Groundwater Pollution
Water Pollution III

- Types of Aquifers
- Groundwater Flow Physics
  - Darcy’s Law and Hydraulic Gradient
  - Movement of Underground Plumes
  - Cleanup
- Stormwater Flows
  - Contamination Sources
  - Impacts, Solutions
Groundwater Pollution Facts

- 1980 Comprehensive Environmental Response, Compensation and Liability Act (CERCLA), more commonly known as Superfund.

- 300,000 – 400,000 sites need remediation. Many can be cleaned up for ~$100,000, but some require millions. Total ~0.5–1 trillion dollars.

→ The annual Gross Domestic Product (GDP) is currently 10 trillion dollars.
• To date, roughly 10 billion has been spent on superfund site remediation.

• 1984 Resource Conservation and Recovery Act (RCRA). This legislation hopes to avoid more superfund sites.
Groundwater Structure

FIGURE 5.26 Identification of subsurface regions.
Unconfined aquifers: typically bounded below by a non-porous layer but are not bounded above.

Confined aquifers: sandwiched between two rock layers.
The quantity of water in an aquifer is determined by its porosity.

\[
\text{Porosity } (\eta) = \frac{\text{volume of voids}}{\text{volume of voids and solids}}
\]

→ Fails to account for the amount of water that will be retained due to surface tension at the solid interfaces.

- The specific yield tells the amount of water that can actually be withdrawn (of the total volume).
<table>
<thead>
<tr>
<th>Material</th>
<th>Porosity (%)</th>
<th>Specific Yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay</td>
<td>45</td>
<td>3</td>
</tr>
<tr>
<td>Sand</td>
<td>34</td>
<td>25</td>
</tr>
<tr>
<td>Gravel</td>
<td>25</td>
<td>22</td>
</tr>
<tr>
<td>Gravel and Sand</td>
<td>20</td>
<td>16</td>
</tr>
<tr>
<td>Sandstone</td>
<td>15</td>
<td>8</td>
</tr>
<tr>
<td>Limestone or Shale</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Quartz or Granite</td>
<td>1</td>
<td>0.5</td>
</tr>
</tbody>
</table>

For an aquifer of sand with cross sectional area of 1 m\(^2\) and depth of 2 m, the volume of water is:

\[
\text{Volume of water} = (\text{Porosity})(\text{Vol. of material}) = 0.34 \times 2 \, \text{m}^3 = 0.68 \, \text{m}^3
\]

\[
\text{Yield of water} = (\text{Specific yield})(\text{Vol. of material}) = 0.25 \times 2 \, \text{m}^3 = 0.5 \, \text{m}^3
\]
Groundwater Flow

The hydraulic gradient is defined as:

\[
\text{Hydraulic gradient} = \frac{h_2 - h_1}{L}
\]

Where \( h_i \) are the vertical heights
\( L \) is the horizontal distance.

The gradient is dimensionless, and can be expressed as:

\[
\text{Hydraulic gradient} = \frac{dh}{dL}
\]
Darcy’s Law for flow through porous media

\[ Q = KA \frac{dh}{dL} \]

\( Q = \) flow rate (m\(^3\)/day)
\( K = \) hydraulic conductivity (m/day)
\( A = \) cross-sectional area (m\(^2\))

<table>
<thead>
<tr>
<th>Material</th>
<th>Hydraulic Conductivity (m/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay</td>
<td>0.0004</td>
</tr>
<tr>
<td>Sand</td>
<td>41</td>
</tr>
<tr>
<td>Gravel</td>
<td>4100</td>
</tr>
<tr>
<td>Gravel and Sand</td>
<td>410</td>
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<tr>
<td>Sandstone</td>
<td>4.1</td>
</tr>
<tr>
<td>Limestone, Shale</td>
<td>0.041</td>
</tr>
<tr>
<td>Quartzite, Granite</td>
<td>0.0004</td>
</tr>
</tbody>
</table>

*Note that the actual values can vary by several orders of magnitude, and aquifers are highly non-homogeneous.*
Example

A confined aquifer 20 m thick has two wells spaced 500 m apart, and the difference in the water levels at the two wells is 2 m. The hydraulic conductivity is 50 m/day (assume an arbitrary width of 1 m). What is the flow rate?

\[ Q = KA \frac{dh}{dL} = \left( \frac{50 \text{ m}}{\text{day}} \right)(1 \text{ m})(20 \text{ m}) \frac{2 \text{ m}}{500 \text{ m}} = 4 \frac{\text{m}^3}{\text{day}} \text{ (per meter of width)} \]
From Darcy’s Law,

\[ Q = KA \frac{dh}{dL} \]

we can get the Darcy Velocity:

\[ v = \frac{Q}{A} \]
Movement of Toxic Plumes

- Darcy’s Law Velocity is for flow through the total porous media per m³ of aquifer volume
  - Underestimates the actual groundwater flow in proportion to the porosity.
  - The cross-sectional area available for flow, A’, is less than the overall cross-sectional area of the aquifer A.
Then, \[ Q = Av = A'v' \]

\[ v' = \frac{ALv}{A'L} = \frac{\text{Total Volume} \times v'}{\text{Void Volume}} \]

