Environmental Water Quality BAE 452/552

Session 13

Hydrologic Components & Mass Balance

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Sources of Pollutants

- Pollutant interaction with soils
- Fate of contaminants in soils
- Isotherms
- Degradation and transformations
- N and P cycles and interactions
- Atmospheric deposition

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Main Course Components

- Definitions
- Receiving water impacts
- Sources of Pollutants
- Transport of Pollutants & Loading Calculations ←
- Control of non-point source pollution

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Transport of Pollutants & Loading Calculations

- Hydrologic components
- Mass balance
- Erosion and sediment transport
- Loading calculations
- Loading functions for nutrients
- Loading functions for pesticides
- Loading functions for urban sources
- Ground water waste loads

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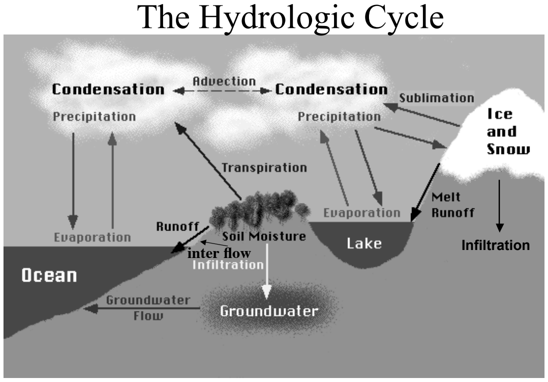
The Hydrologic Cycle



Common Components of the Hydrologic Cycle

- Precipitation (P)
- Interception
- Evaporation (E)
- Transpiration (T)
- Infiltration
- Surface runoff (R)
- Groundwater flow (G)
- Interflow
- Atmospheric circulation
- Condensation
- Surface detention
- Soil moisture (S)
- Lake/ocean storage

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Hydrologic Components Continuity Equation

$$I - O = \frac{\Delta S}{\Delta t}$$

where I = Inflow, O = Outflow, S = Storage, and t = time

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Mass Balance for Surface Runoff

$$Q_s = P - Int - Dep - I - ET$$

where Q_s = surface runoff, P = Precipitation, Int = Interception, Dep = Depression storage, I = Infiltration, and ET = Evapotranspiration

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Mass Balance for Interflow

$$Q_i = I - ET - \Delta S_s - q_g$$

where Q_i = interflow, I = Infiltration, and ET = Evapotranspiration, ΔS_s = change in soil moisture storage, q_g = ground water recharge

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Mass Balance for Ground Water

$$Q_g = q_g - \Delta S_g - q_d$$

where Q_g = ground water flow, q_g = ground water recharge, ΔS_g = change in ground water storage, q_d = geologic water loss

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Mass Balance Time and Scale

- Different components play a different role depending on time and spatial scale
- Smallest scale in watershed is source area (farmer's field, landfill, etc.)
- Watershed is total drainage area above point of interest and may consist of many source areas

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Watershed Scale

Nonpoint sources from a watershed are not simply the sum of all source areas as now the dynamic interactions play a role:

- re-infiltration
- attenuation
- degradation
- ground water - surface water interaction
- stream dynamics

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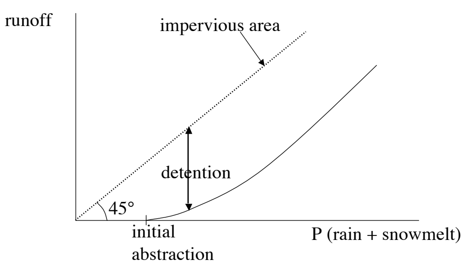
Characteristics of Watershed in NPS Pollution

- Water balance (infiltration vs runoff)
- Antecedent moisture conditions
- Delayed watershed response (snow melt, ground water, interflow, wetlands, ponds, sediment transport)

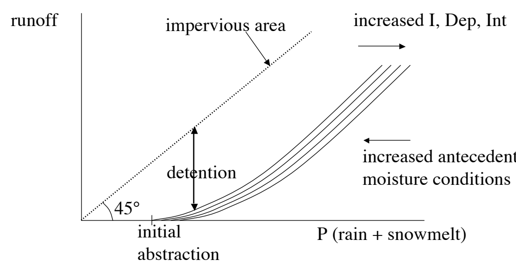
Runoff

- Overland flow which produces potential pollution by mixing with wastes on or near the land surface -> source area
- Can appear as a sheet, small channels, or rivulets

