Hyporheic Exchanges

Jonathan Pearson

School of Engineering, University of Warwick

Dye Tracing Workshop
20th September 2010

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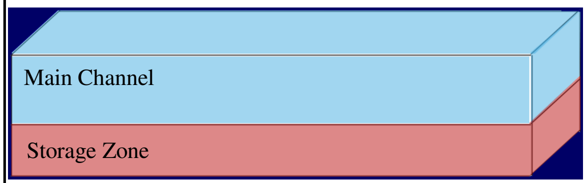
warwick Water
Water & Environmental Resources

Hyporheic Exchange



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Water

Contents

NIWA - field measurements
OTIS modelling

Nunnasbäcken, Scåne, Sweden
Field Study

EU @ HR Ltd. – lab. Study
exchange

EPSRC Studentship – Dutton PhD
lab & modelling (Hart & OTIS)

Warwick Water – The EROSIMESS-System

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NIWA Science

National Institute of Water & Atmospheric Research
Dr Kit Rutherford & Dr Niall Broekhuizen

Conducted at Whatawhata

Investigating the effect of landuse

3 different streams – DB4, PKR, NW5

100m study reach, using both in-stream measurements and in-bed hyporheic wells

Tracer studies with both instantaneous and "step" injection

Application of OTIS (4 parameter) model to determine exchange coefficients

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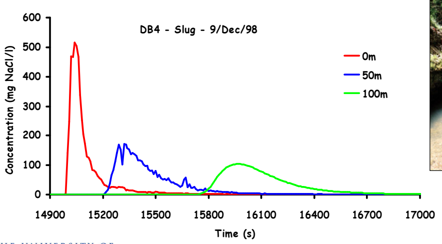
NIWA Science

Results of instantaneous injection of salt tracer, automatic recording at 3 sites in-stream over a 100m study reach.



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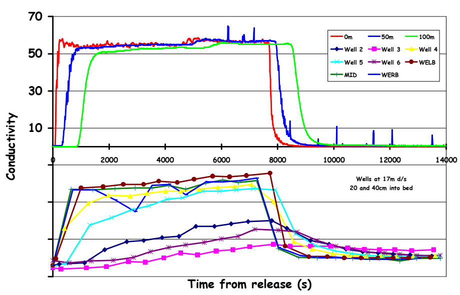
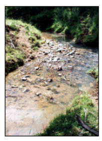
Step release, in-stream and in-bed monitoring.
Estimating parameters from in-stream data:
2 parameter (ADE, ADZ) model gave consistent parameter estimation, unlike the 4 parameter (OTIS) model.

NIWA Science





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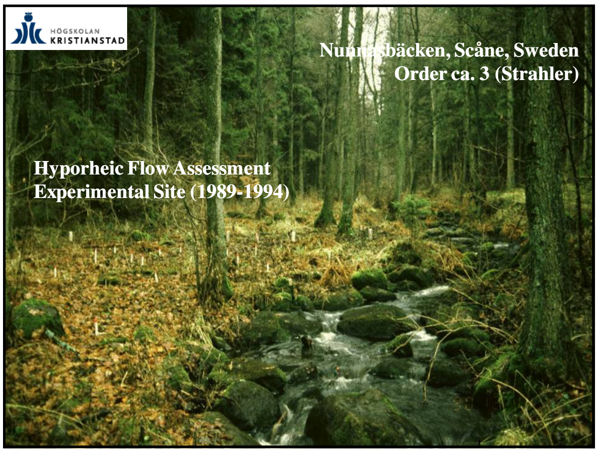
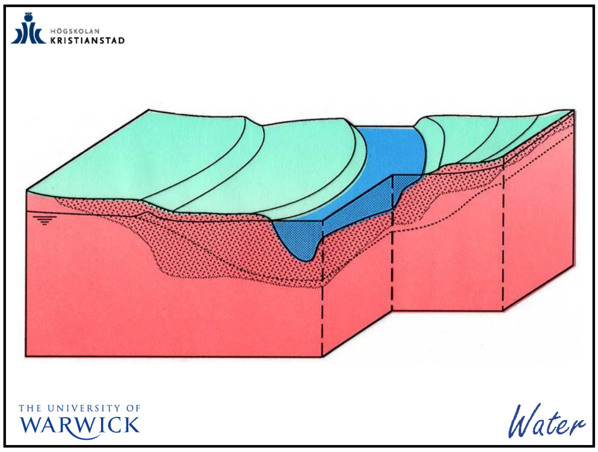