(using an arbitrary length, L)

**Porosity** \[ \eta = \frac{\text{Volume of voids}}{\text{Volume of voids and solids}} \]

\[ v' = \frac{\text{Darcy velocity}}{\text{Porosity}} = \frac{v}{\eta} = \frac{K}{\eta} \left( \frac{dh}{dL} \right) \]
Example
Suppose the second well in the earlier example was a drinking water well, and the first (upstream) well was a monitoring well. If a toxic plume is detected at the first well, how long will it take before it arrives at the second well? The porosity is 35%.

\[
v' = \frac{\text{Darcy velocity}}{\text{Porosity}} = \frac{v}{\eta} = \frac{K}{\eta} \left( \frac{dh}{dL} \right) \quad \Rightarrow \quad v' = \frac{50 \text{ m/day}}{0.35} \times \frac{2 \text{ m}}{500 \text{ m}} = 0.57 \text{ m/day}
\]

Note that the Darcy velocity was

\[
v = 50 \text{ m/day} \times 0.004 = 0.2 \text{ m/day}
\]

The time to travel the 500 m is:

\[
t = \frac{500 \text{ m}}{0.57 \text{ m/day}} = 877 \text{ days} = 2.4 \text{ yr}
\]
This value isn’t very accurate because of the following 3 assumptions:

1. We ignored diffusion and dispersion of the plume, but it does spread out
2. We assumed that the plume moves at the same speed as groundwater—it doesn’t.
3. We ignored the “pulling” effect of the well.
Diffusion and Dispersion

- Diffusion involves the random motion of molecules

  → The macroscopic velocity is an average of molecular velocities

  → The molecular velocities have a distribution of speeds that follows a Boltzmann distribution.
• Dispersion results from the inhomogeneity in the porous media.

→ Some parts of the flow find areas where the pores are larger and move more quickly

→ Some are retarded by other parts of the media.
Diffusion and dispersion combine to create hydrodynamic dispersion. They smear out the edge of the plume.

(a) Laboratory setup

(b) Emerging tracer

FIGURE 5.34 Dispersion and retardation as a continuous feed of tracer passes through a column. With no dispersion, the tracer emerges all at once. With retardation and dispersion, the tracer smears out and emerges with some delay.
• Contaminants can be “sorbed” by the solids in the porous media—either:
  → adsorbed—stuck to the surface of the particle
  → absorbed—taken up into the particle

• The ratio of contaminant per unit volume of aquifer to the contaminant dissolved in the groundwater is called the retardation factor:

\[ R = \frac{\text{average groundwater velocity, } v'}{\text{velocity of the sorbed material, } v_s} \geq 1 \]
Cl⁻ has a retardation factor of 1, since it is completely dissolved in the ground water.

Retardation of 5 means ____ % is in the water.

Implication for water treatment:
You have to pump and treat more than once to get the water clean!
Groundwater and Stormwater Contamination
Groundwater Contamination

- Groundwater flow is typically horizontal and slow, its progress impeded by the soil. 30 m/yr is typical. The residence time may be years, or decades or centuries.

- Contaminants percolate through the soil until they reach the groundwater, where they slowly (or quickly in the case of MTBE) dissolve into the passing flow.
In the San Fernando Valley, groundwater follows the path of the L. A. River, flowing from west to east across the valley (~5 feet/yr), then funneling south through the LA River Narrows (~1300 feet/yr.)
• There are three key water-bearing zones: upper alluvium, lower alluvium, and deep zone. Alluvial aquifers are water-bearing layers of sand and gravel from the slowly eroding surrounding mountains.

• The upper alluvium is from the surface to 200–250 feet, is not fully saturated, and is quite sensitive to recharge and water usage.

• The lower alluvium extends to depths of 400–600 feet, separated from the upper zone by a layer of about 50 feet of finer sediments, which somewhat protects the lower zone from water quality problems.
Historical depths for Well 3700A (near Reseda) and Well 3914H (near Glendale). For both wells, water was at high water levels into the late 1940’s followed by a steady decline due to drought and continued by increased water demands.
In 1980, traces of industrial solvents, especially TCE and PCE, were detected in San Fernando Valley production wells.

This discovery led to drastic reductions in groundwater extraction, particularly in the highly industrialized eastern end of the basin.

The soils underlying many prominent factories of The Valley were affected by spills and leaks of these compounds and other toxic chemicals.