Precipitation-Runoff Response



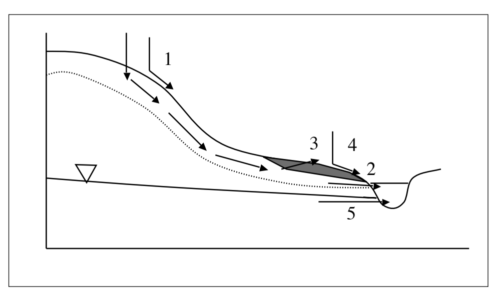
Precipitation-Runoff Response



Runoff Process

1. Hortonian overland flow: infiltration capacity of soil is less than rainfall intensity (infiltration excess)
2. Subsurface storm flow: contribution of flow from shallow soils to stream
3. Return flow: contribution of flow from shallow soil to surface
4. Direct P onto saturated areas
5. Ground water flow (base flow)

Runoff Process



Infiltration Capacity

Infiltration capacity (f_p): the maximum infiltration rate when water is supplied under atmosphere pressure when the water supply rate (rain or irrigation) exceeds the ability of the soil to absorb the water (Horton, 1940)

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Infiltration Process

- Infiltration capacity decreases with time
- The time integral of infiltration rate as a function of time, f(t), shows an increase with time and equals the cumulative infiltration amount curve as a function of time, F(t)
- Final infiltration capacity: when infiltration capacity reaches equilibrium ($=K_s$)

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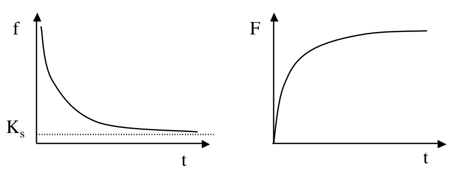
Infiltration Process

$$F = \sum f\Delta t = \int f dt \qquad f = \frac{dF}{dt}$$



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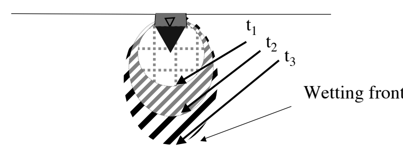
Wetting Process

At first matric or suction gradients are very high so water infiltration occurs uniformly in all directions. Then as the wetted zone thickens, suction gradients become smaller, and vertical movement is greater due to gravitational forces



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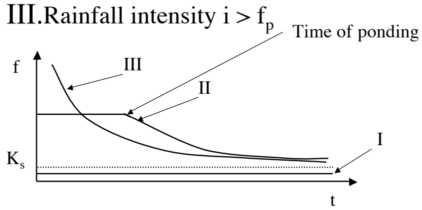
Infiltration Process

Three cases:

I. Rainfall intensity, $i < K_s$

II. Rainfall intensity $K_s < i < f_p$

III. Rainfall intensity $i > f_p$



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Horton Equation

- Horton (1940): $f_p = f_c + (f_o - f_c)e^{-\beta t}$

where

f_p = infiltration capacity

f_c = final infiltration capacity

f_o = initial infiltration capacity

β = constant representing rate of decrease in f_p (1/hr)

t = time (hr)

Need to find 3 parameters: f_c, f_o, and β. These cannot easily be measured, so must be derived experimentally

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Infiltration Excess Overland Flow

- Case II (and III) type infiltration
- Occurs mostly in semi-arid rangelands and cultivated fields in regions with high intensities, and compacted soils (including also urban areas, and frozen soils)

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Saturation Excess Overland Flow

- Case I type infiltration
- Occurs in regions with high infiltration capacities
- Causes partial areas of saturation where either soils become shallow, or where upslope contributing area converges
- Saturated areas expand and contract

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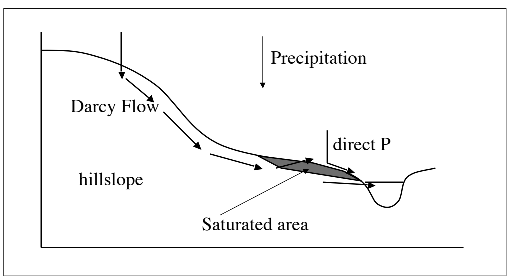
Runoff Process



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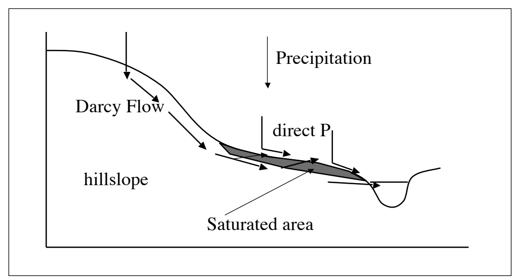
Runoff Process



