How does groundwater move and transport contaminants (e.g., septic system effluent)?
Water Flow in Porous Media
water flows due to a combination of water pressure and gravity
Water flows due to a combination of water pressure and gravity.

- Water pressure "pushes" water flows.
Water flows due to a combination of water pressure and gravity. Water pressure "pushes" and gravity "pulls".
Water pressure “pushes” and gravity “pulls”

The combination of these two quantities is called the **hydraulic head**

Water moves due to a difference in hydraulic head between two locations.

The change in hydraulic head over some distance is called the **hydraulic gradient**.
A water molecule at the surface of the sand senses a water pressure due to the height of the water above the sand. It is called the pressure head or $h_p$.

A water molecule at the surface wants to “fall” to the bottom of the sand due to gravity. This is called elevation head or $h_z$.

The total head at the surface of the sand is

$$h = h_p + h_z$$
The total head at the **bottom** of the sand

A water molecule at the bottom of the sand senses no water pressure because the valve opening is exposed to the atmosphere, therefore \( h_p = 0 \)

A water molecule at the bottom doesn’t fall any distance because it is already at the bottom! Therefore, \( h_z = 0 \)

The total head at the **bottom** of the sand is \( h = 0 \)
The change in total head ($\Delta h$)

$\Delta h = \text{head at the top} \, \text{“minus”} \, \text{the head at the bottom}$

$\Delta h = h - 0 = h_p + h_z$
The length of the sand is defined as $\Delta L$. 

$\Delta L$
The hydraulic gradient

The hydraulic gradient is $\frac{\Delta h}{\Delta L}$
friction along the grain surfaces will resist water flow
Stream-Flow Analogy

- highest stream velocity
- lowest stream velocity
- energy lost due to friction along the stream channel
Stream-Flow Analogy

Equivalent stream-channel volumes.

Which one has the lower velocity? Why?
Water Flow in Porous Media

Pore space between grains

grain

friction along grain

higher water velocity

lower water velocity
The amount of friction along grain boundaries depends on the surface area of the sediment.
Assuming spherical sediments, the surface area per volume is given as

\[ a_v = \frac{6}{d} \]

where \( d = \) grain diameter
gravel having grain diameters of 4.0 mm

\[ a_v = 15 \, \text{cm}^2 \, \text{per cm}^3 \]
sand having grain diameters of 0.4 mm

\[ a_v = 150 \text{ cm}^2 \text{ per cm}^3 \]
silt having grain diameters of 0.04 mm

\[ a_v = 1500 \text{ cm}^2 \text{ per cm}^3 \]
1 gram of smectite clay has 8,000,000 cm² of surface area

or

5 grams of smectite clay has the surface area of a football field!

smectite is a common name for montmorillonite, the clay that attracts water and “swells”
Water flow in porous media is measured with a permeameter
Permeameter

Cylinder has an area = A

Sand filled cylinder (saturated)
Permeameter

water pressure in the vessel “pushes” water into the sand

water flows through the sand and out the valve
Permeameter

The volume of water that flows out is controlled by the **hydraulic gradient** and the amount of **friction** along the grains.
First Experiment

The volume of water that flows out in some length of time is the discharge = $Q = \Delta h \Delta L$

the water height in the vessel remains constant

The volume of water that flows out in some length of time is the discharge = $Q$
Plot the results of the 1st experiment
Second Experiment

increased water height

$\Delta h$

$\Delta L$

larger discharge $Q$
Plot the results of the 2nd experiment
In all experiments the $\Delta h$ is kept constant.
Plot the results of the 3rd experiment

\[
\frac{Q}{A} \quad \text{versus} \quad \frac{\Delta h}{\Delta L}
\]
Darcy’s Law

\[ \frac{Q}{A} = -K\frac{\Delta h}{\Delta L} \]

The slope of the line in the graph is \( K \), which represents the hydraulic conductivity or permeability.
The **hydraulic conductivity** is a measure of the sediments' ability to transmit fluid.

It’s magnitude is controlled by the grain size (or pore size) which determines the amount of **frictional** resistance.
Slope is $K$ for sand

Slope is $K$ for silt
Slope is $K$ for sand

Slope is $K$ for silt
Slope is $K$ for sand

Slope is $K$ for silt
Sand
$K \approx 1 \times 10^{-3}$ cm/s

Silt
$K \approx 1 \times 10^{-6}$ cm/s
To get the same amount of \( Q \) out of both cylinders in the same amount of time, the \( \Delta h \) for the silt would have to be 1000 times that of the sand.
Abbotsford-Sumas Aquifer

The aquifer covers approximately 200 km² and serves as a water supply for approximately 110,000 people in BC and WA.
Ground Water Flow is from North-to-South

Abbotsford-Sumas Aquifer

BC, Canada
WA, USA

Lynden

Abbotsford
Study Area

BC

Sumas

NW-WA Study Area

Socksack River
The aquifer is unconfined and comprised of glacial outwash sands and gravels (Sumas Outwash) deposited about 10,000 years ago.
Sumas Outwash
Well Sampling Sites

Legend
- Deep Wells
- Stream Sampling Sites
- Shallow Wells
- Streams

26 wells
Well Sampling
Monthly Depth to Water Measurements

Depth to Water (ft)

- △ T1
- • H2

The average **hydraulic conductivity** of the glacial sediments is

\[ K = 545 \text{ ft/day} \quad \text{or} \quad K = 0.187 \text{ cm/sec} \]

The average **hydraulic gradient** in the aquifer is

\[ \Delta h / \Delta L = -0.0055 \]

The average **porosity** of the glacial sediments is

\[ n = 0.30 \]
The average pore-water velocity can be determined using Darcy’s Law

\[ \text{velocity} = v = -\frac{K}{n} \left( \frac{\Delta h}{\Delta L} \right) \]

Using the aquifer parameters in the equation above yeilds

\[ \text{velocity} = v = \frac{-545}{0.30(-0.0055)} = 10 \text{ ft/day} \]

which is very fast for groundwater
The average groundwater velocity is 10 ft/day

How long would it take water to travel from well A to well B

If the distance from A to B is 1000 ft
Time = distance / velocity

Time = 1000 ft / 10 ft/day

Time = 100 days
If the aquifer were a fine sand with a hydraulic conductivity of 5.45 ft/day......then the

Velocity = 0.10 ft/day

Time = $\frac{1000 \text{ ft}}{0.10 \text{ ft/day}}$

Time = 10,000 days or 27 years!!
Transport of Septic System Discharge

15 - 25 m

1 - 10 m

N→S

1 - 10 m
$Q_A = Q_B = \text{pumping rate}$

sand

cone of depression

gravel