The reduced pumping of the late 1970s may have first brought the groundwater in contact with many of these spills!

The San Fernando Valley had become a gigantic Superfund site.
Trichloroethylene (TCE) in San Fernando Valley's upper aquifer in the San Fernando Valley in the Spring of 1996

~17 miles long with ~200 trillion gallons of contaminated groundwater.

The time-frame for cleanup (extraction and cleaning of the water) is three decades or longer.
Cleaning Groundwater

- Exploratory drilling and well sampling to characterize the spill and engineer cleanup strategies (~several years).
  - Long legal battles (~decade).
  - Pump and treat the water (~decades).
• This water moves at about 1 km/year.

• Burbank actually pumps and treats water. They spray the water and send the vapor to an activated charcoal filter, which eventually gets saturated, landfilled and replaced.
Stormwater Pollution
Stormwater

• Most of the contaminated water reaching our beaches and coastal waters is through stormwater discharges.

→ Crosses yards, roof tops, parking lots and freeways on its way to the ocean.

• Lawns and gardens release nutrients and pesticides, streets release hydrocarbons, oil and grease and heavy metals associated with motor vehicles.
- Ballona Creek stormwater is elevated in many pollutants, such as heavy metals (zinc, lead, copper, and nickel).

- Another problem with storm drains is dry weather flow:
  - ➔ natural drainage
  - ➔ Excessive irrigation of lawns, leakage, car washing, hosing down of streets and sidewalks, and other small sources.
Ballona Creek during dry weather. (Fairfax Street crossing)
• Average LA rainfall ~15 inches/yr, primarily between November and April.

• Long dry spells allow trash and pollutants to accumulate, and the first large storm of the season washes a slug of trash to the ocean.

• Stormwaters are more difficult to control than wastewaters. They are more dispersed, with a greater number of public agencies responsible for their regulation.
Source of Stormwater

- Stormwater flow
  \[ = (\text{rainfall})(\text{surface area})(\text{runoff coeff.}) \]

  → The runoff coefficient depends on the land surface permeability.

  - Open areas, with vegetation have low runoff coefficients (< 20–30% of the rain flows to the storm drain)—most of the water percolates into the soil.
  
  - Paved areas have higher runoff coefficients.
— In West LA, 60% of rainfall becomes runoff.

— In greater LA, 5% of rainfall once ran into the ocean; now about 50% does.

— Currently we allow $100 million/year of water we could use to recharge our aquifers just flow into the ocean.
Where does the stormwater go?

- Stormwater makes its way from the street in front of your house or your roof drains directly to the ocean through a series of increasingly larger pipes, channels, creeks and rivers.

- Stormwater reaches the ocean untreated.
The stormwater may overload the sanitary sewer and cause it to overflow at a downstream location. This contains bacteria and other pollutants that can cause a serious health risk at the beach.

Ballona Creek during a large storm.
Because the temperature and density of the stormwater are different from sea water, the stormwater requires time and distance to mix with the saltwater.
Beach Water Quality

• Beach water quality is improving.
  → Upgrades of the Hyperion Treatment Plant and replace aging sewers are resulting in far fewer sewage leaks.

• Beaches are posted or closed when the indicator organism count exceeds a specific threshold. Beaches next to a stormdrain are permanently posted.
  → Swim when it hasn’t rained recently!
Possible Solutions

• Can’t use treatment plants
  ➔ One large rainfall, creates more stormwater flow to Santa Monica Bay than our new Hyperion treatment plant treats in a month.

• Porous Pavement
  ➔ Porous pavement results in more infiltration and less stormwater flow.

Figure 1. Porous Asphalt Paving: A Typical Cross-Section
• **Biomass Injection**

  → Stormwater is often directed towards a drain and not to the green space. Green space can actually provide treatment for some of the pollutants.

• **Wetlands, Ponds and Detention Basins**

  → Useful where there is space, which there is little of, here.

• **Trash Screens and Racks**

  → These new technologies may be able to remove trash and gross solids without excessive maintenance or flood control risks.
• Low Flow Diversion

→ It is possible to pump the dry weather flow from stormdrains to sanitary sewers.

• Street Sweeping and Catch Basin Cleaning

→ Street sweeping prevents trash and gross pollutants from entering stormdrains. Need to increase the recovery of small particles.
• **Product Replacement and Pollution Prevention**

  → Certain products are more polluting than others. Some automobile brake pads have high metal content, some do not. Cover for product inventory, reduce leaks, etc. etc.

• **Find and eliminate illegal connections to stormdrains**

  → Many small businesses send some or all of their waste to storm drains.
• Parks, ponds, porous swails
• Most or all of the above.
• Increase capacity of sewers?
• Fix sewer leaks?