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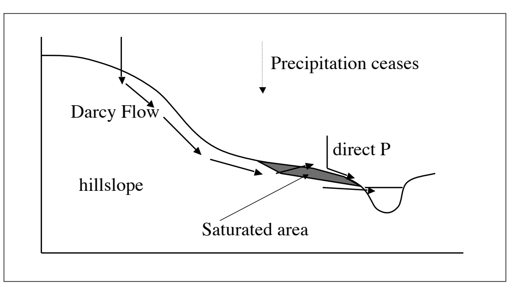
Runoff Process



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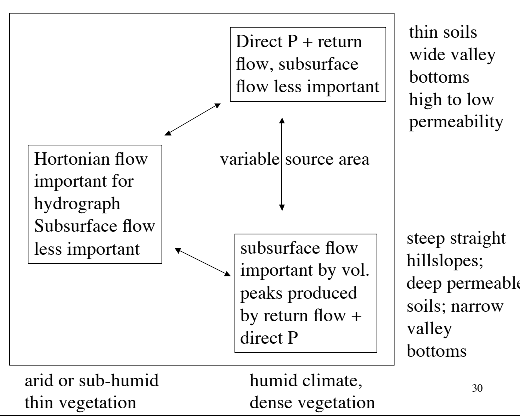

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Nonpoint Source Waste Loads (in runoff)

- Dissolved Pollutant Waste Load (LD):

LD = Runoff water volume x C_{runoff}

- Solid Phase Pollutant Waste Load (LS):

LS = Sediment flux x C_{sed}

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Loading Calculations

- Method for computing runoff volumes
- Method for computing sediment flux
- Methods for determining pollutant concentrations

- http://www.epa.gov/waterscience/pc/watqual.html

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SCS Curve Number Method

- A standard procedure for estimating storm runoff: $$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \text{ for } P \geq 0.2S$$

where

Q = runoff (cm)

P = precipitation (rainfall + snowmelt, cm)

S = water retention parameter (cm)

0.2S = initial precipitation abstraction

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Precipitation

- Rainfall
- Snowmelt using degree-day method:
- $M_t = 0.45\ T_t$ (daily mean temperature in °C on day t) for T_t>0
- M_t = snowmelt in cm/day
- Degree-day method best calibrated to local area of interest

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SCS Curve Number Method

- The retention parameter (S) is computed from dimensionless curve numbers (CN)

$$S = \frac{2540}{CN} - 25.4$$

where

CN is a function of soils, cover, management, and antecedent moisture conditions

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Hydrologic Soil Group A

- **Group A** is sand, loamy sand or sandy loam types of soils. It has low runoff potential and high infiltration rates even when thoroughly wetted. They consist chiefly of deep, well to excessively drained sands or gravels and have a high rate of water transmission.

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Hydrologic Soil Group B

- **Group B** is silt loam or loam. It has a moderate infiltration rate when thoroughly wetted and consists chiefly or moderately deep to deep, moderately well to well drained soils with moderately fine to moderately coarse textures.

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Hydrologic Soil Group C

- **Group C** soils are sandy clay loam. They have low infiltration rates when thoroughly wetted and consist chiefly of soils with a layer that impedes downward movement of water and soils with moderately fine to fine structure.

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Hydrologic Soil Group D

- **Group D** soils are clay loam, silty clay loam, sandy clay, silty clay or clay. This HSG has the highest runoff potential. They have very low infiltration rates when thoroughly wetted and consist chiefly of clay soils with a high swelling potential, soils with a permanent high water table, soils with a claypan or clay layer at or near the surface and shallow soils over nearly impervious material.

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Land Use, Treatment & Condition

- Land Use: Fallow, row crops, small grain, close-seeded legumes, pasture, meadow, woods, roads, residential
- Treatment: straight row, contoured, terraced, lot size
- Condition: "Poor" versus "Good"

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Antecedent Moisture

Antecedent Conditions	5-day Antecedent Precipitation (cm)	
	Dormant Season*	Growing Season
I	< 1.3	< 3.6
II	1.3 – 2.8	3.6 – 5.3
III	> 2.8	> 5.3

* During snowmelt, condition III is always assumed

$$CN_I = \frac{CN_{II}}{2.38 - 0.0138CN_{II}} \qquad CN_{III} = \frac{CN_{II}}{0.43 + 0.0057CN_{II}}$$

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Curve Number Example

Land use or cover	Treatment or practice	Hydrologic condition	Hydrologic soil group			
			A	B	C	D
Row crops	straight row	poor	72	81	88	91
Row crops	straight row	good	67	78	85	89

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Internet Source for CN Method

- http://www.ecn.purdue.edu/runoff/documentation/scs.htm (Long-Term Hydrologic Impact Assessments, L-THIA)
- Urban Hydrology for Small Watersheds' published by the Engineering Division of the Natural Resource Conservation Service, United States Department of Agriculture, Technical Release–55.