HÖGSKOLAN KRISTIANSTAD
Nunnäsbäcken, Scåne, Sweden
Order ca. 3 (Strahler)
Hyporheic Flow Assessment
Experimental Site (1989-1994)


HÖGSKOLAN KRISTIANSTAD
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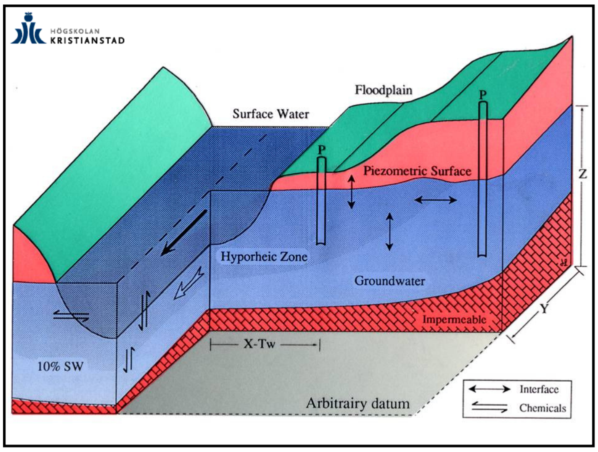
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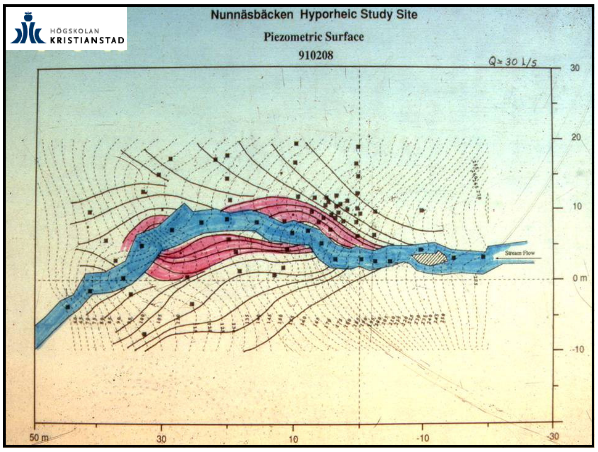
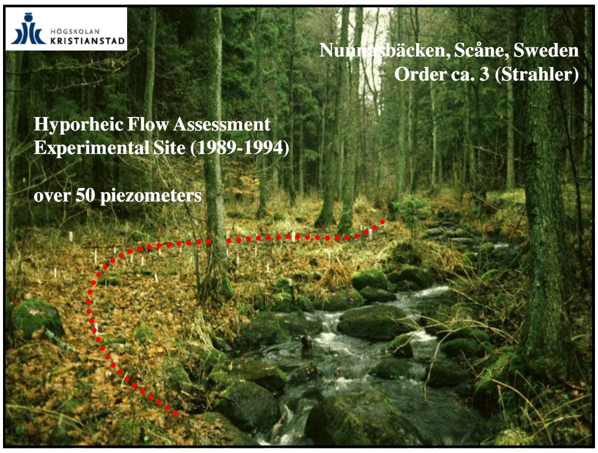
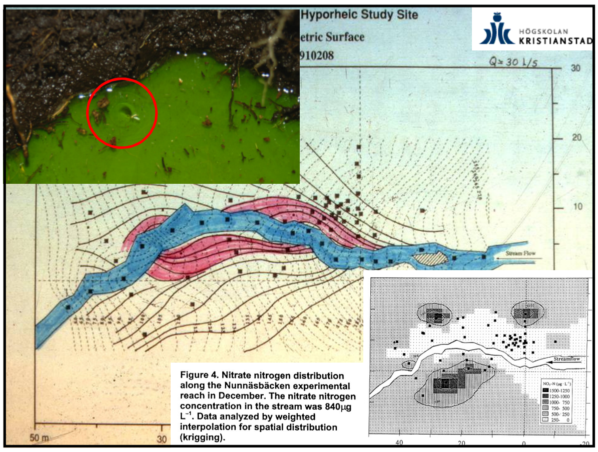
Floodplain
Surface Water
P
P
Piezometric Surface
Z
Hyporheic Zone
Groundwater
Impermeable
Y
X-Tw
10% SW
Arbitrairy datum
Interface
Chemicals


