Environmental Water Quality
BAE 452/552

Session 19

Groundwater Waste Loads

Transport of Pollutants & Loading Calculations

- Mass balance & hydrologic components
- Erosion and sediment transport
- Loading calculations
- Solid-phase and dissolved chemical loads
- Distributed-phase chemical loads
- Salt loads in irrigation return flows & urban runoff loads
- Ground water waste loads ←

Ground Water

- Approximately 50% of US population depends on ground water for its supply of potable water
- 36% of all municipal drinking water supply systems
- 95% of rural population uses ground water for drinking water supply

Ground Water

- Ground water and surface water systems are connected:
- recharge of surface water to ground water
- discharge of ground water to surface water
- NPS pollution can reach surface water bodies via ground water

Ground Water Quantity

The amount of ground water in US mainland is very large:

- Amount in top 800 meters of earth surface is equal to 35 years of all surface water runoff
- Surface water is used more than ground water

Ground Water Quantity

World wide

- 130 x 10^6 km^2
- 60 x 10^6 km^3
- 4% by volume
- 120 m equivalent depth
- 2 weeks - 10,000 years residence times

Ground Water Quality

- Ground water is of high quality in most cases, but increased usage of ground water resources and increased inputs at the surface have caused contamination in many places
- Nitrate contamination is has been showing up in many areas, organic chemicals may follow
- Process by which contamination occurs is called leaching

Ground Water Quality

- Monitoring of ground water quality is still being done on a limited scale using monitoring wells
- When contamination is detected in wells it is usually too late to eliminate the pollution source due to slow response times
- Clean up costs are high and extremely challenging due to scale, geologic constraints, and absence of oxygen, nutrients

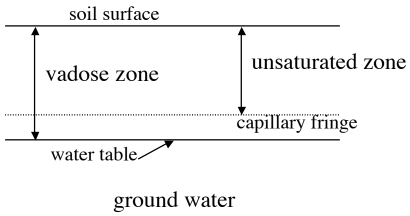
Ground Water Quality

- Regulation of ground water quality is done through three acts:
- Safe Drinking Water Act (1974)
- Federal Environmental Pesticide Control Act (1972)
- Toxic Substance Control Act (1976)
- Note: Drinking Water Act regulates at point of use, Clean Water Act at the source

Vadose Zone

- The earth layer that contains both solids, water and air is the unsaturated zone, zone of aeration or <u>the vadose zone</u>
- Strictly speaking, the saturated zone above the water table (the capillary fringe) is also part of the vadose zone

Subsurface Terminology



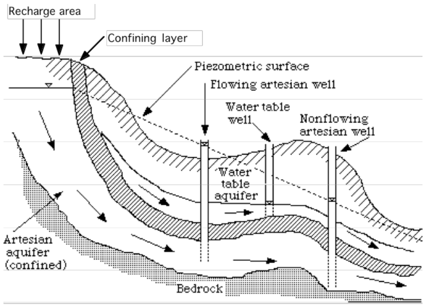
Water Movement in Vadose Zone

- Generally, water movement in the vadose zone is downward
- If restrictive layers are present, lateral movement can occur
- If the water table is less than 2 meters from the root zone, and evaporation exceeds rainfall, significant amounts of water can be transport upwards
- Therefore, a daily or monthly balance may be needed to estimate annual recharge

Water Movement in Saturated Zone

- Movement is governed by pressure gradient and is mostly horizontal
- For unconfined aquifers (with free water table), water flows from regions of high water table to low water table
- For confined aquifers (bounded by impermeable layers), water flow depends on the height of the piezometric surface

Aquifer Types



Screening Methodology

Estimation of pollution loads to ground water

- Water balance
- Nitrate loads
- Organic chemical loads

(Follows EPA document for the most part)

Water Balance

- Recharge or percolation (Q):
- Q = P + I - E
- where
- P = annual precipitation (cm)
- I = annual irrigation (cm)
- E = annual evapotranspiration (cm)

Pollutant Categorization

Using the linear partition coefficient (K_d):

- Group I: $K_d \sim 1000$, strongly adsorbed
- Group II: $K_d \sim 5$, moderately adsorbed
- Group III: $K_d \sim < 0.5$, non-adsorbed or soluble pollutants

Pollutant Categorization

Example pollutants:

- Group I: solid phase organic nitrogen, DDT, paraquat)
- Group II: atrazine, most herbicides,
- Group III: nitrate

Mass Pollutant Flow

The direction of mass pollutant flow is determined by the direction of water flow (vertical in vadose zone, horizontal in ground water)

The distance that the pollutant will move in the direction of flow is dependent on the magnitude of water flow and the adsorption characteristics of the pollutant

Mass Pollutant Flow

Average displacement of pollutants can be estimated by the following equations:

- Unsaturated zone: $\text{Displacement} = \dfrac{Q}{\theta_{fc} + \rho_{dry} K_d}$
- Saturated zone: $\text{Displacement} = \dfrac{Q}{\theta_s + \rho_{dry} K_d}$

Mass Pollutant Flow

- Unsaturated zone: $\text{Displacement} = \dfrac{Q}{\theta_{fc} + \rho_{dry} K_d}$
- Saturated zone: $\text{Displacement} = \dfrac{Q}{\theta_s + \rho_{dry} K_d}$

where

- Q = water flow per unit area ($cm^3\ cm^{-2}$)
- θ_{fc}, θ_s = moisture content at field capacity and saturation, respectively ($cm^3\ cm^{-3}$)

