properties**
- ❑ **Oxidation/reduction capacity**
- ❑ **Ion exchange capacity**
- ❑ **Sorption properties**

DFRTT

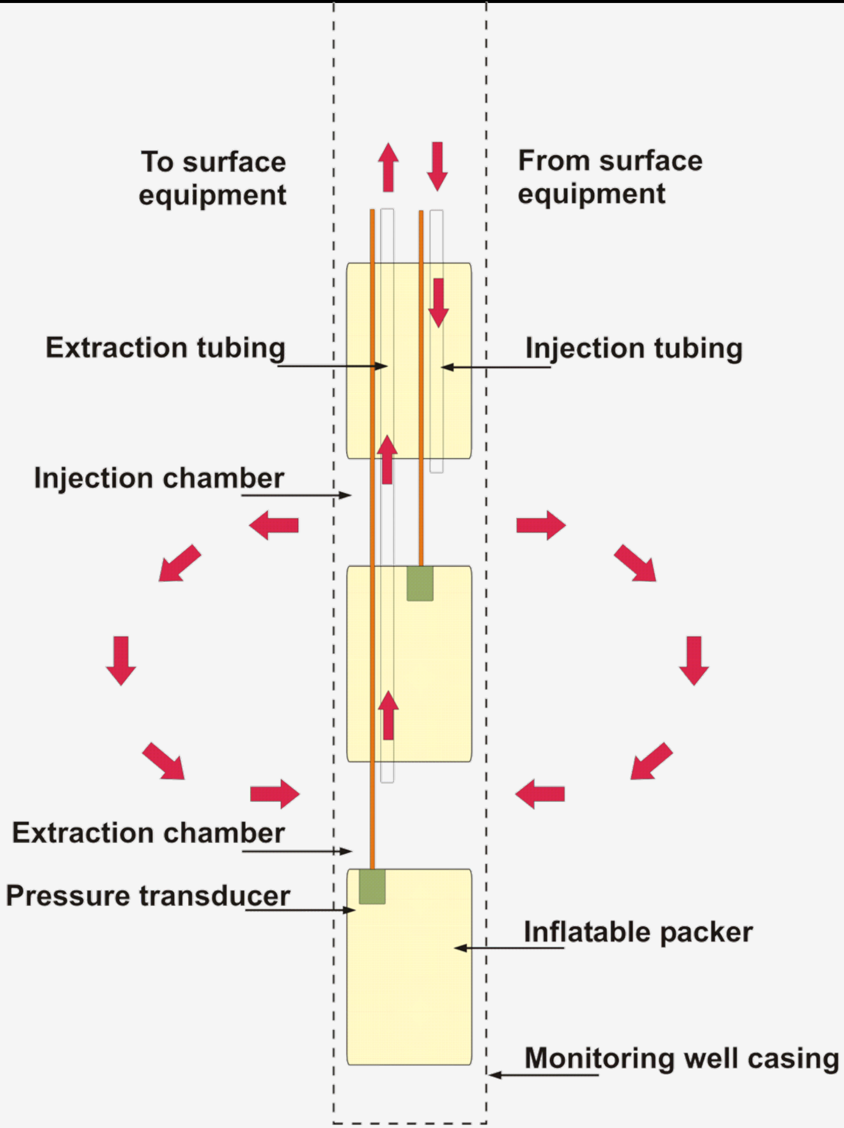
UNIVERSITY OF WATERLOO



- Dependent on dipole probe dimensions and aquifer anisotropy
- Horizontal extent ~2 m
- Vertical extent ~0.8 m