HÖGSKOLAN KRISTIANSTAD
Nunnäsbäcken Hyporheic Study Site
Piezometric Surface
910208
Q≈ 30 l/s
30
20
10
0 m
-10
50 m
30
10
-10
-30

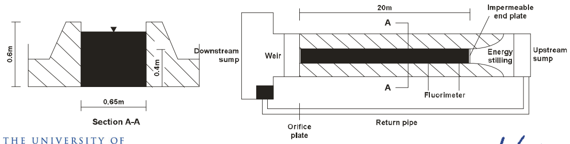

HÖGSKOLAN KRISTIANSTAD
Nunnäsbäcken, Scåne, Sweden
Order ca. 3 (Strahler)
Hyporheic Flow Assessment
Experimental Site (1989-1994)
over 50 piezometers


Hyporheic Study Site
etric Surface
910208
HÖGSKOLAN KRISTIANSTAD
Q≈ 30 l/s
30
20
10
50 m
30
Figure 4. Nitrate nitrogen distribution along the Nunnäsbäcken experimental reach in December. The nitrate nitrogen concentration in the stream was 840µg L-1. Data analyzed by weighted interpolation for spatial distribution (kriging).

EC Commission, HCM Large Installation Programme with

Dr Andrea Marion, University of Padua, Italy

Recirculating water & sediment tilting flume.



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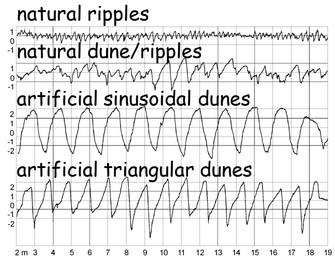
Tracer introduced into recirculating flow
Clear water in bed, measure temporal changes in concentration.
Bed forms studied



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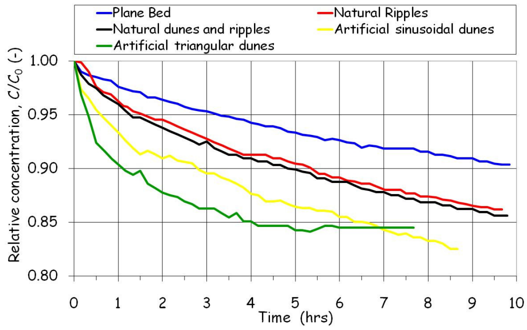
Decay of salt concentration in the surface flow



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Marion, A., Bellinello, M., Guymer, I. and Packman, A. 'Effect of bed form geometry on the penetration of nonreactive solutes into a streambed', Water Resources Research, 2002, 38, 10.

Water

Hyporheic Exchange - Rich Dutton

The University Of Sheffield.