Mass Pollutant Flow: Examples

Q = 10cm	Sand		Clay	
Pollutant (K_d)	unsat.	sat.	unsat.	sat.
$K_d = 0$	100	22	25	20
$K_d = 0.5$	12	9	9	9
$K_d = 5$	1	1	1	1
$K_d = 1000$	<1	<1	<1	<1

Sand: $\theta_{fc} = 0.10$, $\theta_s = 0.45$; Clay: $\theta_{fc} = 0.40$, $\theta_s = 0.50$

Hydrodynamic Dispersion

- Dispersion reflects the tendency of a pollutant band to spread out. The average displacement is not affected by dispersion
- Hydrodynamic dispersion causes dilution of the pollutant due to mixing during fluid advection (mechanical dispersion) and because of molecular diffusion due to thermal-kinetic energy of the solute particles
- Mechanical dispersion is important at high flow velocities, diffusion is important at low velocities

Mechanical Dispersion

- Three mechanisms can be identified:

1. Differences in flow velocities in pores due to drag exerted on fluid by roughness of pore surfaces
2. Differences in pore sizes along the flow path
3. Tortuosity, branching and interfingering of pore channels in soil

- Spreading in direction of flow is known as longitudinal dispersion
- Spreading in perpendicular to flow direction is transverse dispersion

Diffusion

- Diffusion is the process whereby ionic or molecular constituents move under the influence of their kinetic activity in the direction of their concentration gradient
- Terms: self-diffusion, molecular diffusion, ionic diffusion

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Diffusion

Fick's Law: $F = -D\frac{dC}{dx}$

where

- F = mass flux of pollutant per unit area per unit time ($M\,L^{-2}T^{-1}$)
- D = diffusion coefficient ($L^2\,T^{-1}$)
- C = pollutant concentration ($M\,L^{-3}$)
- dC/dx = concentration gradient

Diffusion Coefficients

- Typical values for ionic species in water are:
- 1×10^{-9} to 2×10^{-9} $m^2\,s^{-1}$ at 25 degrees C
- At 5 degrees C these quantities are ~50% less
- In porous media, D is even smaller due to presence of solids and flow paths of diffusion

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Attenuation

- Different processes such as adsorption, degradation and transformation (mostly by microbial activity) causes pollutant attenuation in the root zone
- Once the pollutant leaves the root zone, microbial processes are slow
- Self cleaning times of aquifers therefore are measured in hundred of years

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Nitrate Loads

- Municipal sewage, sewage sludges, fertilizer, manure are often applied to land
- These may pose a ground water pollution problem
- A simple nitrate loading calculation procedure estimates nitrate concentrations (as N) in percolation from the root zone of a land application site

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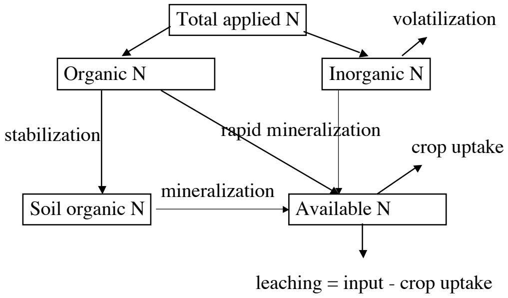
Nitrate Loading Model



Nitrate Loading Model

Assuming all available N is nitrate

- $O_{t+1} = O_t(1\text{-}m) + (1\text{-}a)\ N\ F\ X_t$
- $A_t = mO_t + (1\text{-}v)\ N\ (1\text{-}F)\ X_t + a\ N\ F\ X_t$
- $\quad = mO_t + N[(1\text{-}v)(1\text{-}F) + a\ F]\ X_t$

where

- O_t = soil organic nitrogen (incl. stabilized Org N) at the beginning of year t (kg ha^{-1})
- X_t = waste application of dry solids in year t (kg ha^{-1})
- m = annual mineralization rate for soil nitrogen
- a = fraction of waste organic N mineralized during year of application
- N = nitrogen fraction of solids
- F = organic fraction of waste NITROGEN
- A_t = available N in year t (kg ha^{-1})
- v = fraction of waste inorganic N volatilized

Nitrogen Loss

Nitrogen loss by leaching:

- $L_t = A_t - Cn_t$

where

- L_t = N leachate in year t (kg ha^{-1})
- Cn_t = crop N uptake in year t (kg ha^{-1})

For N crop uptake (see Table III-26)

L_t is the N load to ground water

Steady State Loading Model

After many years of waste application at an average rate X (kg ha^{-1})

- $O_t = O_0(1\text{-}m)^t + BX[1+(1\text{-}m) + (1\text{-}m)^2 +..]$
- $\quad \approx O_0(1\text{-}m)^t\ BX/m$

where

- B = (1-a) N F and
- O_0 initial organic N level

Steady State Loading Model

If O_0 is negligible, steady state organic N = BX/m:

- $O_{ss} = BX/m = (1\text{-}a)\ N\ F\ X/m$

Finally, the steady-state loading function:

- $L = NX\ [1\text{-}v(1\text{-}F)] - Cn$

where all subscripts t are dropped and variables are average annual values

Example III-11

Nitrate-N Load from Sludge Land Application Site

Determine the steady-state loading of nitrate-N from a land application site for sewage sludge in central Florida. The sludge is spread on fescue at an annual rate of 10 t ha^{-1}. The sludge solids are 5% nitrogen and 70% of the nitrogen is organic. The inorganic nitrogen is 90% ammonia nitrogen. (Also estimate the average nitrate-N concentration in percolation entering the saturated zone.)