DFRTT

UNIVERSITY OF WATERLOO

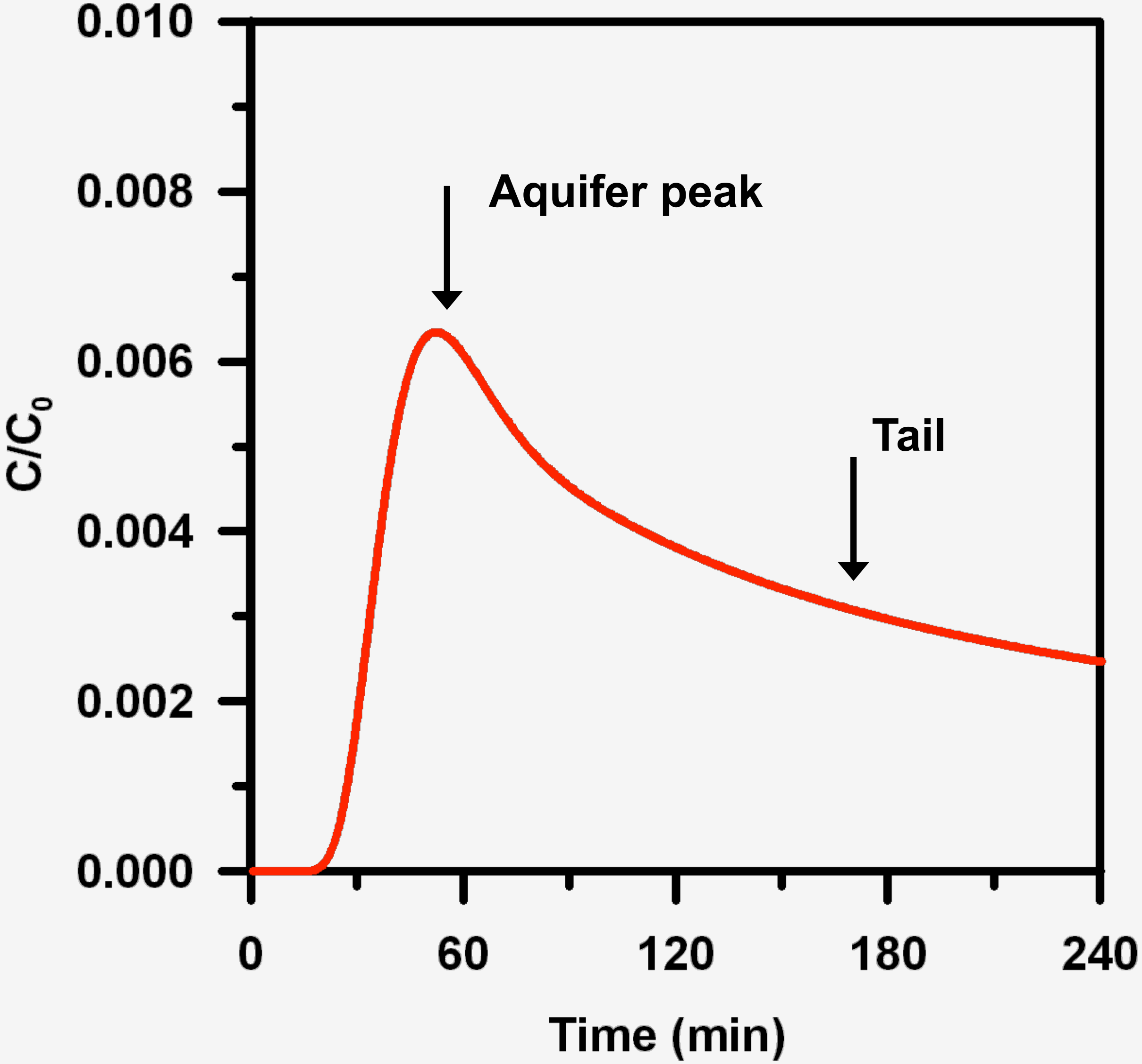


DFRTT

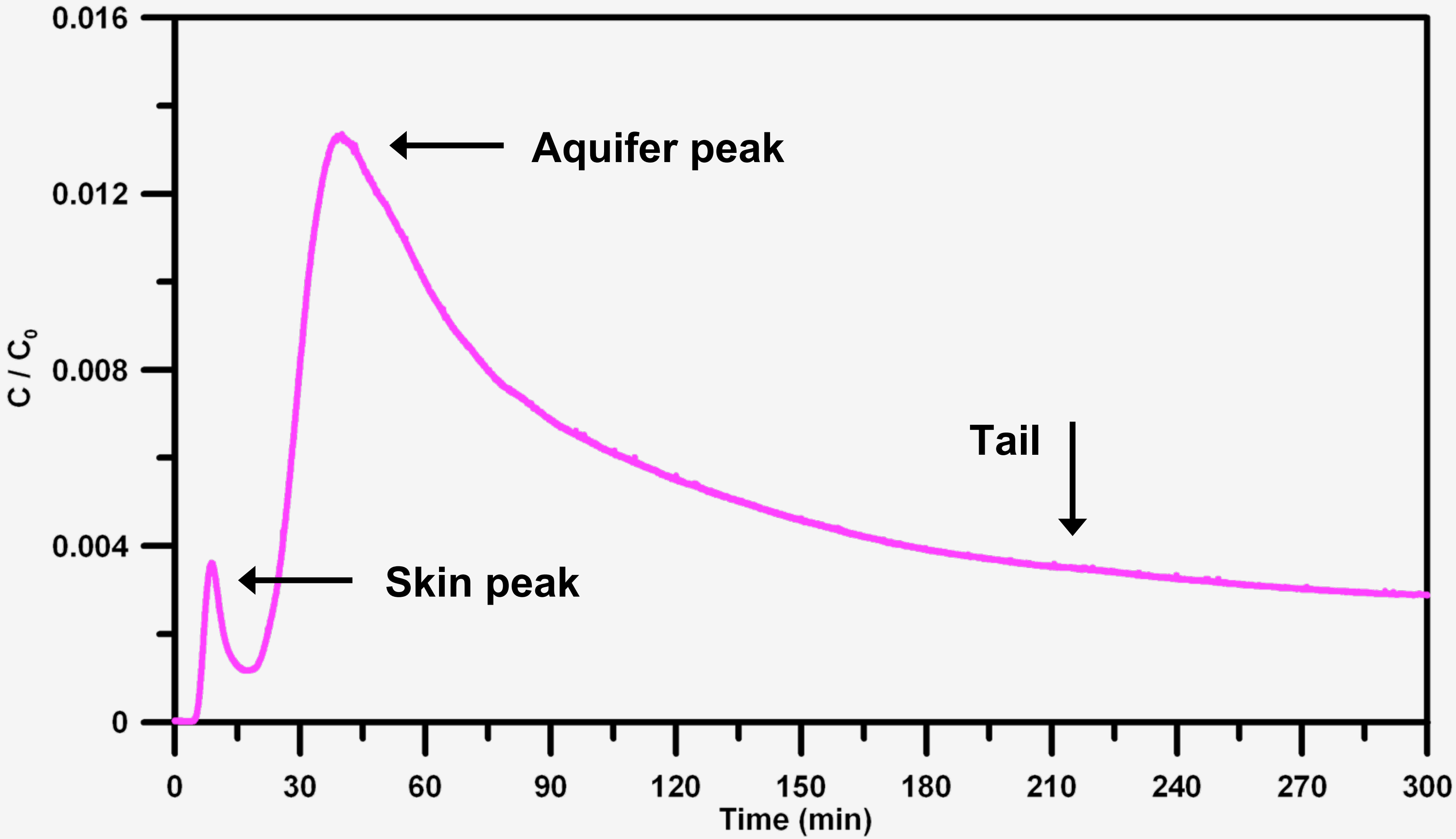
UNIVERSITY OF WATERLOO

Expected Behaviour

UNIVERSITY OF WATERLOO

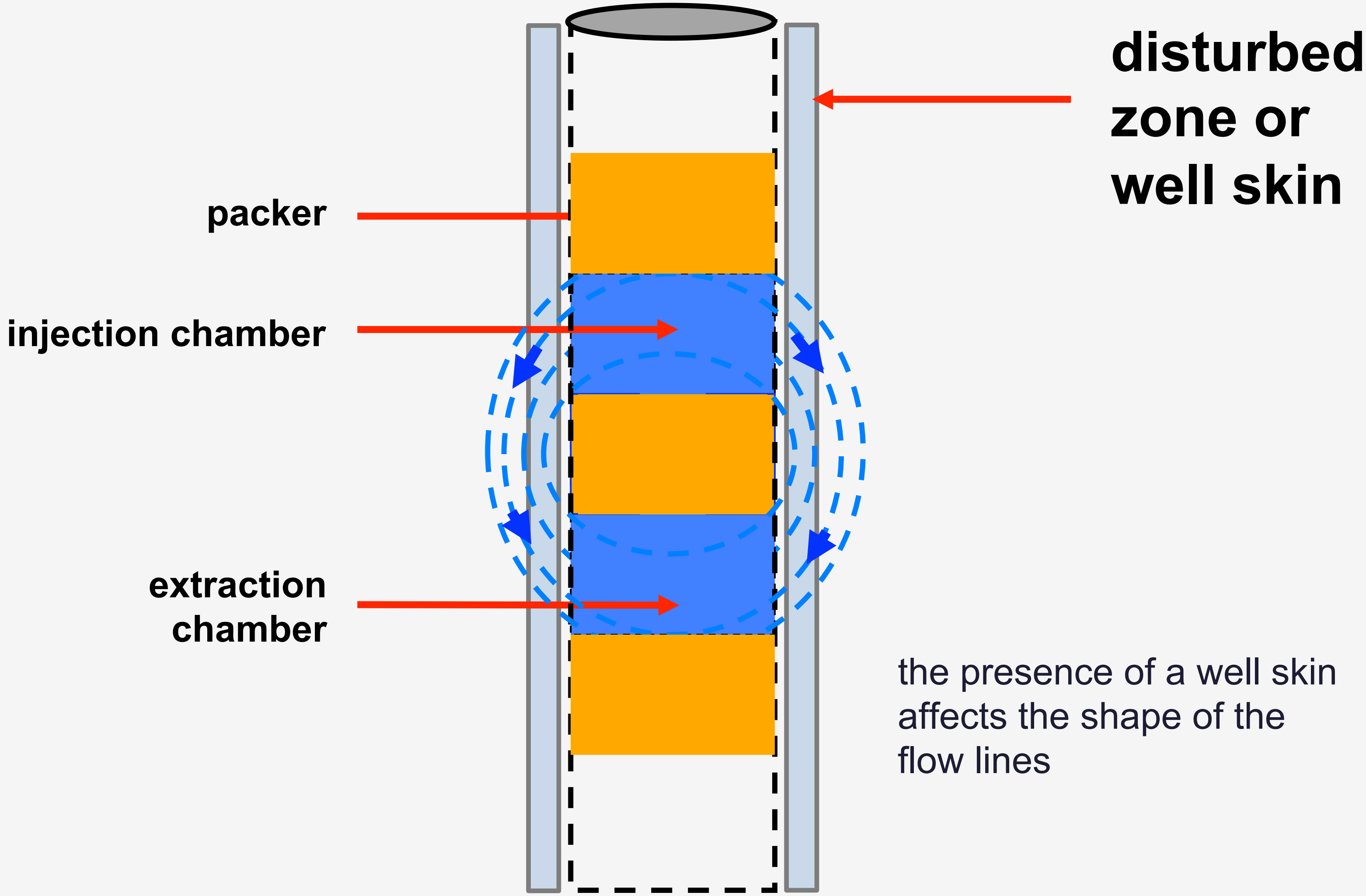


Observed behaviour



Well skin

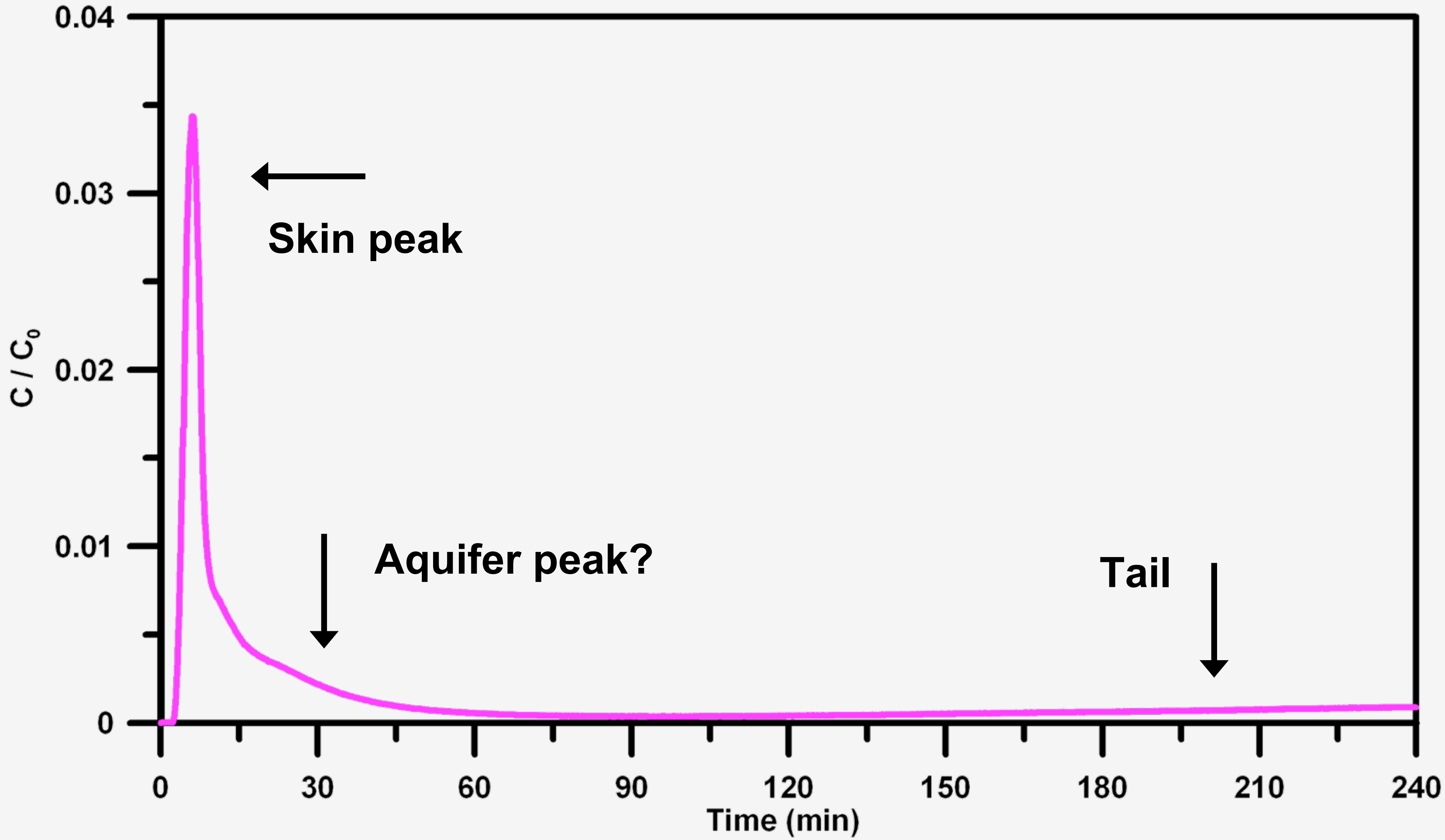
UNIVERSITY OF WATERLOO



the presence of a well skin affects the shape of the flow lines

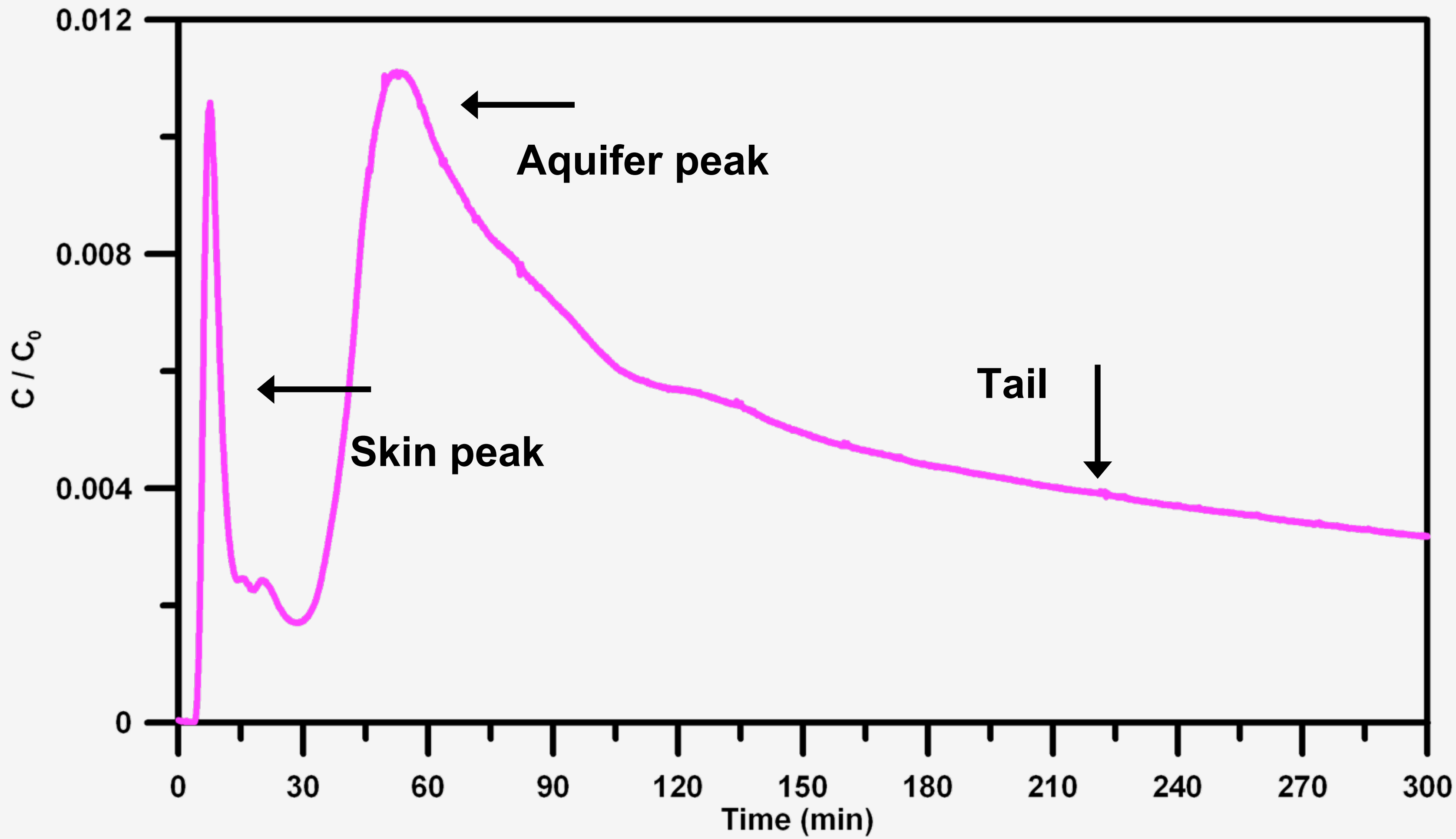
Observed behaviour

UNIVERSITY OF WATERLOO



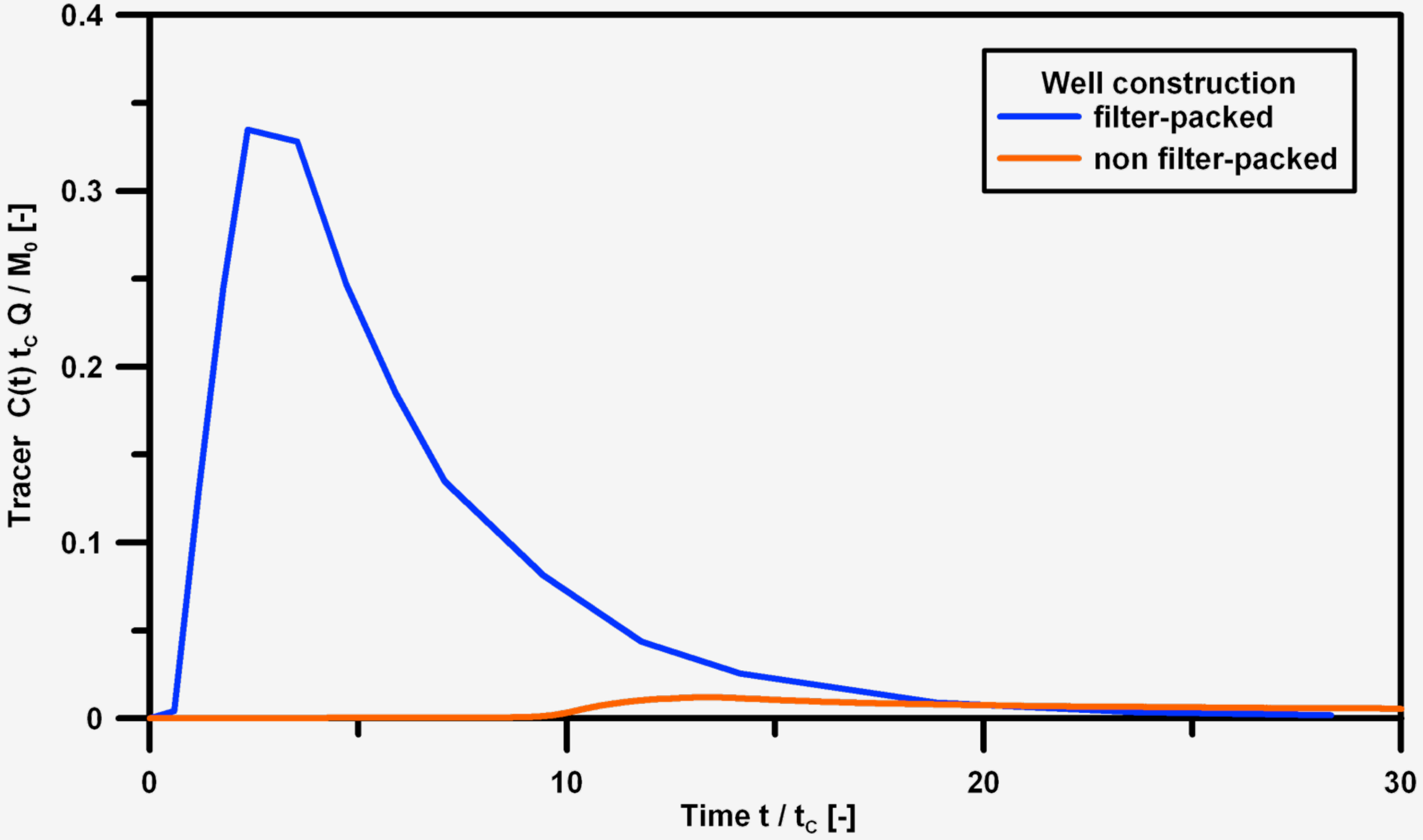
Observed Behaviour

UNIVERSITY OF WATERLOO



Filter packed wells

UNIVERSITY OF WATERLOO



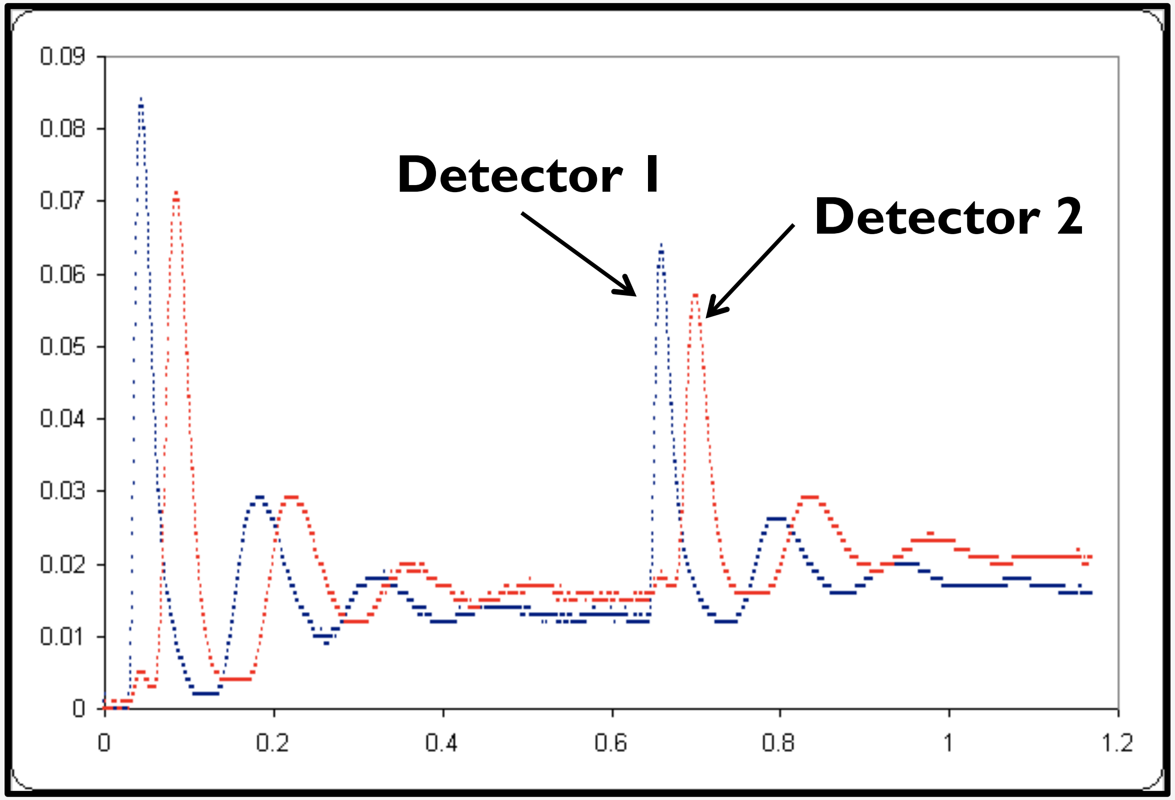
Velocity in well skin

UNIVERSITY OF WATERLOO

- Conductivity detectors
- Relate arrive to velocity

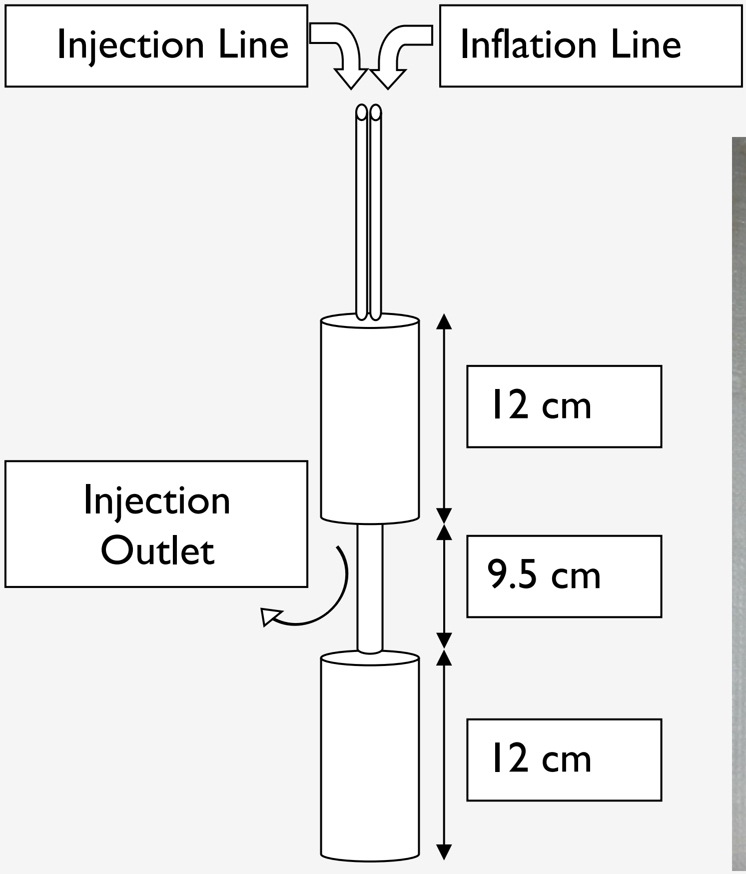
Velocity in well skin

UNIVERSITY OF WATERLOO

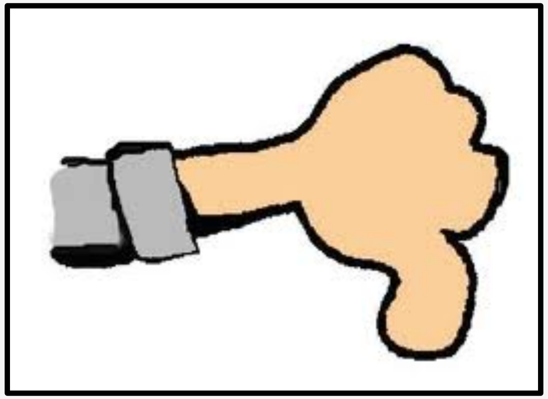


~100 m/day!

Alterations to the well skin



Added various drilling muds to temporary seal the skin



Lesson learned - 5

UNIVERSITY OF WATERLOO

- Simple things are hard to change
- Cannot engineer the system!

Example 6

UNIVERSITY OF WATERLOO

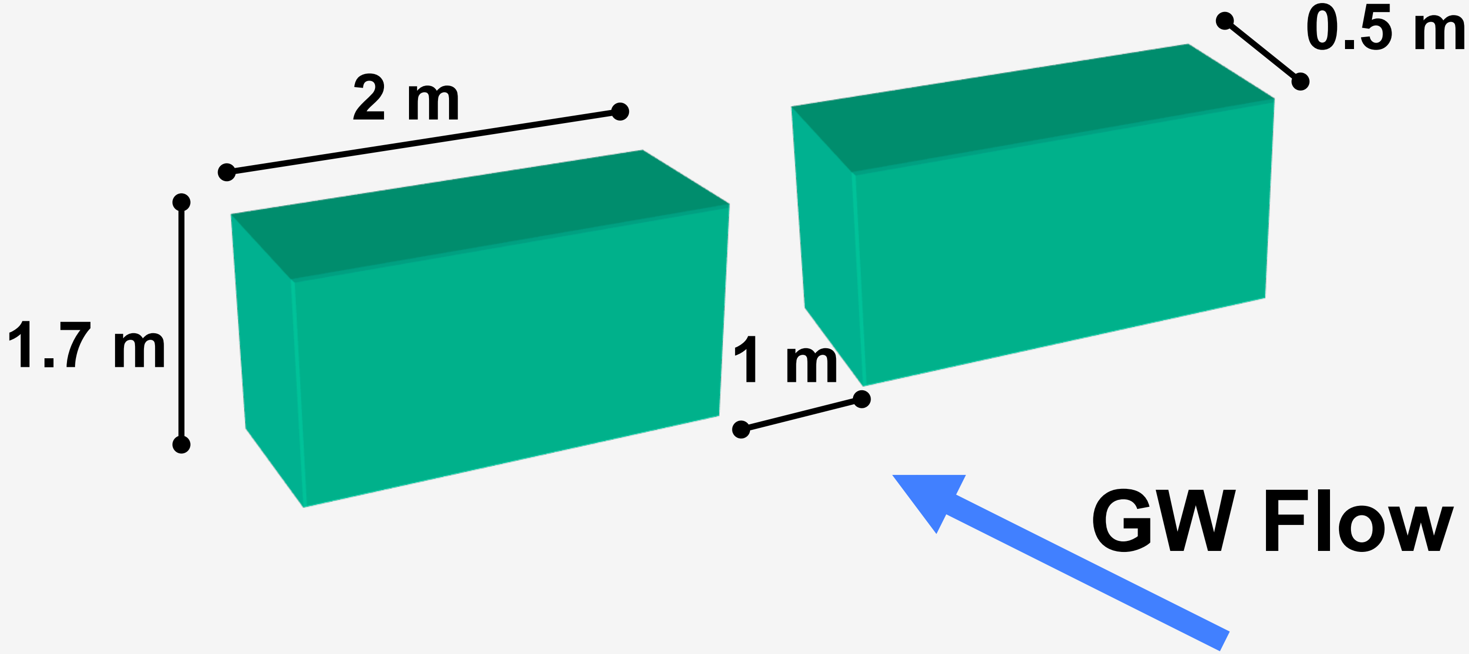
Be patient…

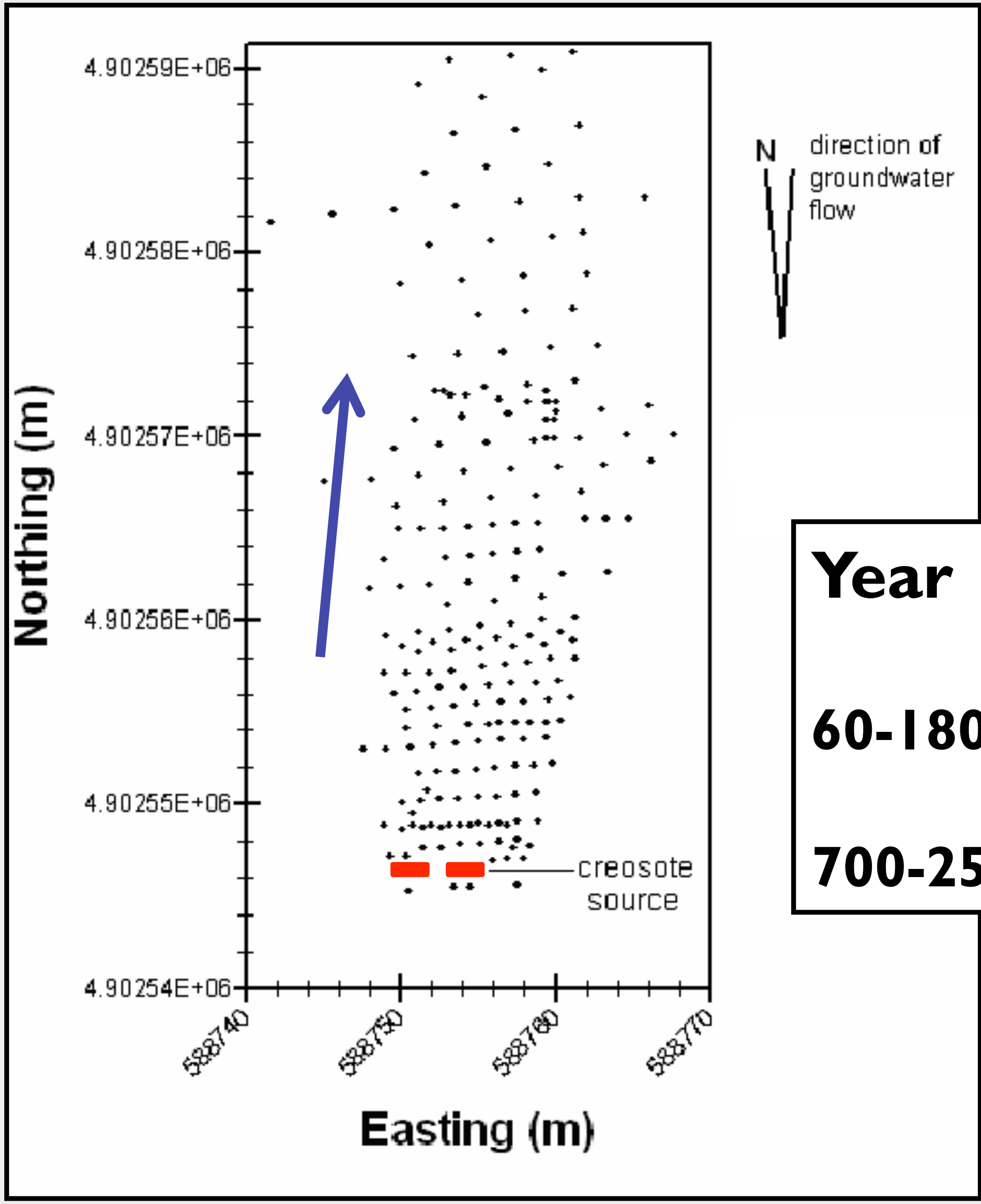
good things will happen!