EPSRC

Hart (1995) Density Function

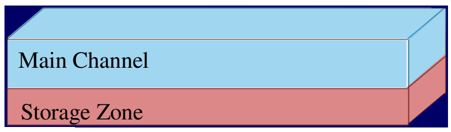
$$f_Z(t) = p_0(f_U * g_0)(t) + \sum_{n=1}^{\infty} p_n(f_U * g_n * \gamma_n)(t)$$

The n^{th} term of the series:
- concentration of solute at the detection site that has made n trips into the storage zone
- allows decomposition into constituent parts
- infers distribution of time spent in the storage zone

OTIS Model

$$\frac{\partial C}{\partial t} + \frac{Q}{A}\frac{\partial C}{\partial x} = \frac{1}{A}\frac{\partial}{\partial x}\left(AD\frac{\partial C}{\partial x}\right) + k_1(C_S - C) + k_L(C_L - C)$$

$$\frac{\partial C_S}{\partial t} = k_2(C - C_S)$$



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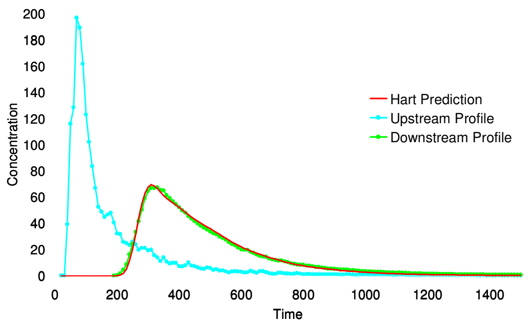
Water

Decomposed Hart Model



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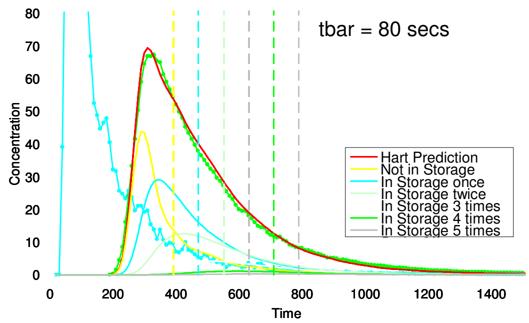
Decomposed Hart Model



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Laboratory Channel Studies

Meandering Channel

Natural sand formed porous bed

Tracer studies using both sealed and porous bed

In-stream measurements unable to determine difference in exchange coefficients using a 4 parameter model

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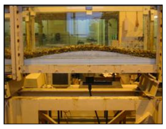
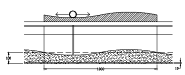
Straight Channel

Flat or undulating bed

Gravel & styrofoam

Test Series	Slope (1 in…)	Bedform	Bed thickness (mm)
1	11000	Flat	10, 20, 30, 55, 75, 100
2	4000	Flat	30, 100
3	4000	Oscillating	30, 100





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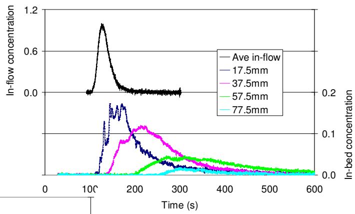
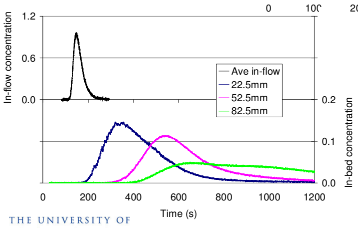
Flat gravel
Flow rate 3.1 l/s
100mm thick





Undulating gravel
Flow rate 2.46 l/s
100mm thick

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Comments:

Difficulty in quantifying exchange parameters (OTIS or Hart).

To ensure a 'unique' solution, in-stream longitudinal dispersion coefficient predefined using an ADE fit to the rising limb of the downstream profile.

Transient storage model is reduced to a three parameter process.

From three parameter optimisation technique :

•Exchange rate parameter is proportional to discharge, suggesting that exchange is a turbulent driven process.

•Rate of exchange into storage is constant over all bed shapes and bed forms with the exception of flow over the 100mm undulating thick bed.

•In-bed residence time appears independent of bed slope and bed form.