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Event-based CN Method

A three-day rainstorm falls on a 30 ha soybean field during early August. The crop is continuously grown in straight rows. The soil is in hydrologic group B. The relevant precipitation data are as follows:

Date	Aug 1	2	3	4	5	6	7	8	9
Rain (cm)	0	0	0	0	0	3.8	5.1	0.3	0

Determine the runoff for this storm.

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Event-based CN Method: Solution

CN_{II} = 81 (see Table). Using equations presented:

$$CN_I = \frac{81}{2.38 - 0.0138x81} = 64.2$$

$$CN_{III} = \frac{81}{0.43 + 0.0057x81} = 90.8$$

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Event-based CN Method Solution

Date	Aug 1	2	3	4	5	6
Rain (cm)	0	0	0	0	0	3.8

Aug 6: CN_I=64.2, S = (2540/64.2)-25.4 = 14.2 cm

Initial abstraction: 0.2S = 2.8 cm < 3.8 cm

Runoff:
$$Q = \frac{(3.8 - 0.2x14.2)^2}{(3.8 + 0.8x14.2)} = 0.06cm$$

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Event-based CN Method Solution

Date	Aug 1	2	3	4	5	6	7
Rain (cm)	0	0	0	0	0	3.8	5.1

Aug 7: CN_{II}=81, S = (2540/81)-25.4 = 5.96 cm

Initial abstraction: 0.2S = 1.2 cm < 5.1 cm

Runoff:
$$Q = \frac{(5.1 - 0.2x5.96)^2}{(5.1 + 0.8x5.96)} = 1.55cm$$

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Event-based CN Method Solution

Date	Aug 1	2	3	4	5	6	7	8
Rain (cm)	0	0	0	0	0	3.8	5.1	0.3

Aug 8: CN_{III}= 90.8, S = (2540/90.8)-25.4 = 2.57 cm

Initial abstraction: 0.2S = 0.51 cm > 0.3 cm

Runoff: Q = 0

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Event-based CN Method Solution

- Total Rainfall = 3.8 + 5.1 + 0.3 = 9.2 cm
- Total Runoff = 0.06 + 1.55 + 0 = 1.61 cm
- Over 30 ha field, 1.61 cm is converted as*:

$$1.61(30)100 = 4{,}830 \text{ m}^3$$

*(1 cm on 1 ha = 0.01 m x 10,000 m^2 = 100 m^3)

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Characteristics of Runoff

- Runoff is nonlinear function of precipitation (not constant portion of precipitation)
- Runoff is generally small fraction of precipitation, particularly in growing season
- Runoff is strongly dependent on antecedent moisture conditions

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Annual Runoff

- CN method applies only to events, so for annual estimates, the sum of each storm in a year must be calculated
- For average annual runoff, the process must be repeated for each of a number of years
- A spreadsheet program can easily achieve these calculations

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Watershed Runoff

- Runoff from an entire watershed is the sum of runoff from all source areas within a watershed

$$Q = \sum_k a_k Q_k$$

where Q_k = runoff from source area k (cm)

a_k = fraction of watershed covered by source area k = A_k/A_{tot}

A_k = area of source area k (ha)

A_{tot} = total watershed area (ha)

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Watershed Runoff

- Watershed runoff volume V(m^3) is:

$$V = 100\sum_k A_k Q_k \quad \text{or} \quad V = 100AT\sum_k a_k Q_k$$

- Alternatively, you can determine the weighted average CN: $CN = \sum_k a_k CN_k$

This method gives slightly lower estimates

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Urban Runoff

- Rational method can be used
- If CN method is used, the assumption is that pervious area corresponds to a pasture in good hydrologic condition and that the impervious area is directly connected with a CN = 98
- ‘directly connected’: flow travels directly to drainage or occurs as concentrated flow over pervious area

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