Contaminant treatment

UNIVERSITY OF WATERLOO

Coal tar creosote was emplaced below the water table in August 1991 (Year 0)



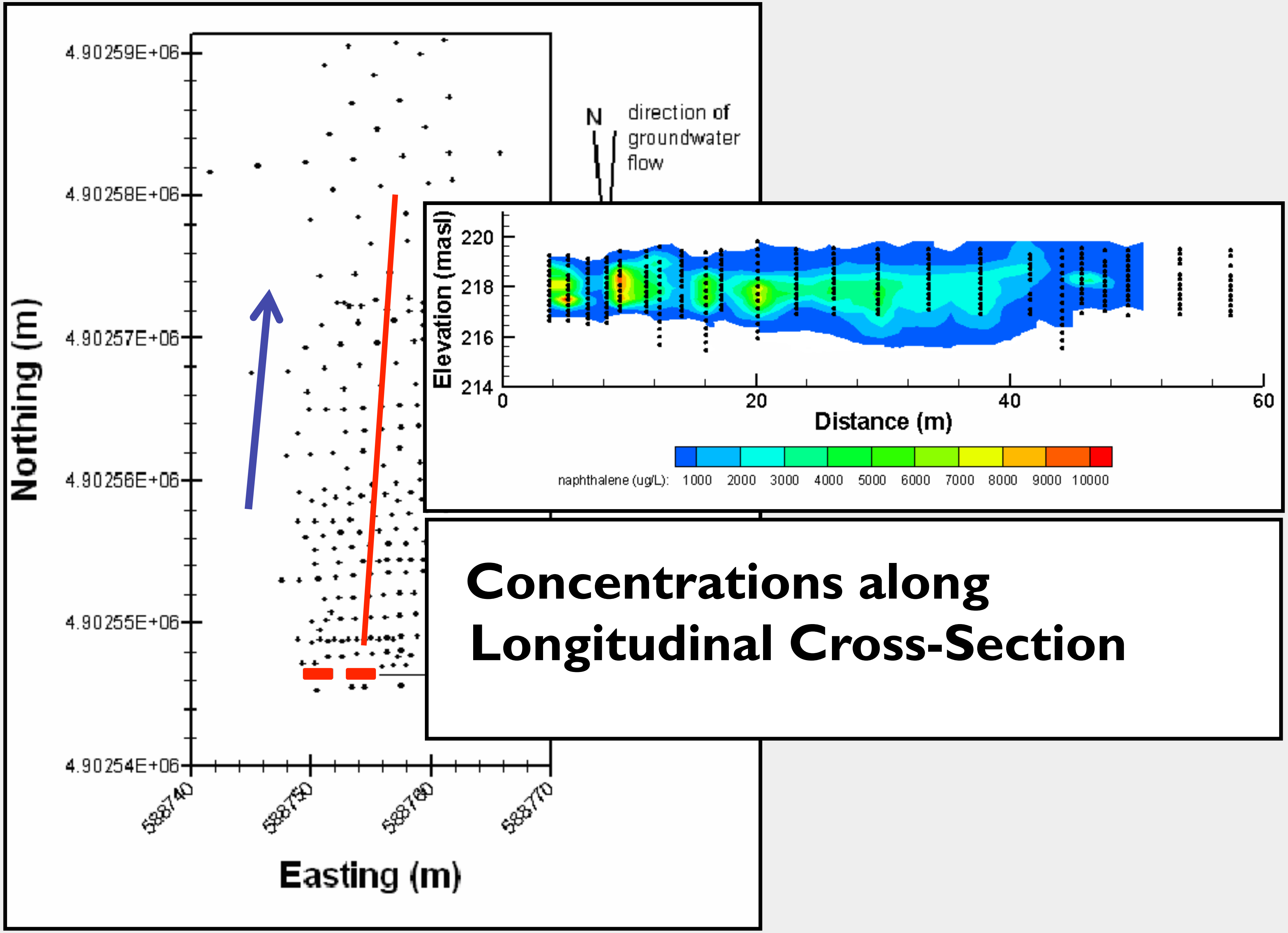


Initial Plume Monitoring

Year 1, 2, 4, 10

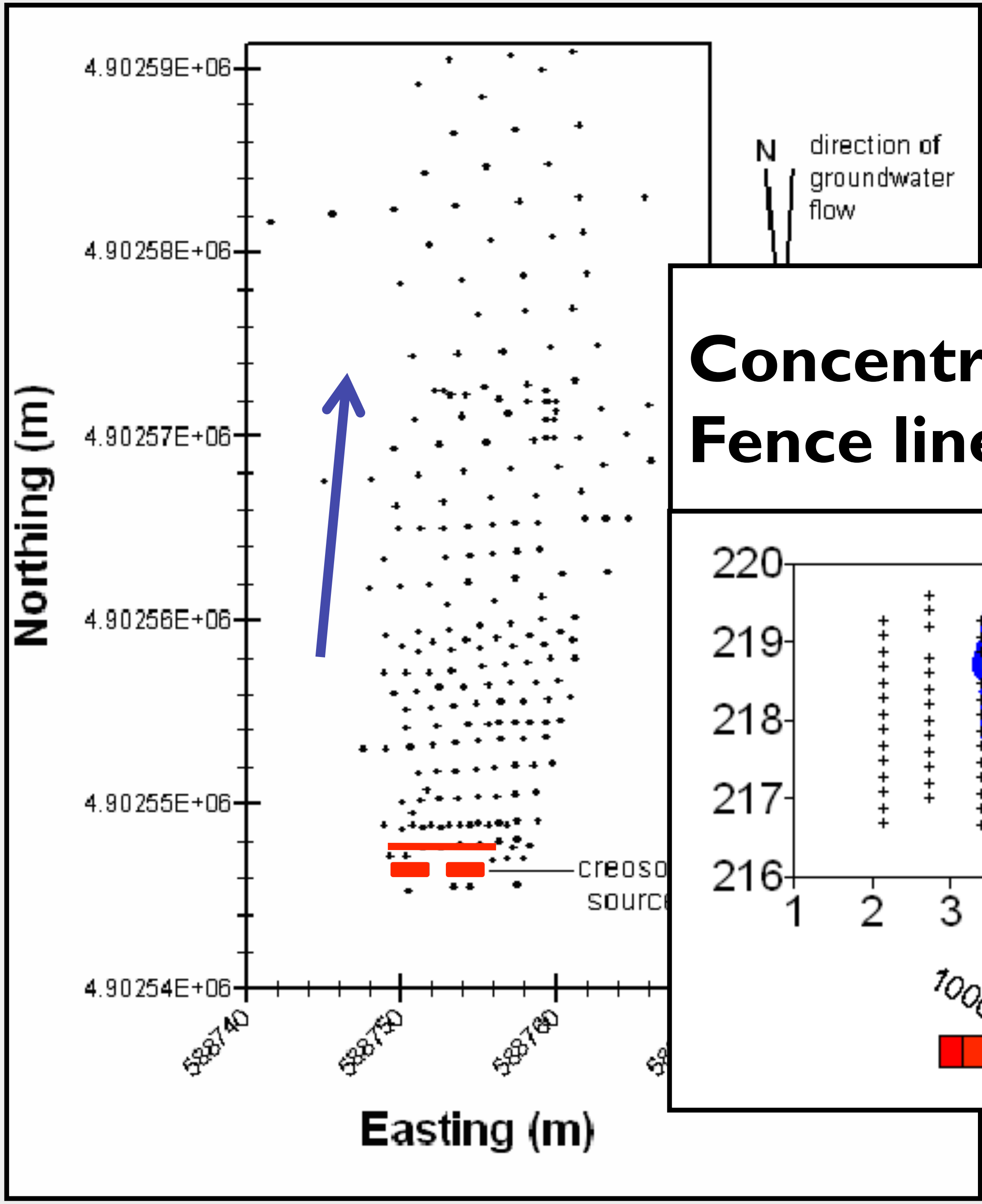
60-180 multilevel wells

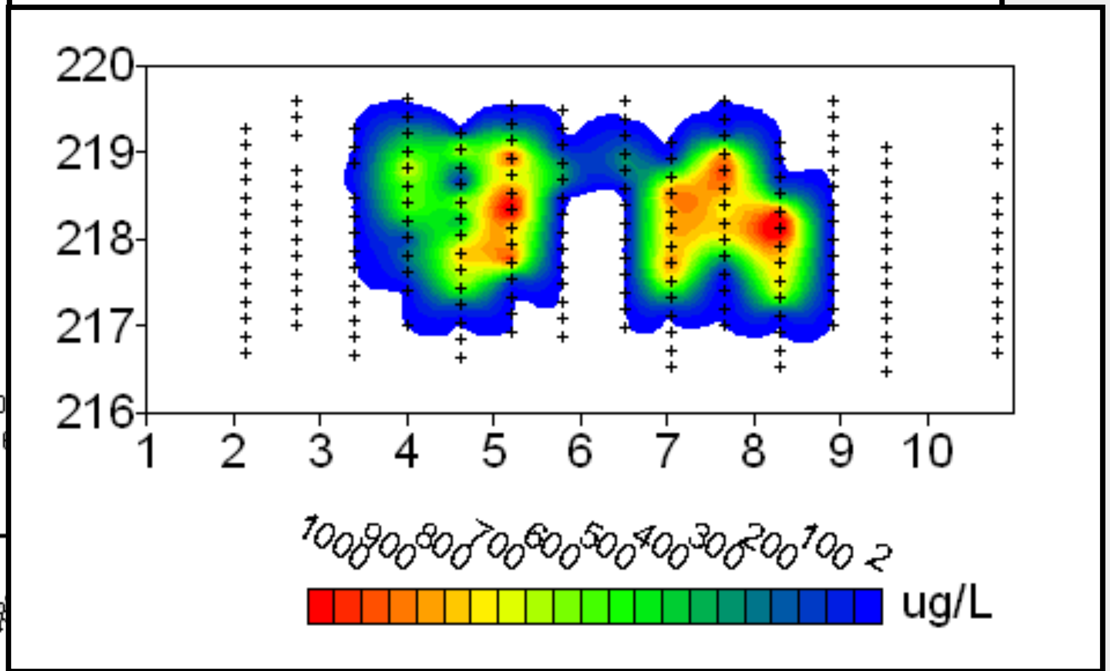
700-2500 samples/episode



Concentrations along Longitudinal Cross-Section

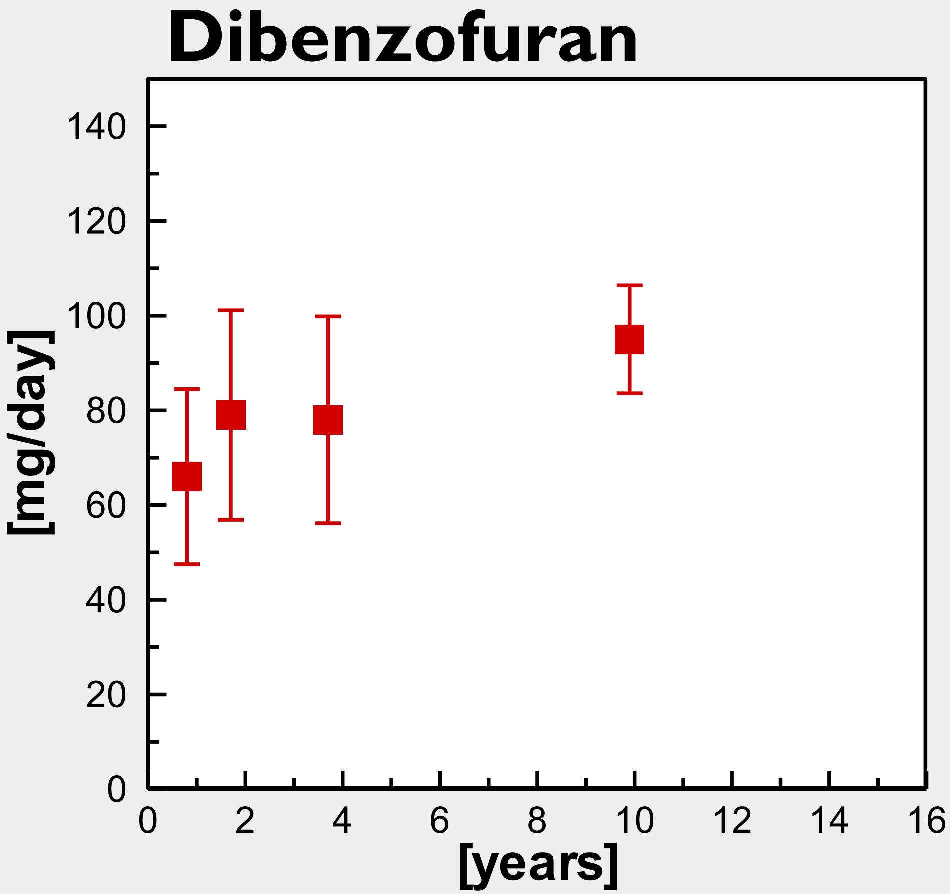
Concentrations at the 3-m Fence line





Mass loading

UNIVERSITY OF WATERLOO



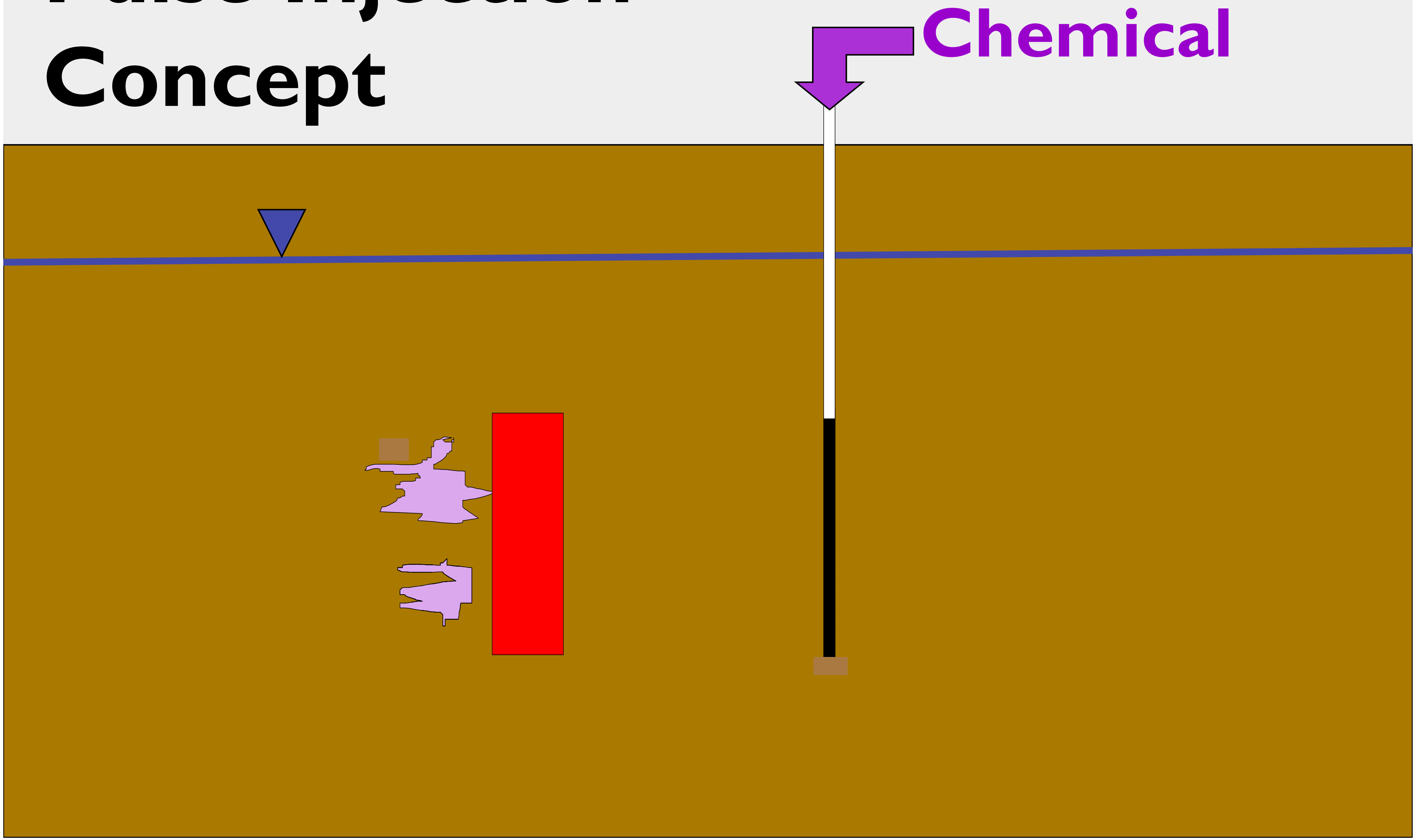
$$\dot{M} = \int q\, C\, dA$$

Treatment details

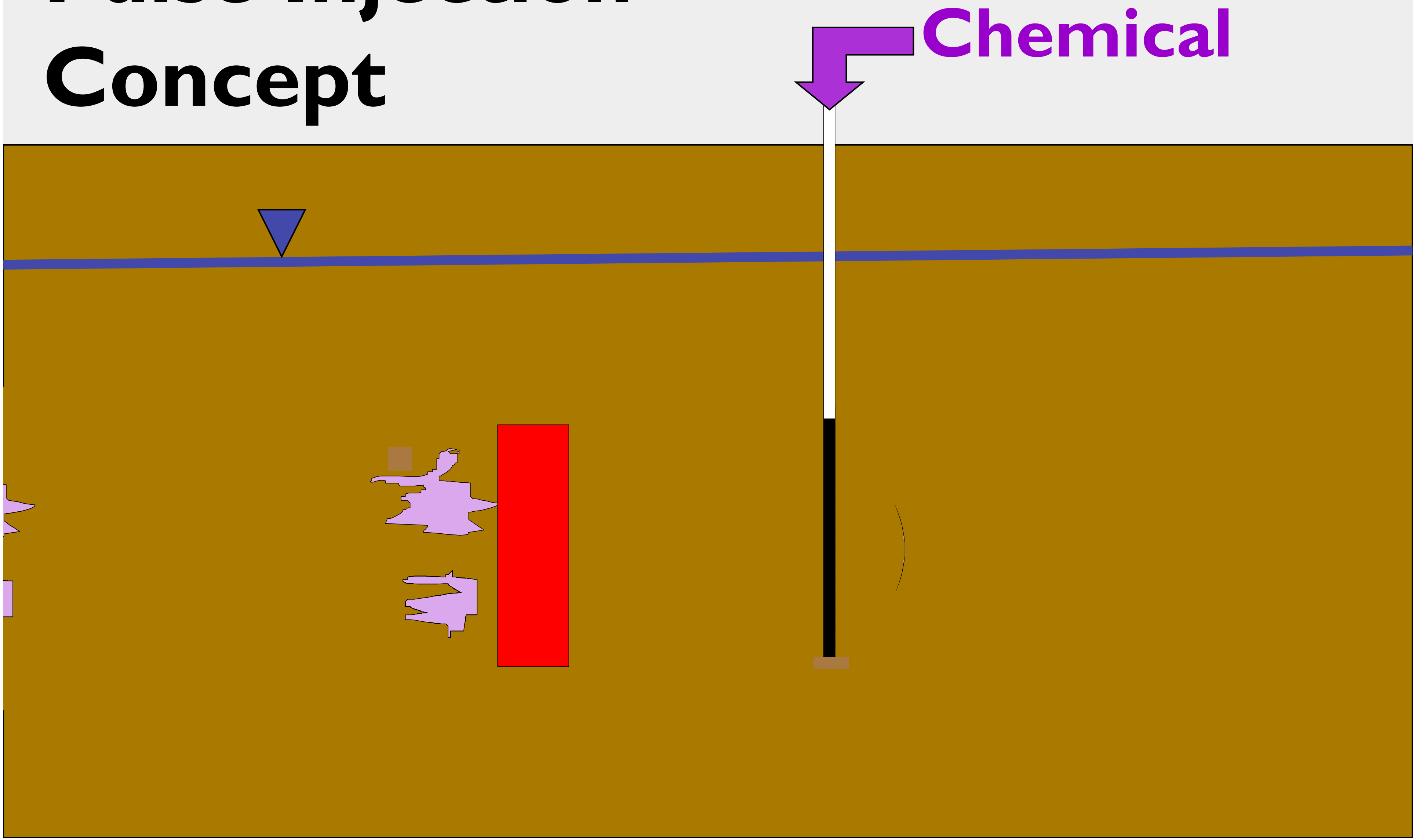
UNIVERSITY OF WATERLOO

- semi-passive pulse injection system
- 7-day intervals
- 6 episodes / 125 kg
- ~ 20 pore volumes