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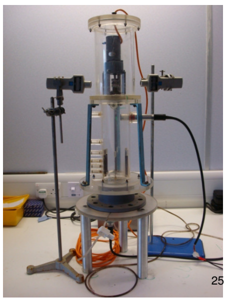
The EROSIMESS-System

- An in-situ erosion-meter (erosimeter)
- Designed to cause sediment motion
- Modified to study effects of sediment re-suspension on dissolved oxygen content
- Now modified for hyporheic exchange studies



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Historically

- Studied in the field or the laboratory
- Most laboratory studies conducted on re-circulating flumes
- Setup time approximately two days
- Run time approximately 10 to 100+ hours
- restricting the range of conditions tested

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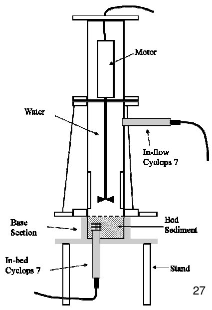
Dutton, R. J. (2004), Modelling Transient Storage Processes, PhD thesis, University of Sheffield, UK.

Experimental setup

- Instrumentation
  - In-flow and in-bed Cyclops 7 fluorometers
- Main section
  - Height = 300 mm, diameter = 97 mm
  - 6 baffles create uniform bed shear stress
- Base section
  - Depth = 70 mm
- Motor and propeller
  - Tri-bladed 20mm diameter propeller
  - Max. 600 rpm ($u_* = 0.056$ m/s)
  - Min. 50 rpm ($u_* = 0.002$ m/s)



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Experimental setup

- Examine capabilities of system
- Test procedure
  - Instrument placed
  - Base filled with tracer
  - Sediment placed and tracer drained to sediment surface
  - 2 litres clean water placed above in main section
  - Motor placed and started
- Test run until equilibrium concentration reached

Test No.	u_* (m/s)	d_g (m) (×10⁻³)	k_s (m)	K (m²) (×10⁻⁹)
1	0.0171	2	0.00708	2.55
2	0.0171	2	0.00708	2.55
3	0.0175	2	0.00708	2.55
4	0.0176	2	0.00708	2.55
5	0.0162	2	0.00708	2.55
6	0.0278	7.5	0.03	94.9
7	0.028	7.5	0.03	94.9
8	0.0099	1	0.00354	0.64

Test No.	D'_m (m²/s) ($\times 10^{-11}$)	V_s (l) ($\times 10^{-3}$)	Initial Gradient In-flow ($\times 10^{-8}$) (kg/m²s$^{1/2}$)	Initial Gradient In-bed ($\times 10^{-2}$) (s$^{-1/2}$)
1	5.61	300	8.15	
2	5.61	245	9.69	
3	5.61	300	13.5	
4	5.61	300	6.76	
5	5.61	300	7.42	-4.33
6	5.71	300	60.0	-16.6
7	5.71	275	34.1	-12.0
8	6.65	300	0.676	-0.136

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Theory

- In-bed D_e calculation

$$D_e = \left(\frac{\sqrt{\pi}}{2}\frac{V_s}{A_s}\frac{dC_s^*}{d(t^{1/2})}\right)^2$$

- D_e = effective diffusion coefficient (m²/s)
- V_s = volume of fluid in the sediment pores (m³)
- A_s = sediment surface area (m²)
- $C_s^* = C/C_{0,s}$ = normalised solute concentration in the sediment pore water

- In-flow D_e calculation

$$D_e = \left(\frac{\sqrt{\pi}}{2C_{0,s}}\frac{dM_w}{d(t^{1/2})}\right)^2$$

- M_w = accumulated mass of solute tracer in the overlying fluid (kg/m²)
- C = solute concentration (kg/m³)
- $C_{0,s}$ = initial solute concentration within the sediment pore water (kg/m³)
- t = time (s)

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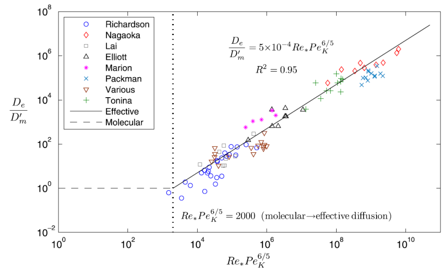
O'Connor, B. L., & Harvey, J. W. (2008), Scaling hyporheic exchange and its influence on biogeochemical reactions in aquatic ecosystems, Water Resources Res., Vol. 44, W12423, doi:10.1029/2008WR007160, Figure 3, p 10.