Semi-Passive Pulse Injection Concept



Semi-Passive Pulse Injection Concept

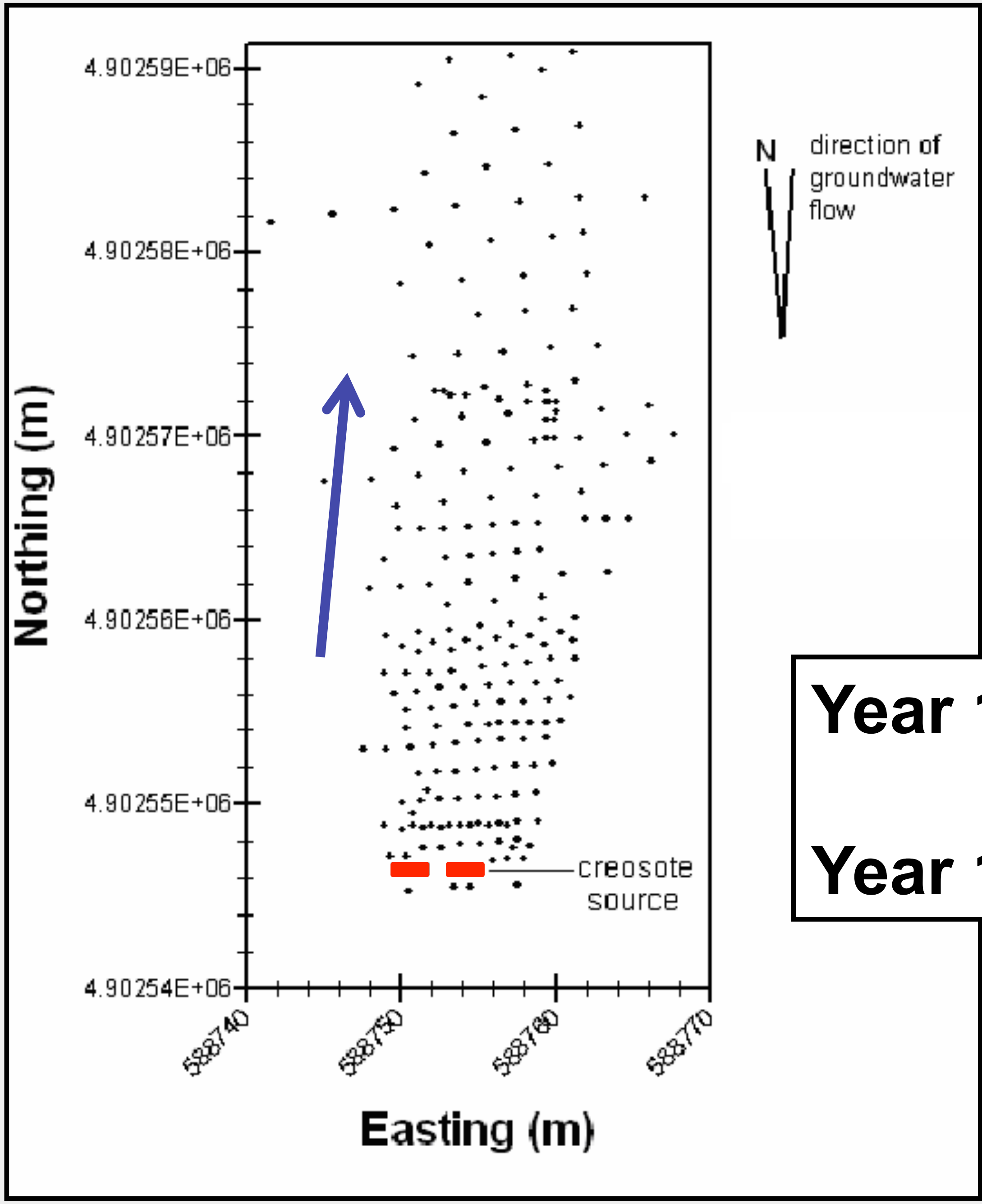


Short-term monitoring

UNIVERSITY OF WATERLOO

Compound	Pre [mg/day]	Post [mg/day]	Percent Change
naphthalene	750	310	-59
1-methylnaphthalene	200	120	-40
acenaphthylene	15	6	-58
biphenyl	84	71	-15
acenaphthene	430	200	-53
fluorene	110	51	-54
carbazole	61	18	-70
dibenzofuran	250	210	-16
phenanthrene	96	60	-37
anthracene	31	14	-55
fluoranthene	13	11	-11
pyrene	9	3	-63
Total	2048	1075	-47

Changes in mass load at fence line 150 days after treatment



Post-Treatment Plume Monitoring

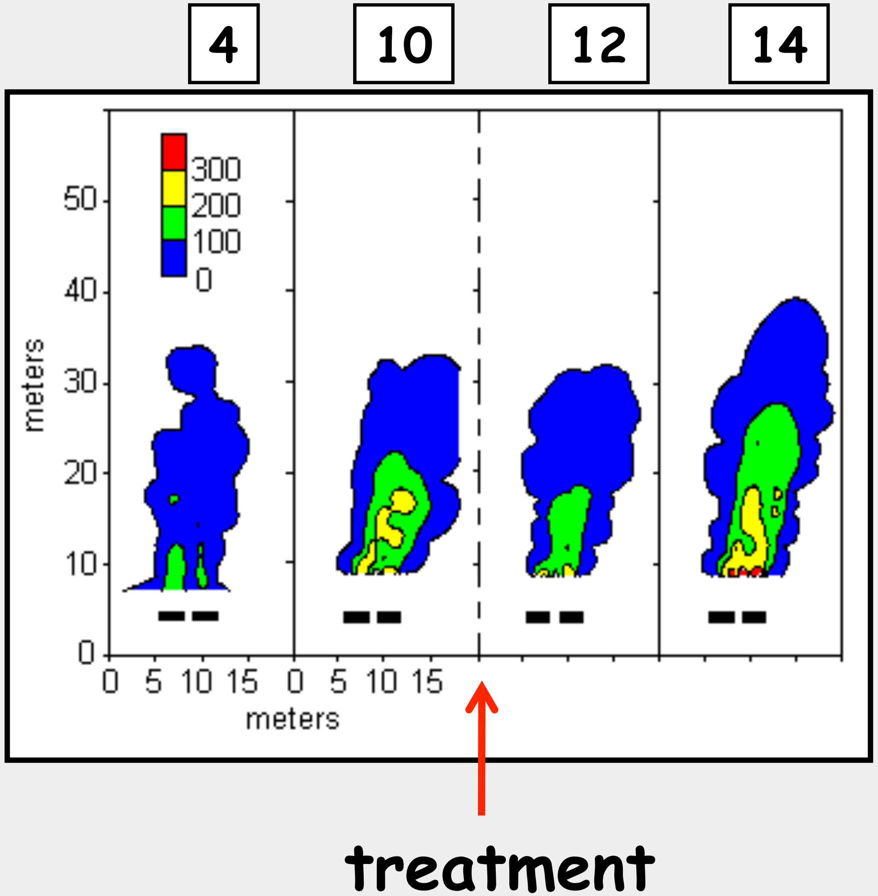
Year 1, 2, 4, 10 (pre)

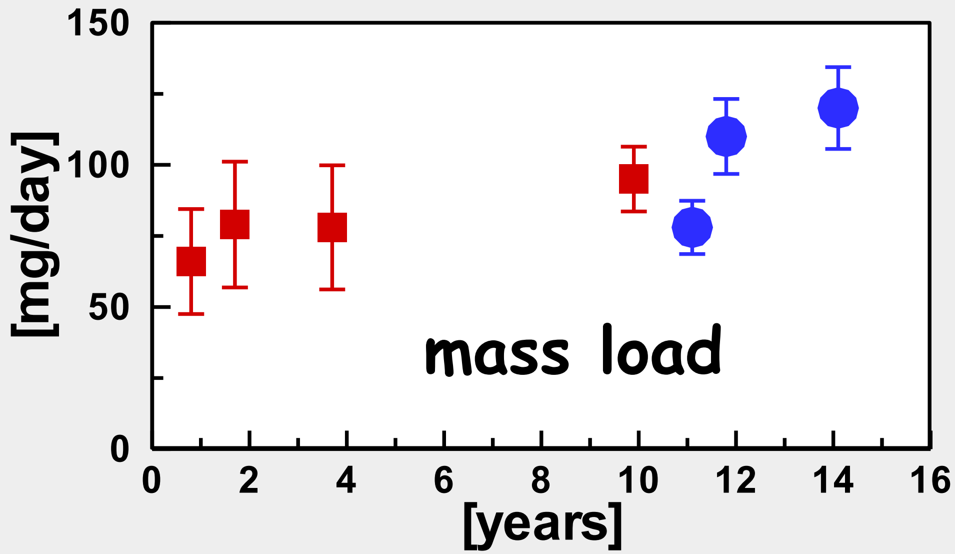
Year 11, 12, 14 (post)

Long-term monitoring

UNIVERSITY OF WATERLOO

Dibenzofuran





Lesson learned - 6

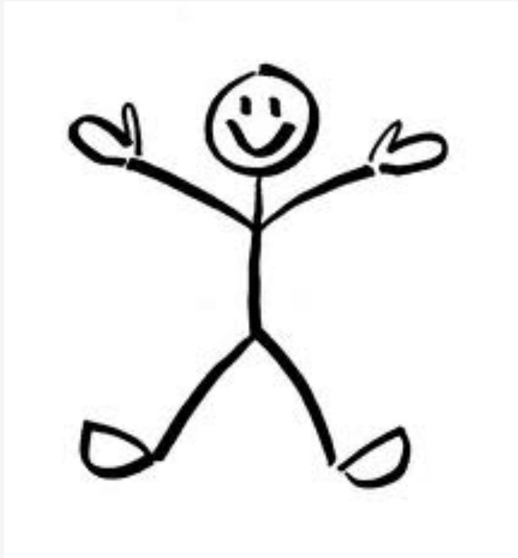
UNIVERSITY OF WATERLOO

- Groundwater systems are slow to respond
- Not chemical reactors

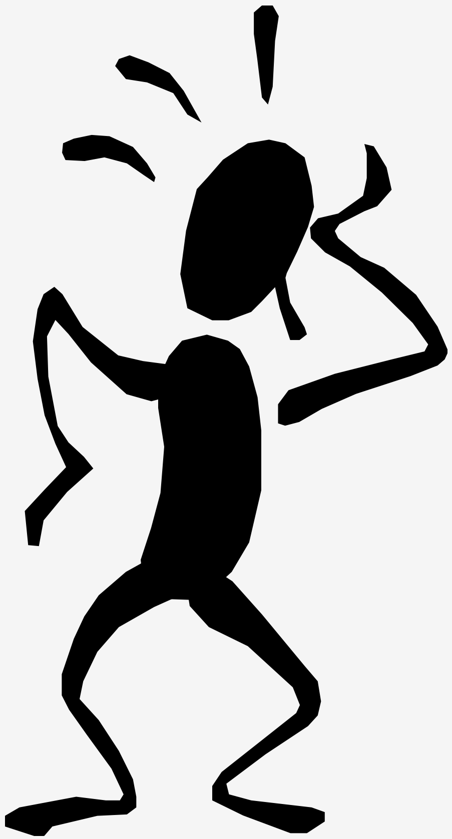
Example 7

UNIVERSITY OF WATERLOO

Dealing with difficult problems…

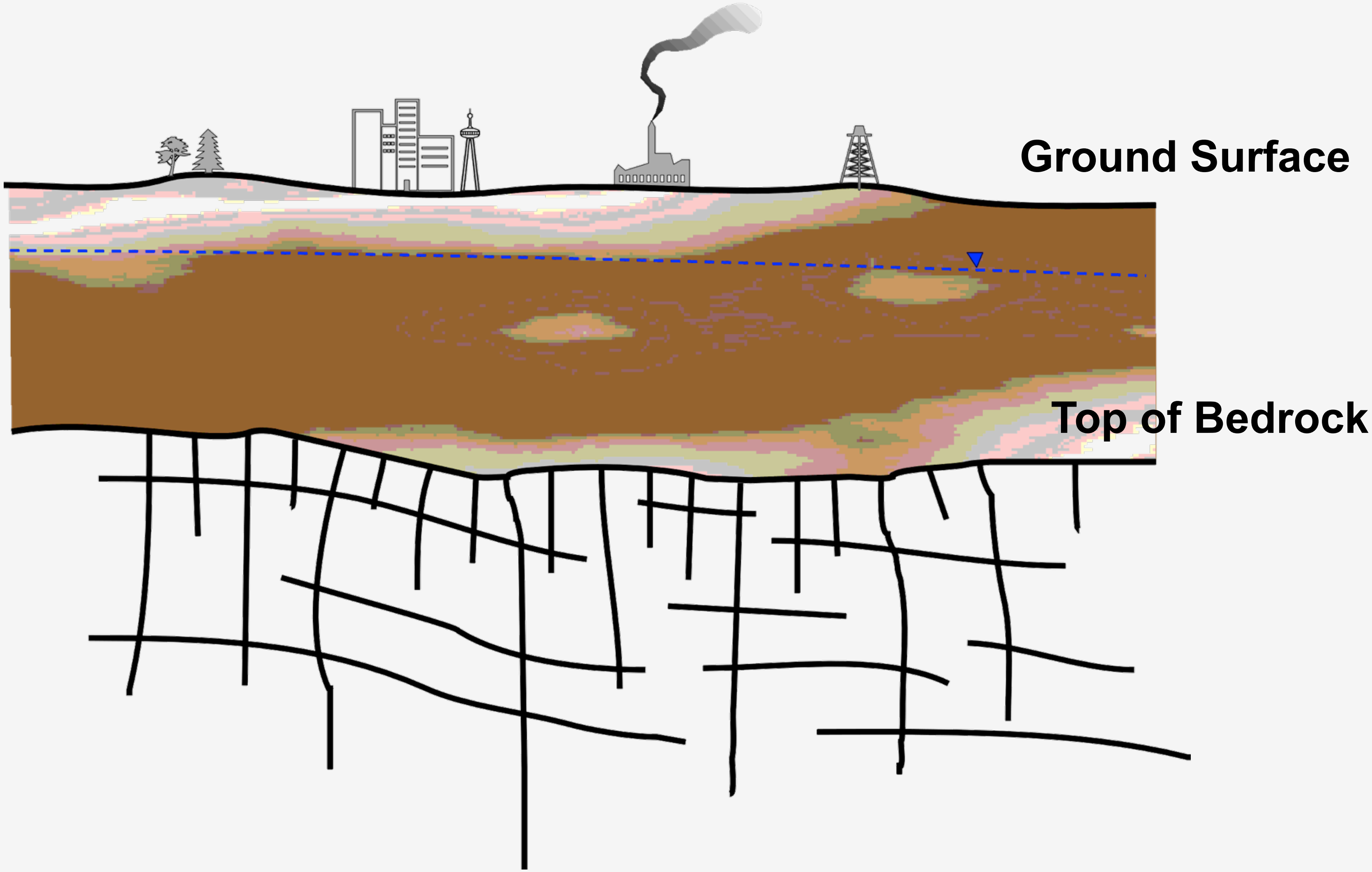


Groundwater flow in fractured media



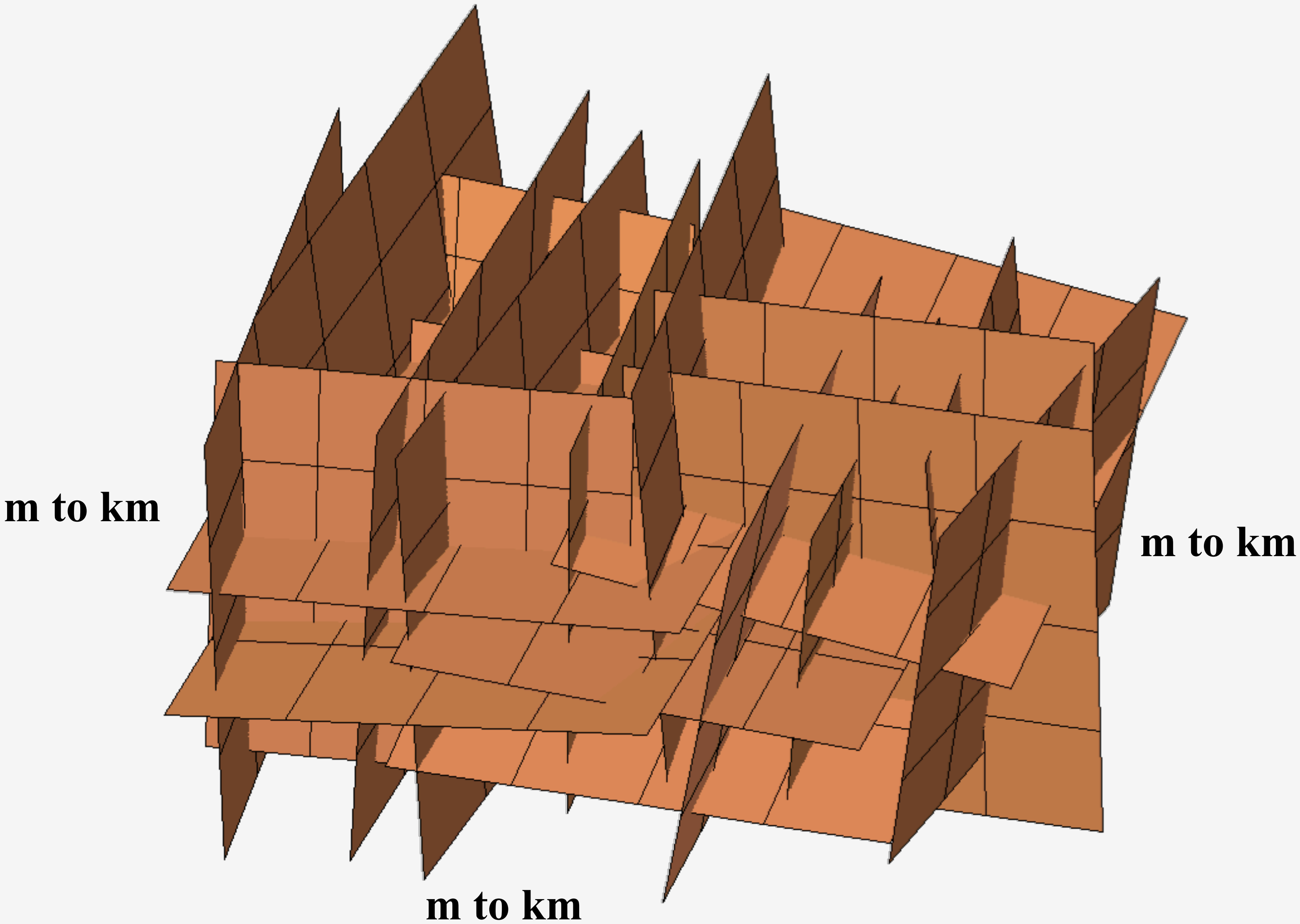
Problem

UNIVERSITY OF WATERLOO



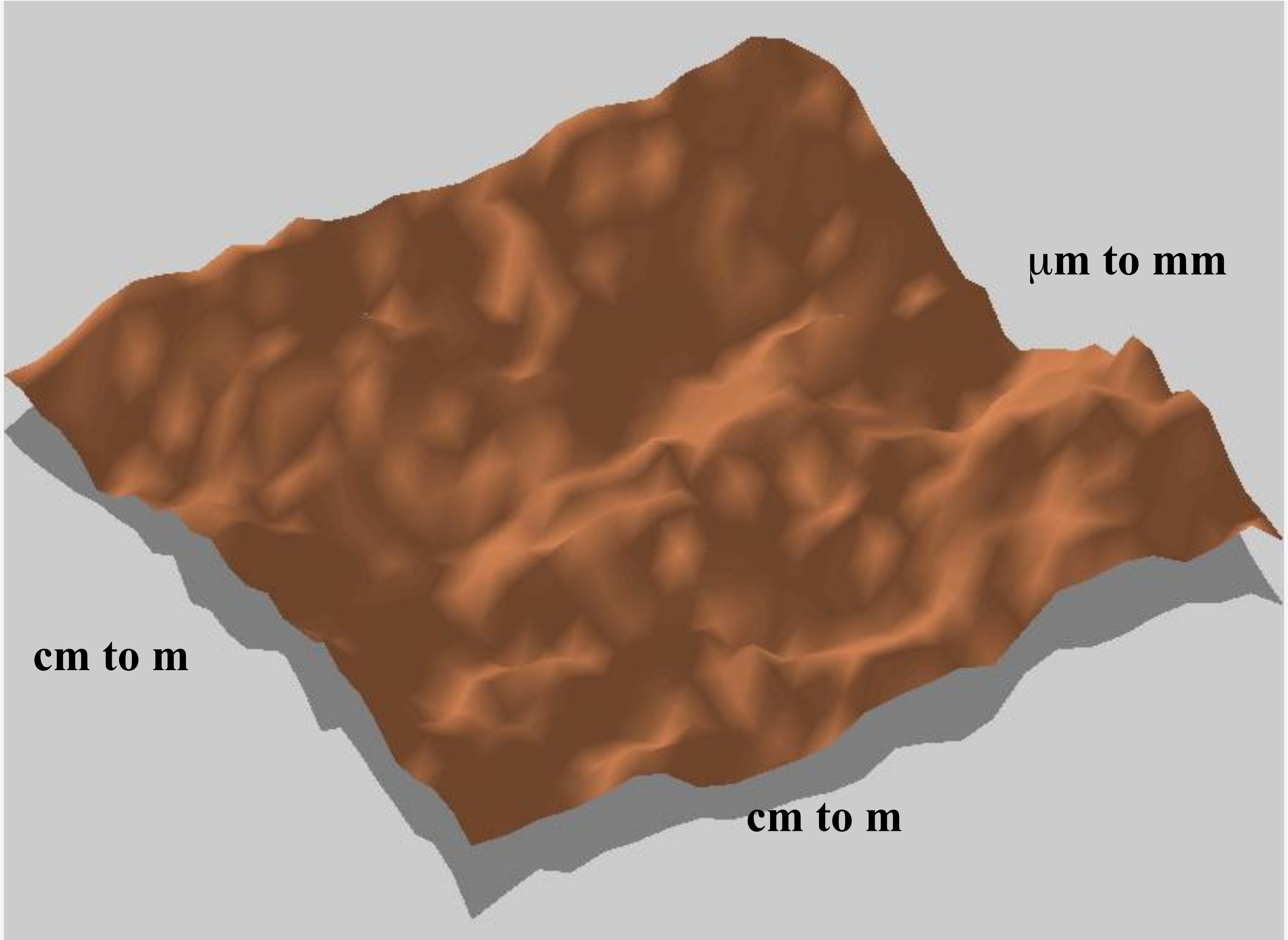
Fracture network

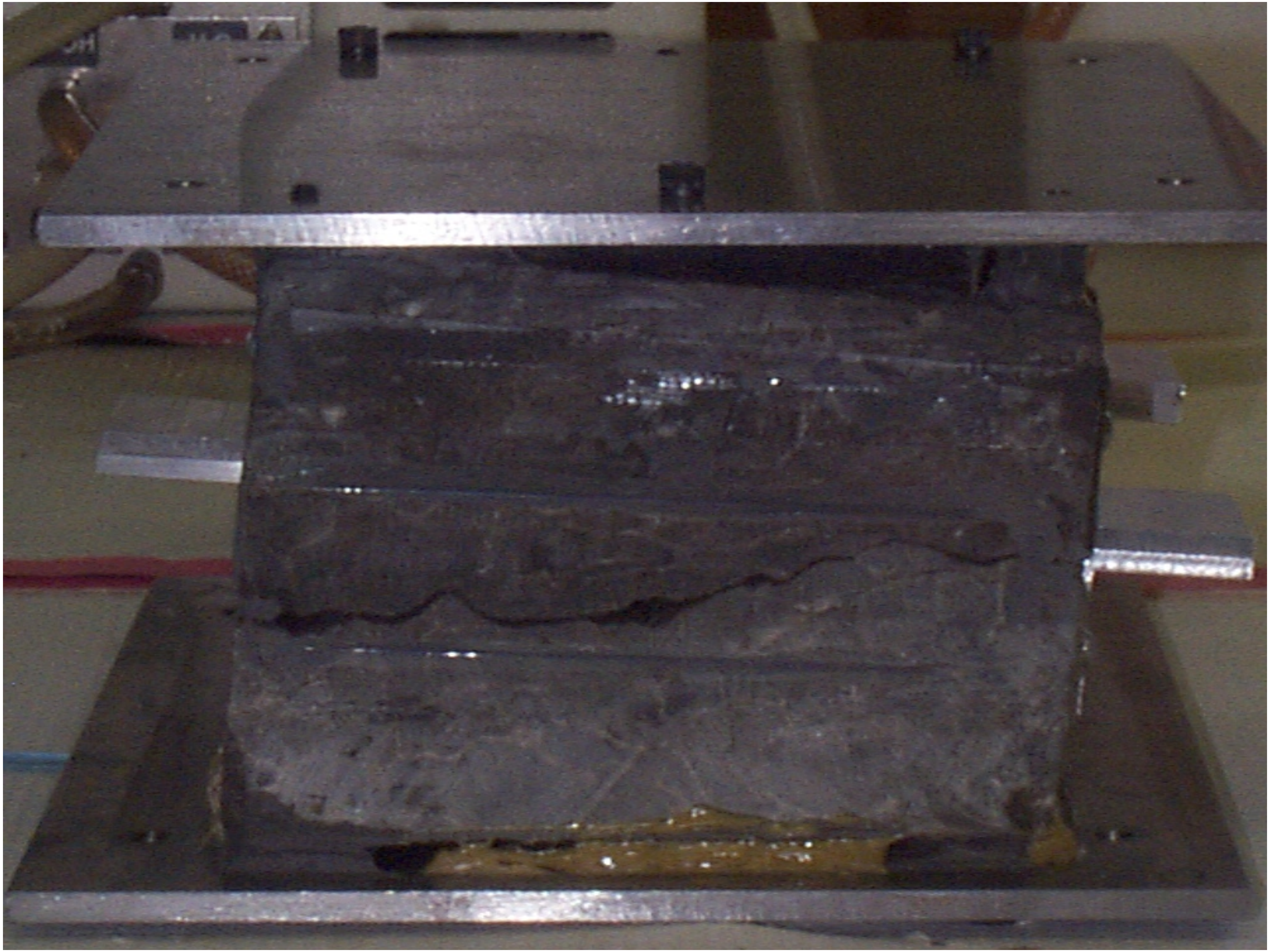