Theory

- O'Connor and Harvey (2008), Scaling hyporheic exchange and its influence on biogeochemical reactions in aquatic ecosystems



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Theory

Effective diffusion scaling relationship

$$\frac{D_e}{D'_m} = \begin{cases} 5\times10^{-4} Re_* Pe_K^{6/5} & \text{for } Re_* Pe_K^{6/5} \geq 2000 \\ 1 & \text{for } Re_* Pe_K^{6/5} < 2000 \end{cases}$$

- Shear Reynolds number

$$Re_* = u_* \frac{k_s}{\nu}$$

- u_* = bed shear velocity (m/s)
- k_s = roughness height (m)
- ν = kinematic viscosity (m²/s)

- Permeability Péclet number

$$Pe_K = u_* \frac{\sqrt{K}}{D'_m}$$

- K = permeability (m²)
- D'_m = molecular diffusion coefficient through the sediment pore water (m²/s)

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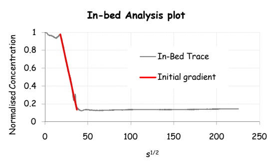
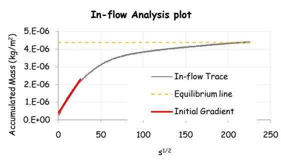
O'Connor, B. L., & Harvey, J. W. (2008), Scaling hyporheic exchange and its influence on biogeochemical reactions in aquatic ecosystems, Water Resources Res., Vol. 44, W12423, doi:10.1029/2008WR007160, Figure 3, p 10.

Results





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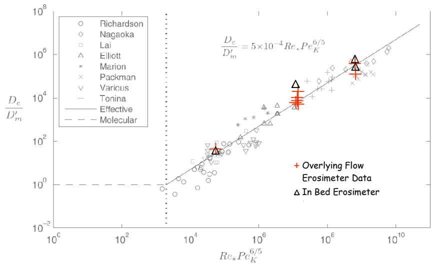
Results



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O'Connor, B. L., & Harvey, J. W. (2008), Scaling hyporheic exchange and its influence on biogeochemical reactions in aquatic ecosystems, Water Resources Res., Vol. 44, W12423, doi:10.1029/2008WR007160, Figure 3, p 10.

Summary

- EROSIMESS-System can be used to study hyporheic exchange for a wide range of conditions
- The scatter of erosimeter derived exchange coefficients lies within that of the previous flume studies
- Advantages over flume tests
  - Repeatability of tests
  - Ability to generate a wide range of bed shear velocities
  - Small quantities of sediment and fluid required
  - Reduced testing time, whilst still achieving full scale hyporheic exchange
- The erosimeter system could be used to study many factors that affect hyporheic exchange
  - Chemical sorption and the initial location of pollutants
  - Sediment depth and stratification

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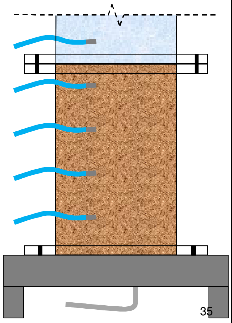
Ongoing work

- Re-built erosimeter to include an in-situ permeability test and fibre optic fluorometer heads
- Proposed tests
  - Depth to which turbulence driven hyporheic exchange penetrates into the bed
  - Effects of chemical sorption on exchange coefficients, through the introduction of organic carbon to the sediment bed



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Thankyou for listening

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