UNIVERSITY OF WATERLOO

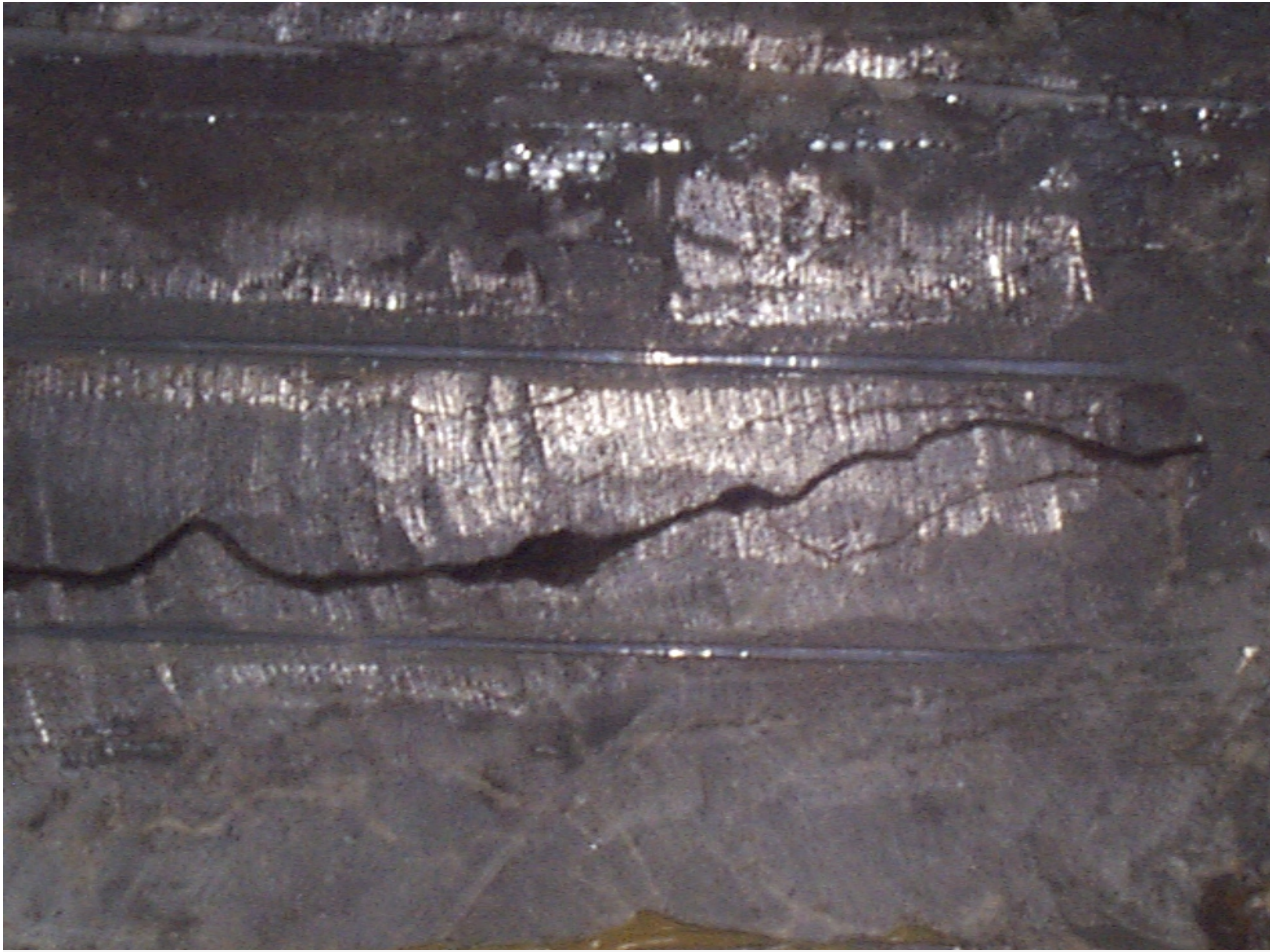


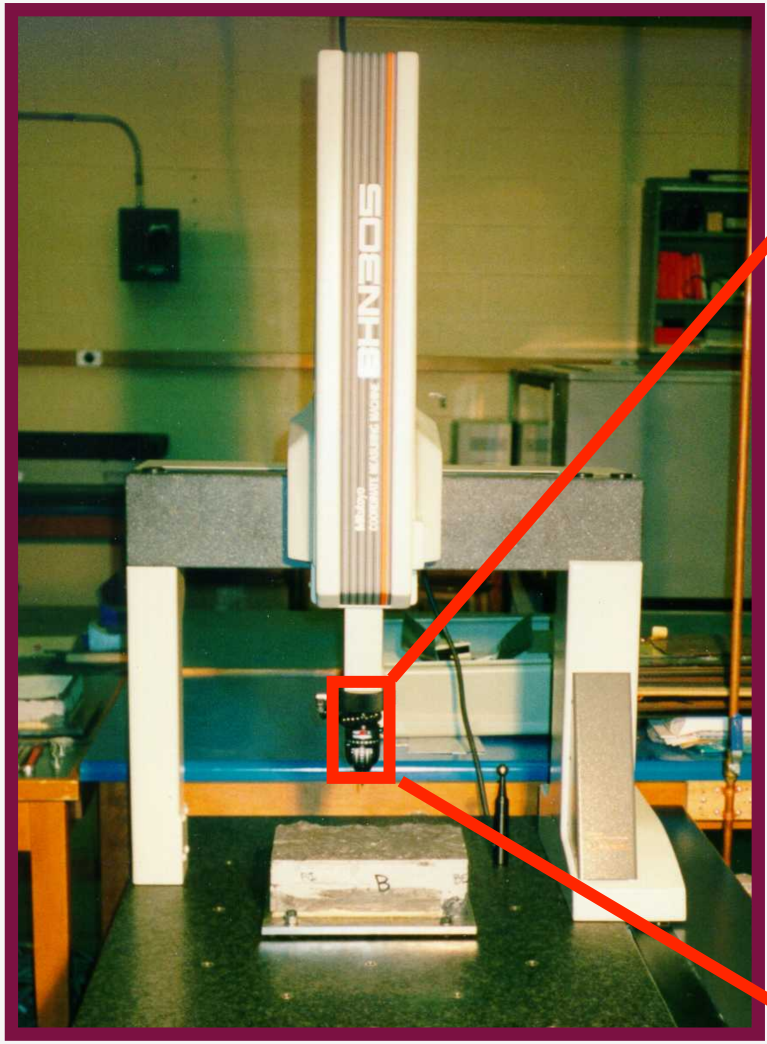
Single fracture

UNIVERSITY OF WATERLOO







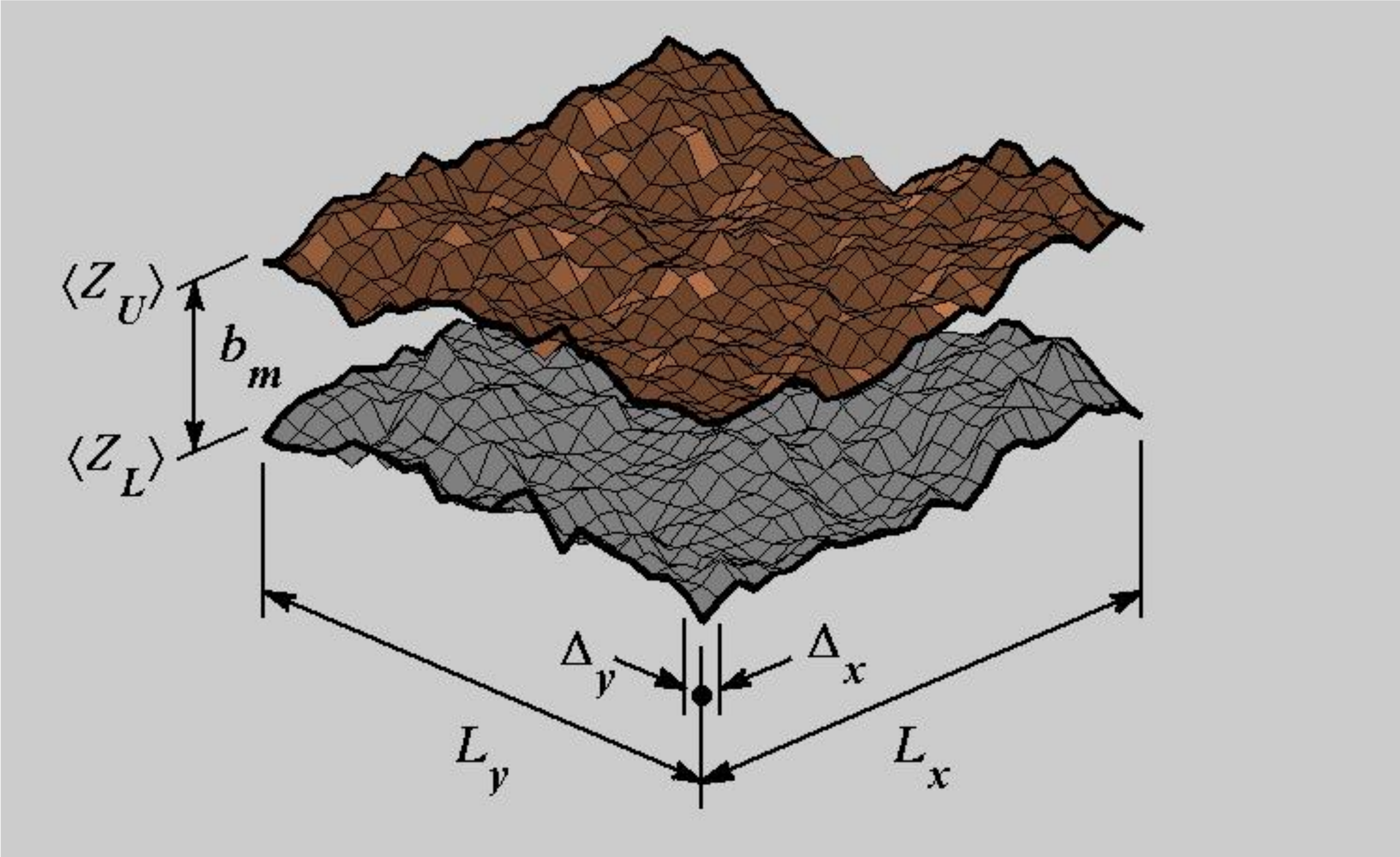


CMM

Stylus

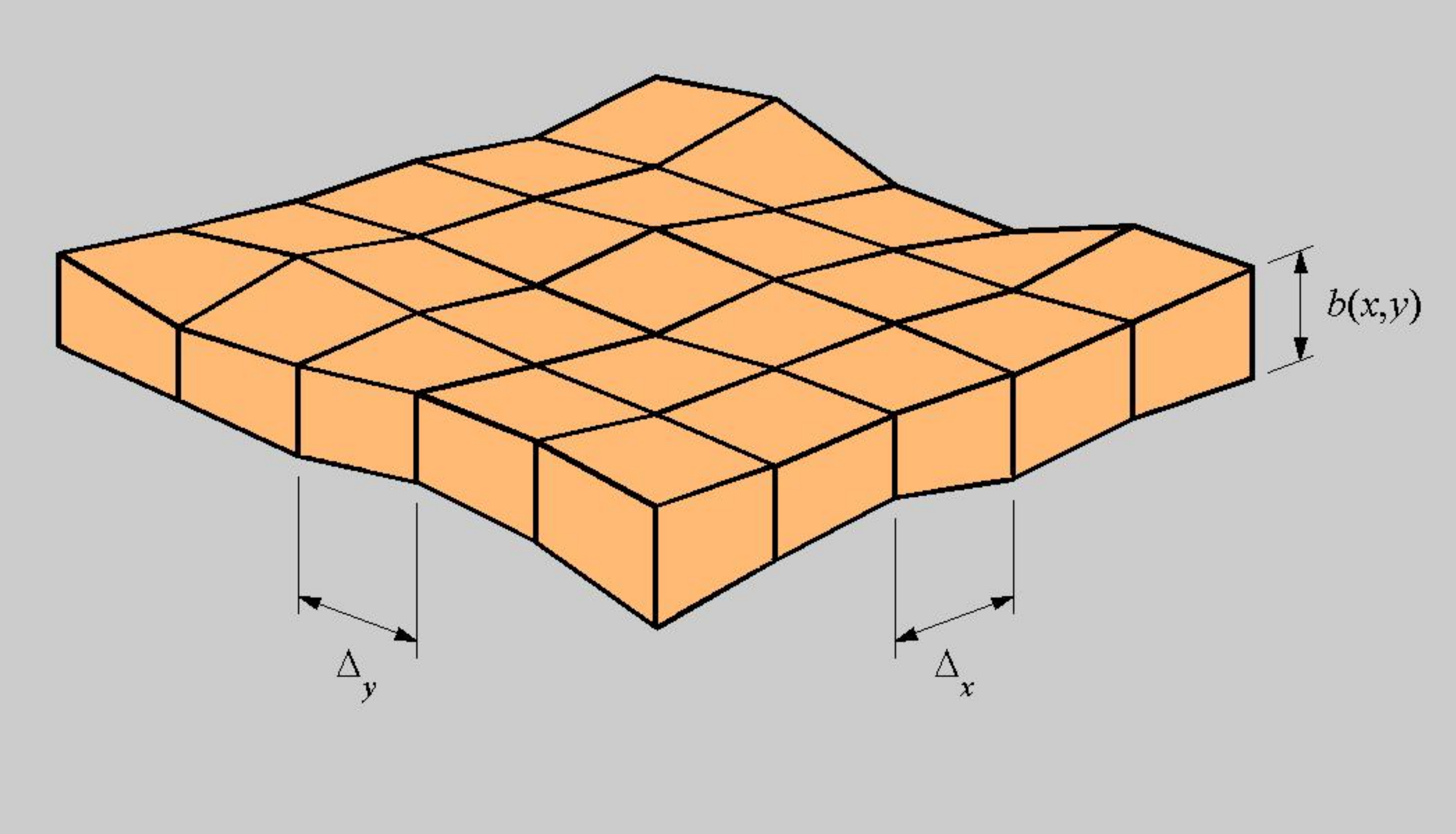
Fracture walls

UNIVERSITY OF
WATERLOO



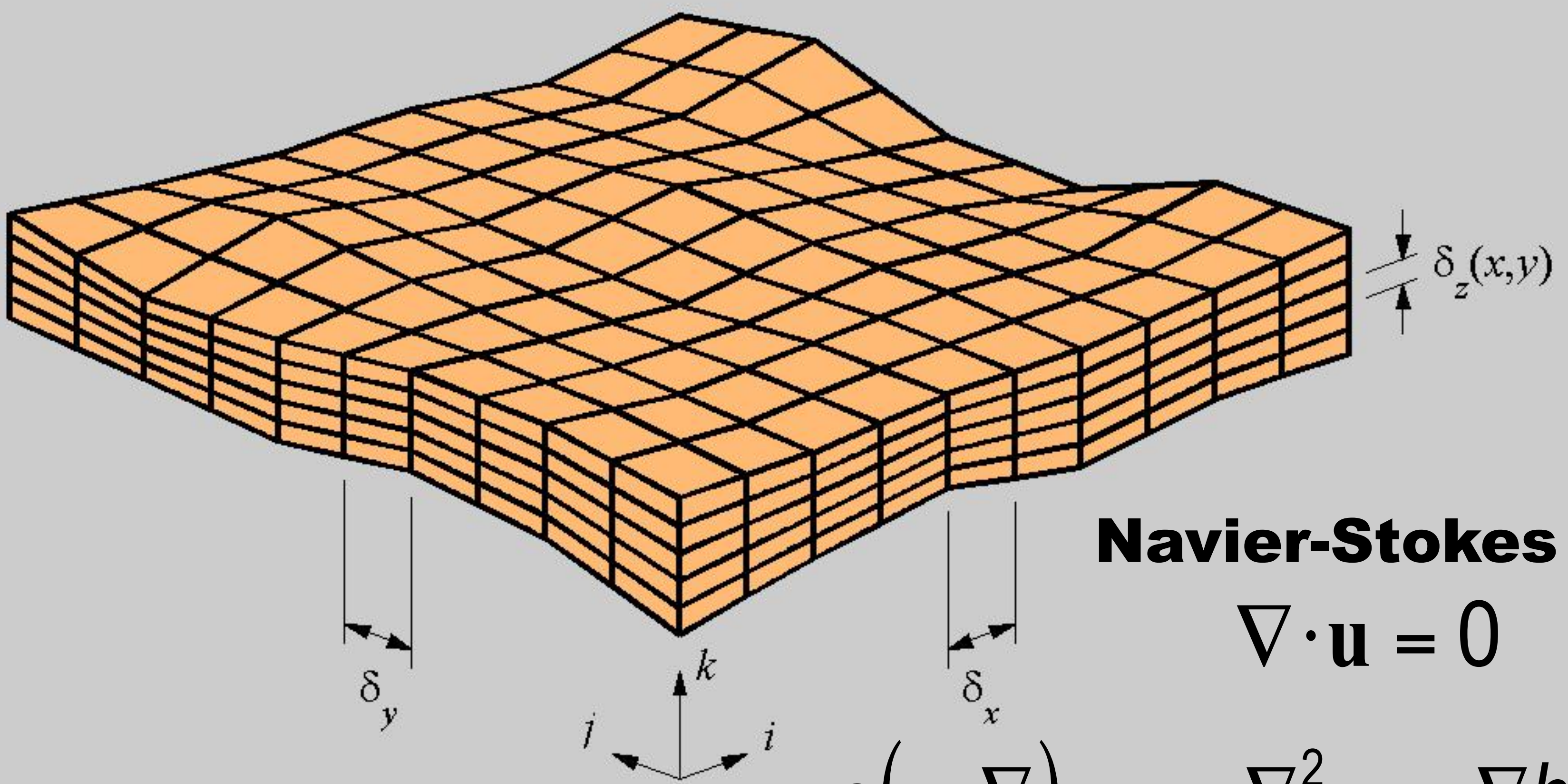
3D void space

UNIVERSITY OF WATERLOO



3-D flow

UNIVERSITY OF WATERLOO



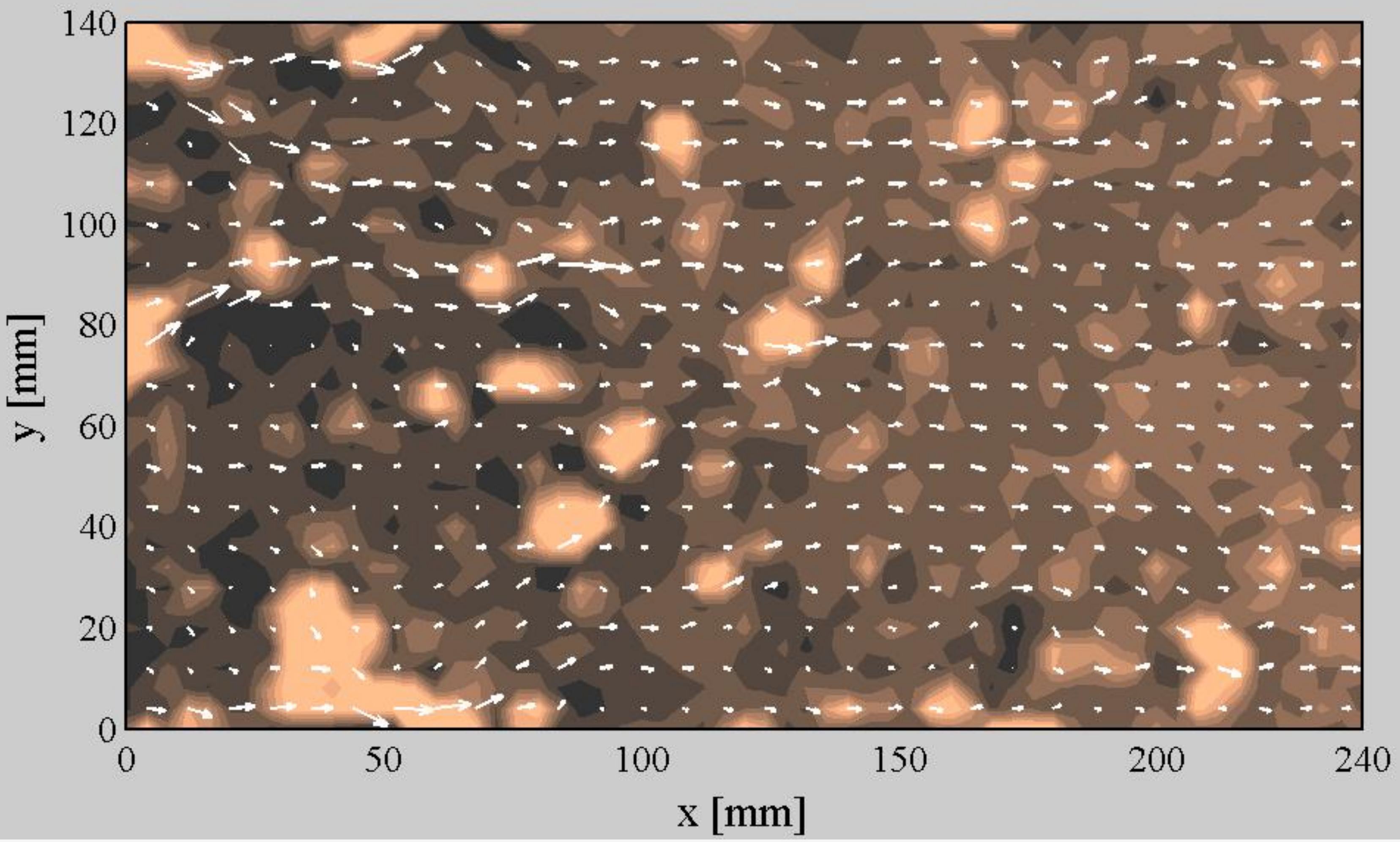
Navier-Stokes

$$\nabla \cdot \mathbf{u} = 0$$

$$\rho(\mathbf{u} \cdot \nabla)\mathbf{u} = \mu \nabla^2 \mathbf{u} - \gamma \nabla h$$

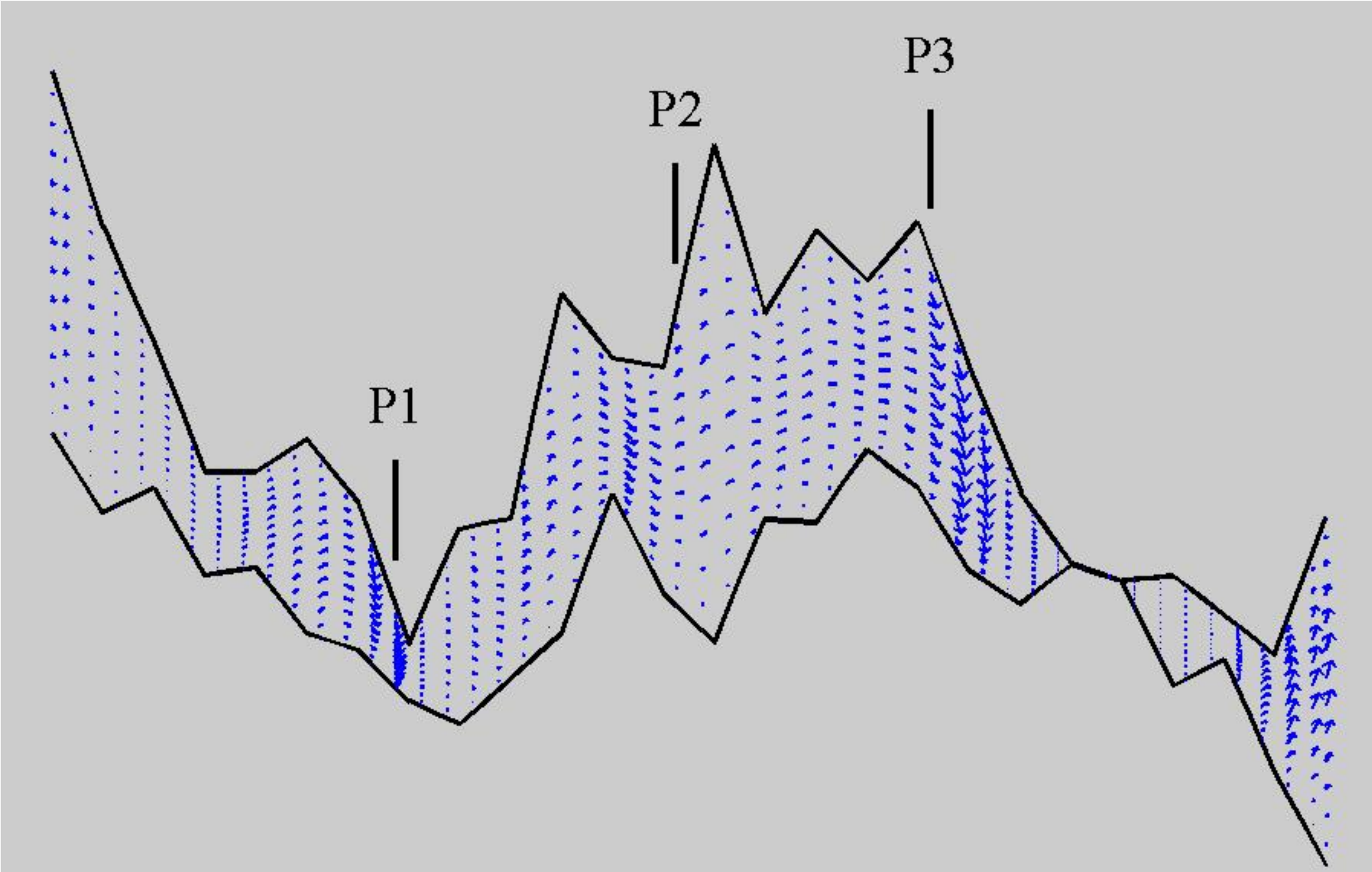
3-D flow

UNIVERSITY OF WATERLOO



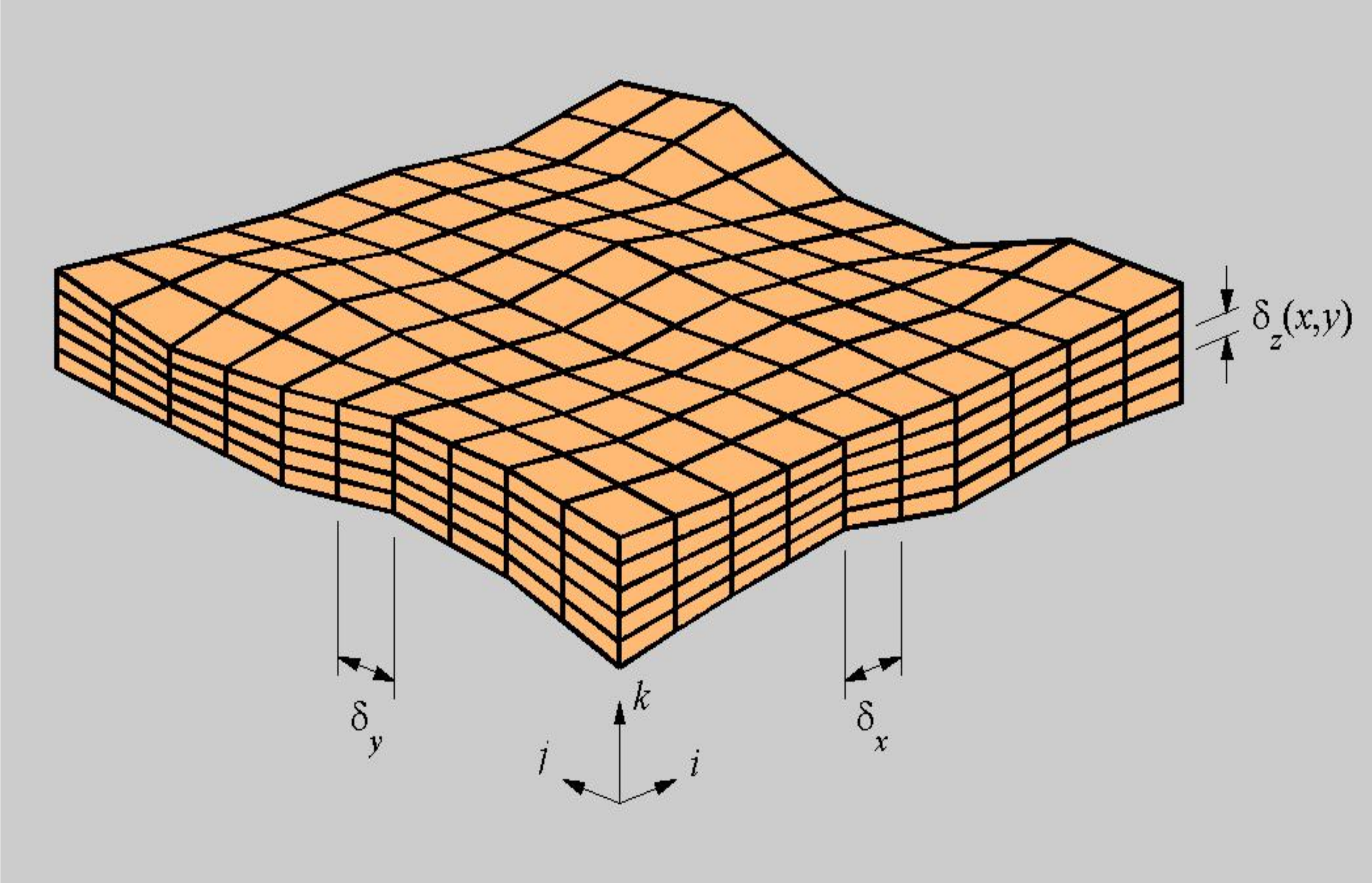
Velocity along profile

UNIVERSITY OF WATERLOO



Solute transport

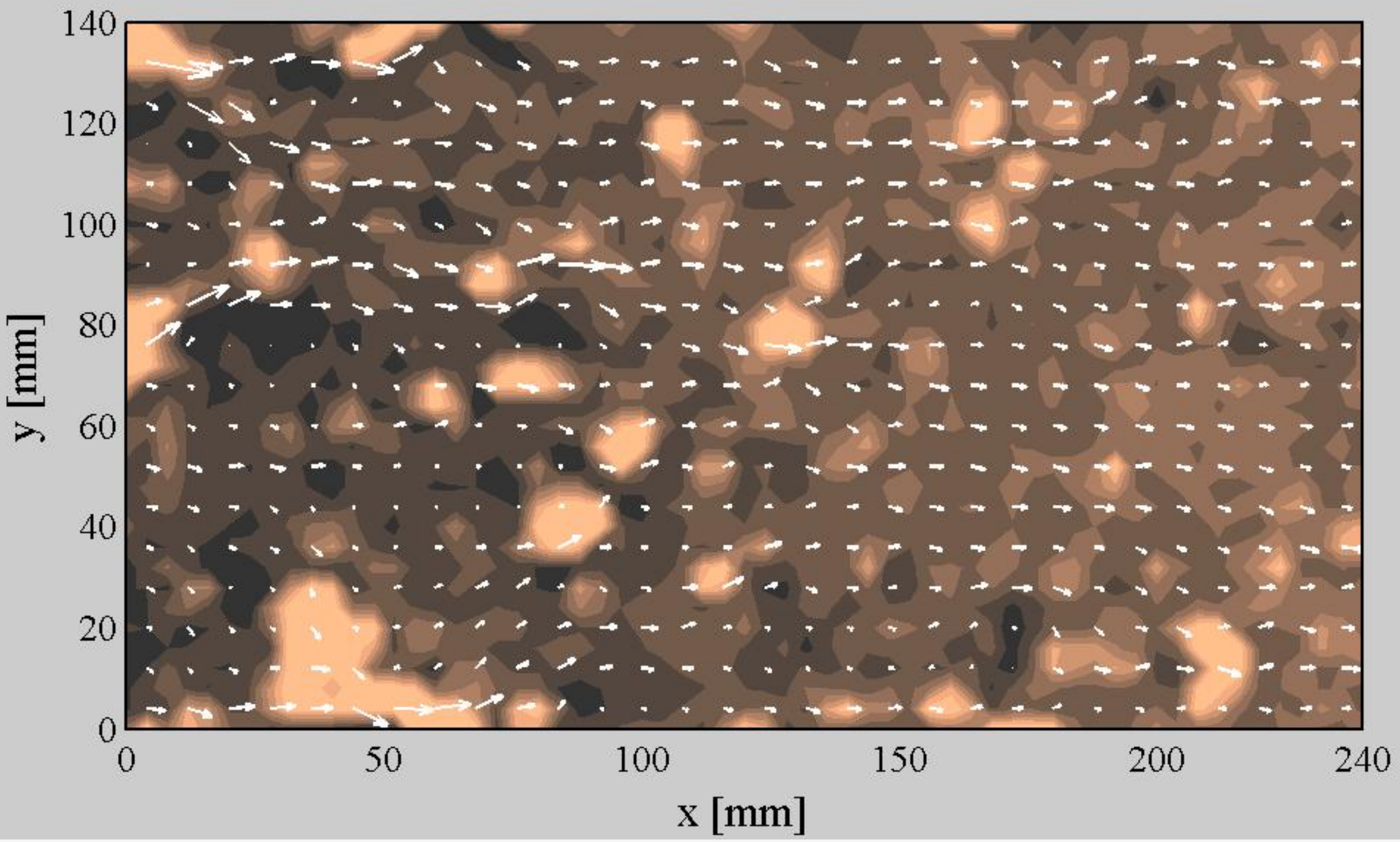
UNIVERSITY OF WATERLOO



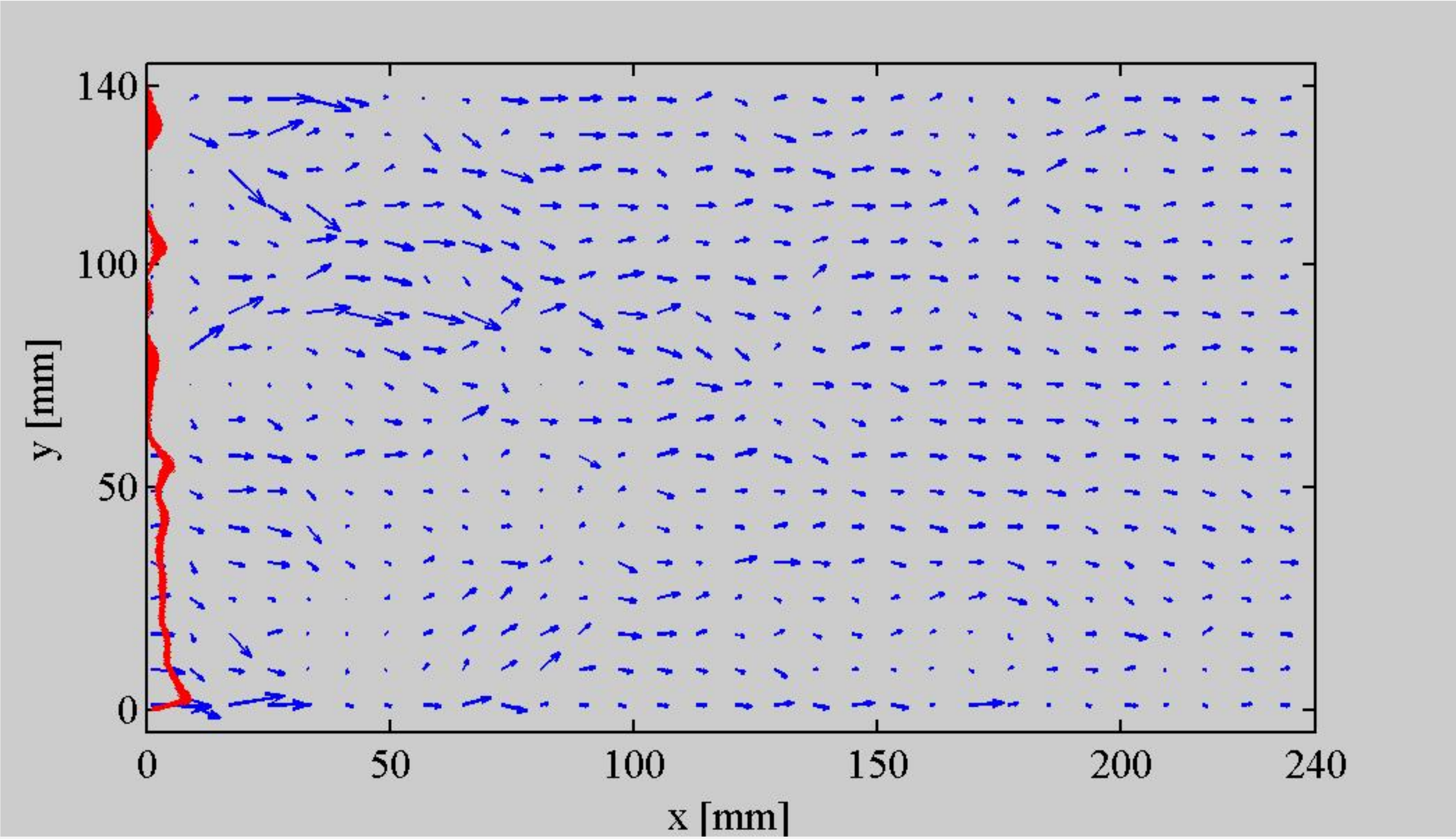
Advection - Dispersion - Diffusion

3-D flow

UNIVERSITY OF WATERLOO

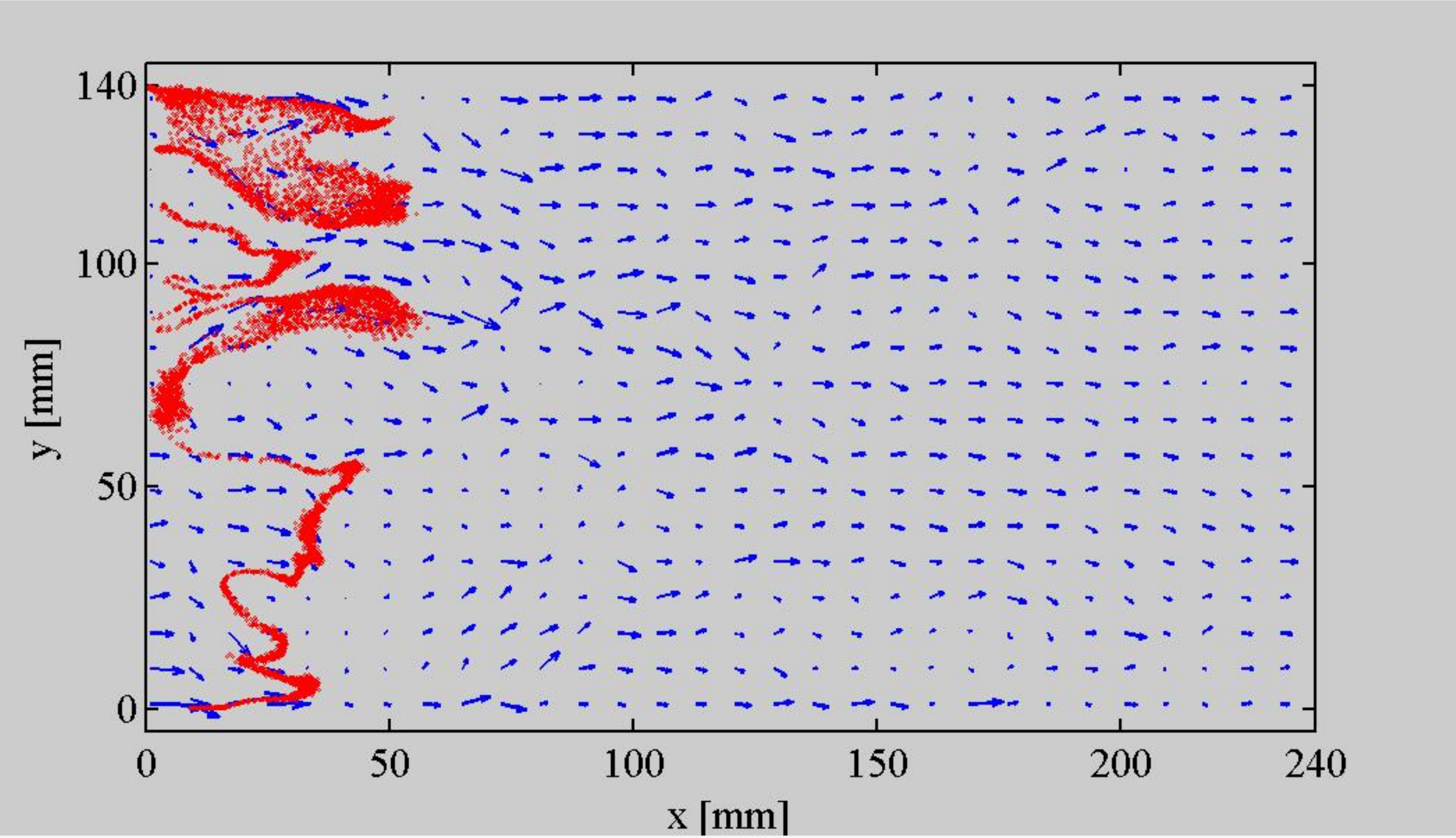


$t/t_r = 0.01$



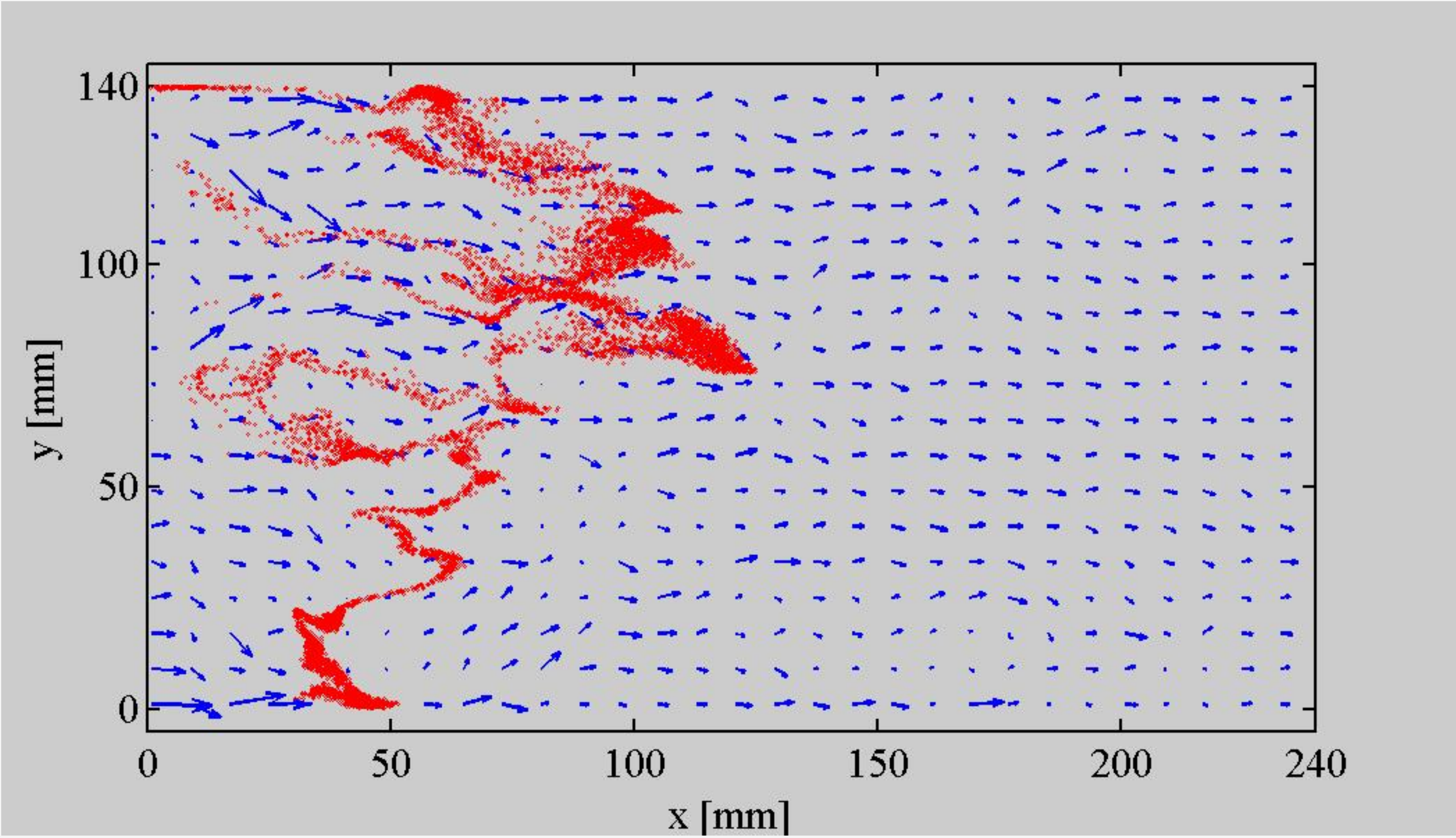
$t/t_r = 0.1$

UNIVERSITY OF WATERLOO



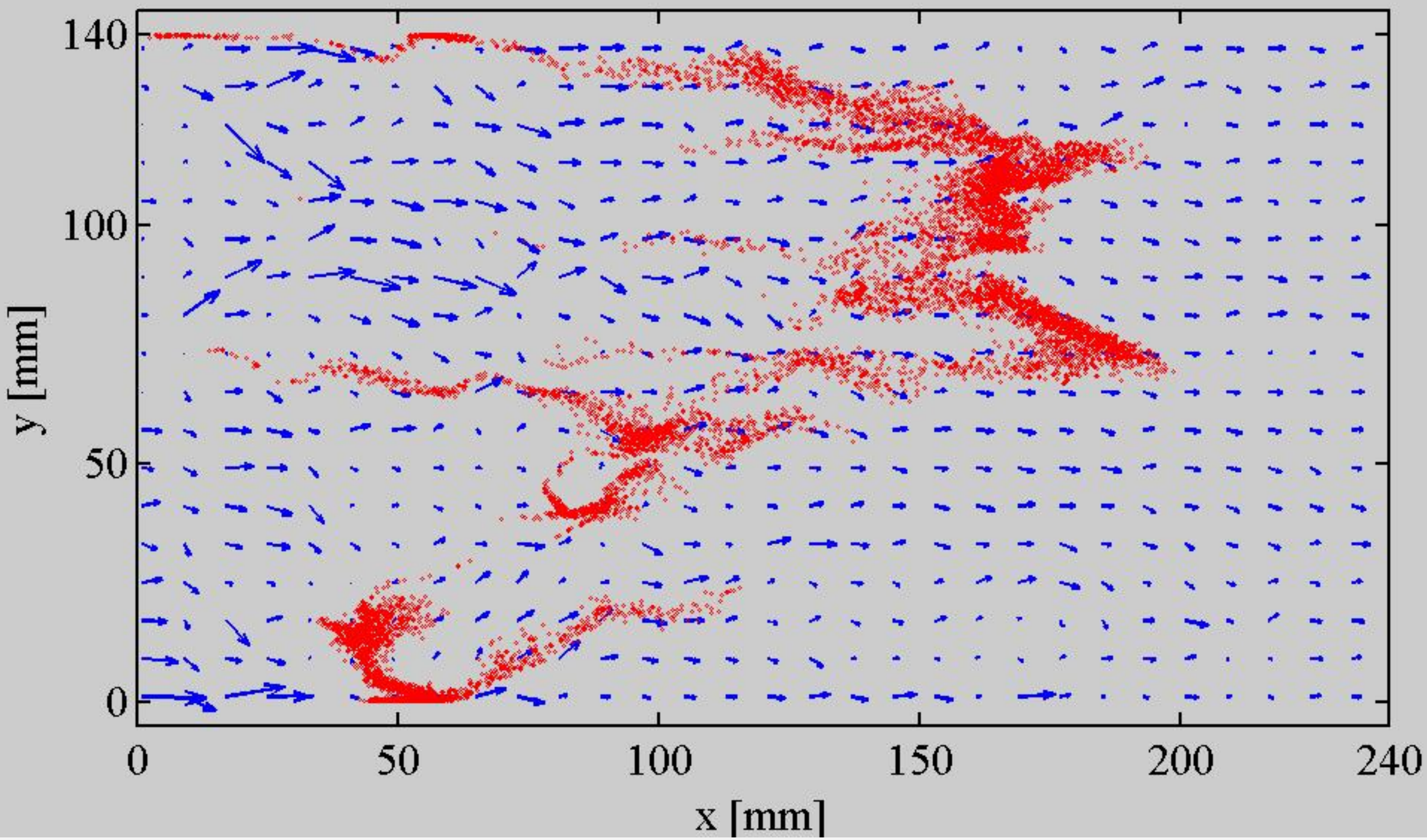
$t/t_r = 0.25$

UNIVERSITY OF WATERLOO



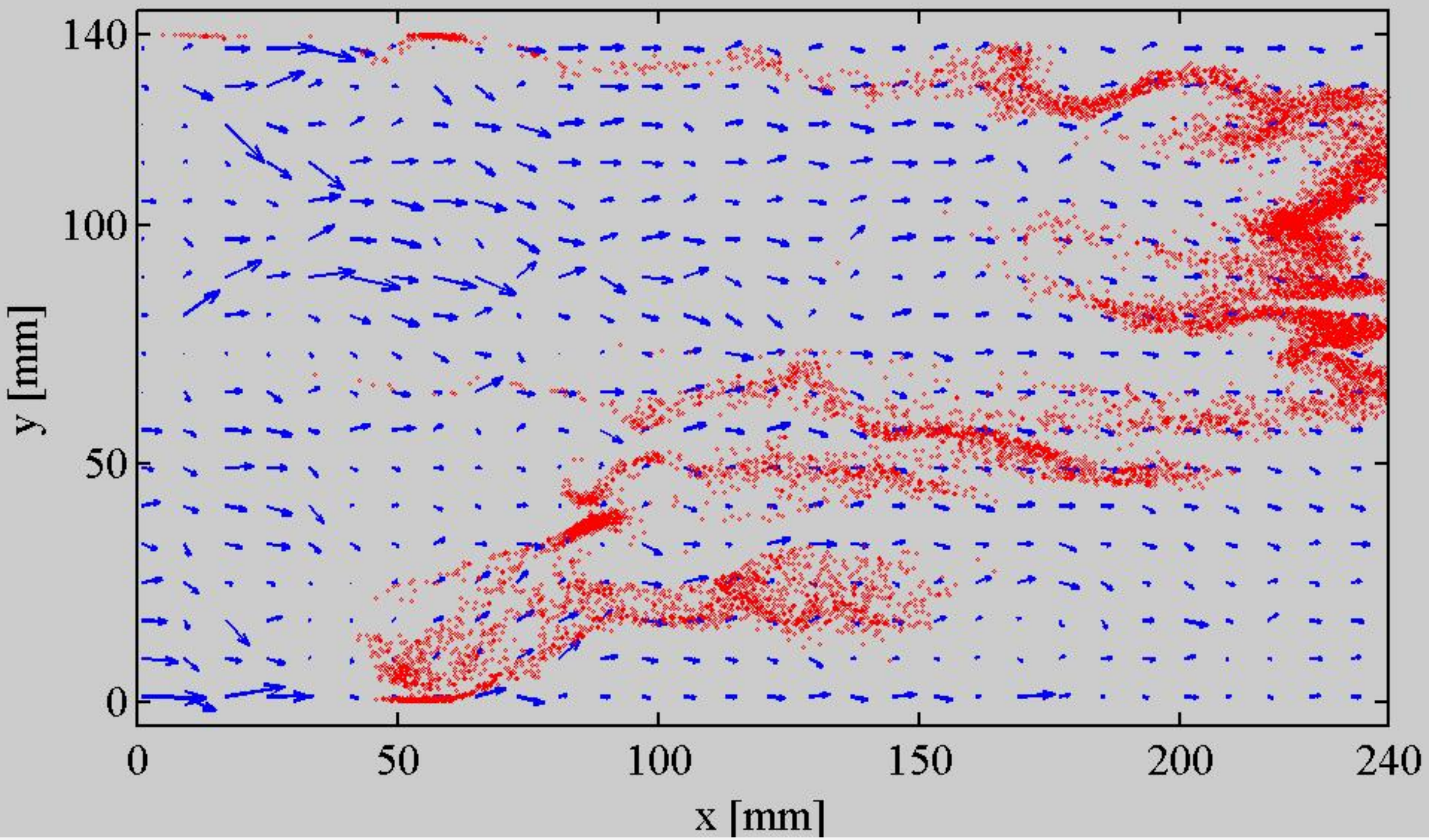
$t/t_r = 0.50$

UNIVERSITY OF WATERLOO



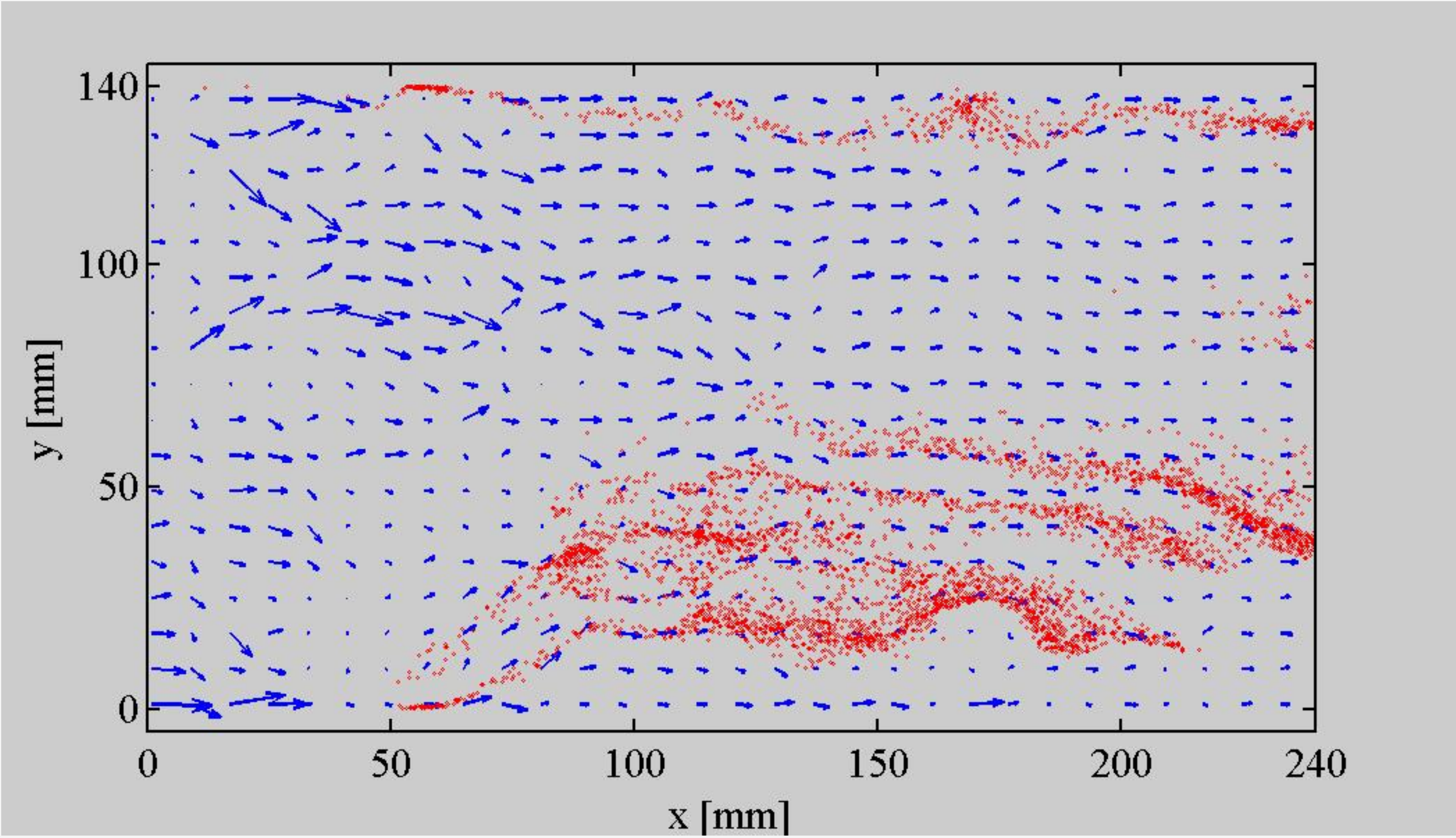
$t/t_r = 0.75$

UNIVERSITY OF WATERLOO



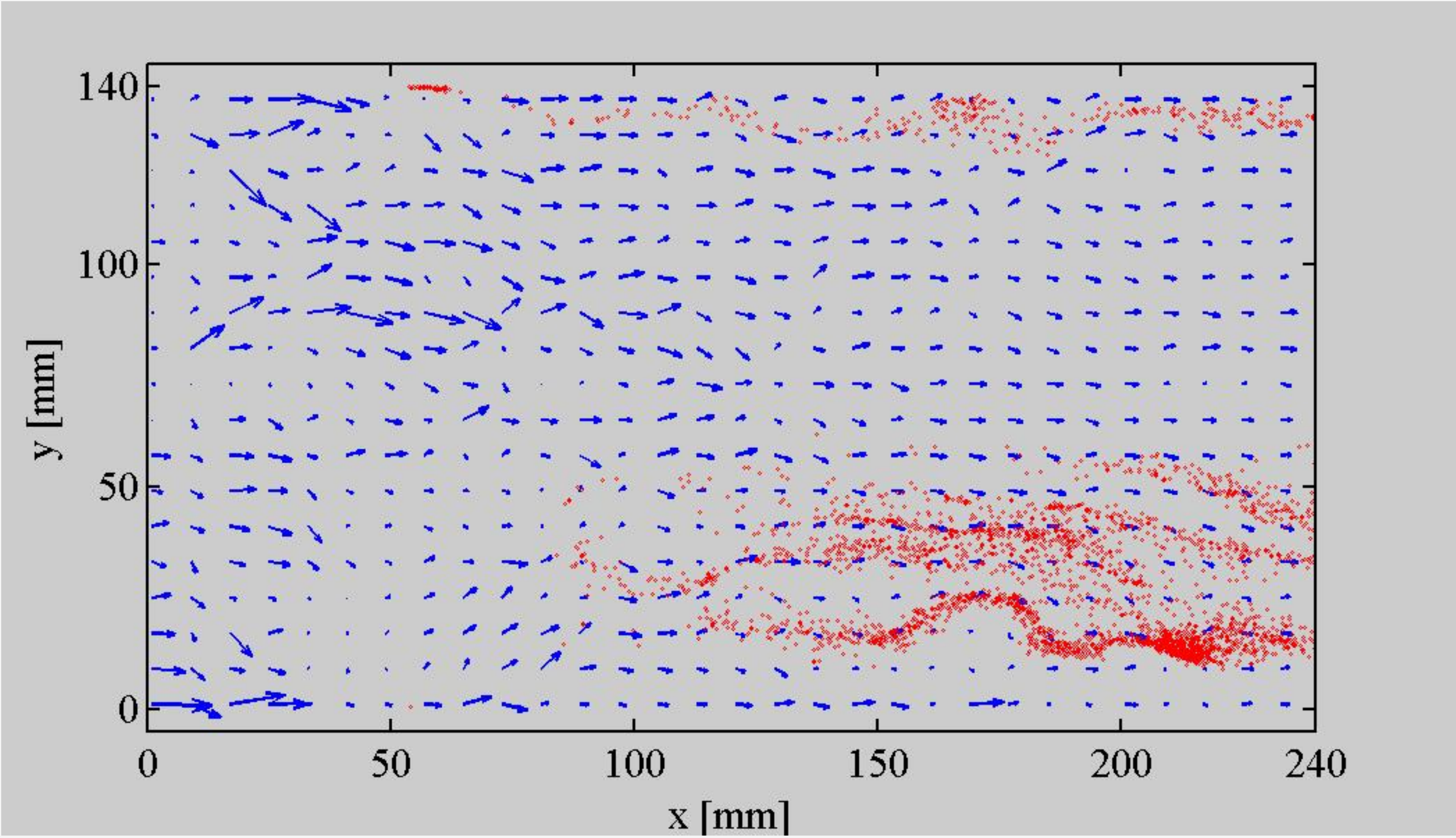
$t/t_r = 0.10$

UNIVERSITY OF WATERLOO



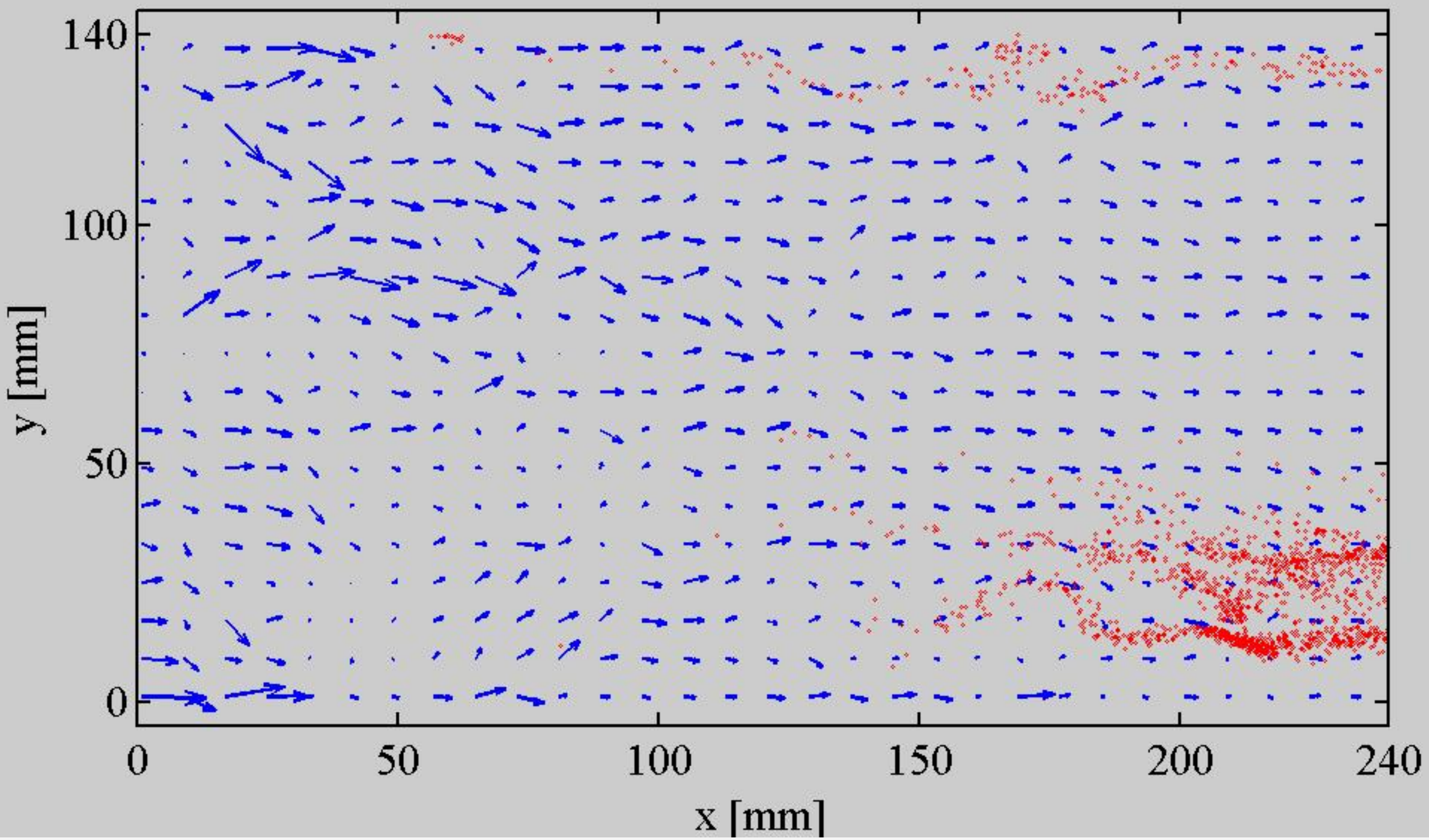
$t/t_r = 1.25$

UNIVERSITY OF WATERLOO



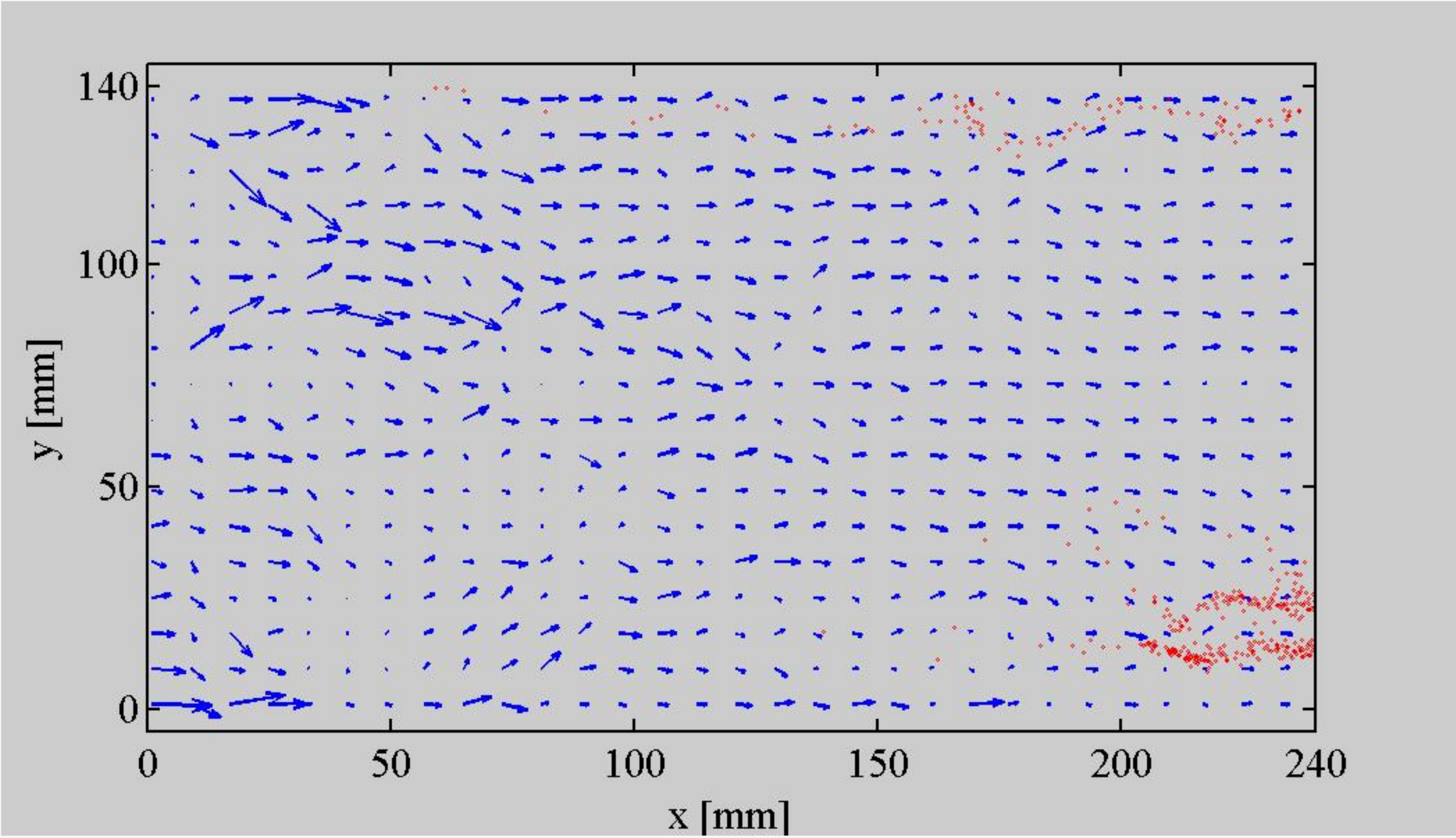
$t/t_r = 1.50$

UNIVERSITY OF WATERLOO

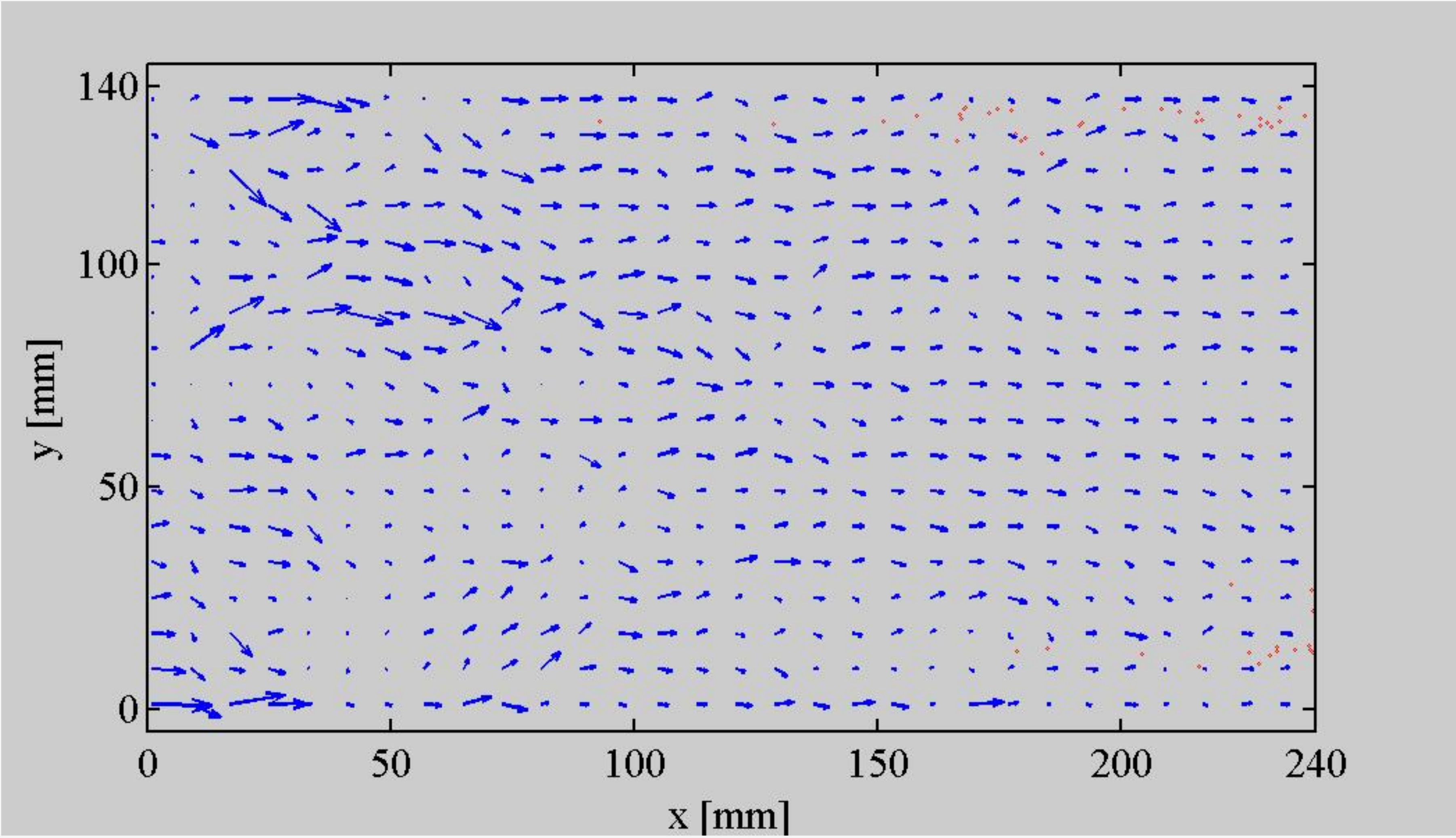


t/t_r = 1.75

UNIVERSITY OF WATERLOO



$t/t_r = 2.00$



Lesson learned - 7

UNIVERSITY OF WATERLOO

- ❑ **Fracture flow and transport not simulated as parallel plates**
- ❑ **Breakdown complex problems**

Example 8

UNIVERSITY OF WATERLOO

Dealing with field work…

Winter field work

UNIVERSITY OF WATERLOO

Winter field work

UNIVERSITY OF
WATERLOO

Lesson learned - 6

UNIVERSITY OF WATERLOO

Perhaps work in Brazil?

Thanks to…

UNIVERSITY OF WATERLOO

- ❑ **Many, many graduate students**
- ❑ **Invaluable colleagues**
- ❑ **Outstanding technicians**