**EROSION and SEDIMENT TRANSPORT**

**Sediment:** Most visible and significant pollutant on a mass basis. Responsible for reduced aesthetic value of water, reduced storage capacity, habitat destruction, benthic oxygen demand, and pollutant transport. Early NPS pollution efforts focused on sediment almost exclusively.

**Sediment losses due to natural and man-made erosion.**

Sediment Source Sediment Yield, Mg/ha-yr

Natural erosion 0.4

Agricultural erosion 0.1-40.0

Urban erosion 0-500

Highway erosion 0-500

Streambank, channel and shoreline erosion ?

**Sediment-bound Pollutants:** Transported by sediment fines (clay and silt) and organic matter (PCBs, P, metals, organic compounds)

Soil typically formed at a rate of 0.2 - 1.0 mm/yr or 3 to 15 Mg/h-yr (typical values are 3-5 Mg/h-yr). Thus it takes 300 to 1500 years to form 30 cm of soil. It is not possible or desirable to stop all natural erosion. Why is natural erosion important?

**Soil Loss Tolerance (T-value):** The rate at which new soil is formed. If the erosion rate exceeds the soil T-value, the depth of soil is gradually being diminished and soil productivity will decline in the long-run.

**Principal objective of erosion and sediment control:** To minimize excessive erosion caused by man's activities. Of particular concern is the control of critical or **hazardous sediment sources** such as: agricultural land (nutrients, pathogens, pesticides), urban areas (nutrients, pesticides, metals, toxic organics, pathogens), and landfills.

**Fundamental rule of erosion control:** Control sediment loss at its source. Prevent sediment from being detached from the soil surface. Then there is no need to remove it from surface runoff and prevent it from reaching water bodies. In-stream control measures such as dredging and sedimentation are expensive, temporary cosmetic techniques. What do you do with the dredged material?

**DEFINITIONS:**

**Erosion:** The wearing away of the earth's surface by water, wind, ice, and gravity.

**Rill erosion:** Erosion occurring in small channels (1-200 mm in depth and width) on the soil surface. Responsible for almost all downslope soil movement in upland areas.

**Interrill (or sheet) erosion:** Erosion occurring in areas between rills. Sediment eroded via interrill processes (raindrop impact and shallow overland flow) moves to rills and is then transported downslope if sufficient sediment transport capacity is available. Source of most sediment-bound pollutants. One mm of soil loss over a hectare is equivalent to l 15 Mg/ha.

**Gully erosion:** Ephemeral erosion in channels greater than 200 mm in depth and width. Gullies differ from rills in that they cannot normally be obliterated by tillage. Rills feed gullies as interrill erosion feeds rills.

**Channel erosion:** Erosion occurring within the boundaries of streams, rivers, and their flood plains during normal and flood flow conditions. Includes scour of stream bottoms and banks. Wave action can also cause significant "channel like" erosion.

**Delivery ratio (DR):** Ratio of the amount of sediment which leaves a watershed to the gross amount of sediment that was originally eroded or detached from the soil mass in the watershed. Gross erosion or sediment detachment is usually estimated using the Universal Soil Loss Equation (USLE). Normally, DR < 1 because most detached sediment deposits before it reaches the watershed outlet. DR can be > 1 if there is significant channel erosion, because the USLE and other erosion or detachment prediction equations do not consider gully erosion.

**Particle size:** Sediment is usually classified according to its particle size. Particles may be classified as either primary particles or aggregates. The smaller particles (clay, silt, and organic matter) and their aggregates are the most significant environmentally as they are responsible for most sediment-bound pollutant transport.

**Sediment characteristics.**

Particle Effective Specific Specific Fall Time to

Size Diameter, Gravity, Surface Velocity, Fall 1 mm,

Class Area,

mm g/cm3 m2/g mm/s sec

Clay 0.002 2.60 20-800 0.003 330

Silt 0.010 2.65 4 0.080 13

Small aggregate 0.030 1.80 35 0.350 2.9

Sand 0.200 2.65 0.05 24 0.04

Large aggregate 0.500 1.60 15 40 0.03

Gravel 1.0 2.65 0 > 250

Organic matter 1000

**Cohesive sediment:** Clay, silt, organic matter and other fine particles which tend to bind together to form larger particles or aggregates. Responsible for most sediment-bound pollutant transport.

**Noncohesive sediment:** Individual soil particles (sand and gravel) which do not tend to bind together. Transports very few pollutants because of low specific surface area. Reduces storage capacity of reservoirs and stream channels.

**Suspended sediment (washload):** Portion of the sediment in transport in streams which is carried in suspension. Composed principally of fine sediment (smaller than fine sand, < 0.1 mm) from upland areas. Accounts for the bulk of sediment transport in streams. Carries almost all sediment-bound pollutants. Difficult to estimate - few good equations or models.

**Bedload:** Larger noncohesive sediment particles which move along the stream bottom by saltation, rolling, or mass creep. Carries relatively little sediment-bound pollutants. Heavily researched (easy to work with) and some good prediction equations exist.

**Enrichment ratio:** Refers to the ratio of the change in particle size distribution, specific surface area, or pollutant content of sediment in washload compared to the original composition of the soil mass before erosion. Enrichment is the result of the preferential transport of fine soil materials and the preferential deposition of larger soil particles. Ratios of 1.1 to 3.0 are typical but they vary dramatically.

**Detachment:** Dislodgement of soil particles from the soil mass due to the kinetic energy of raindrops or shear stress of flowing water. Usually described as a function of the kinetic energy of water and the cohesiveness or shear strength of the soil.

**Sediment transport:** Movement of dislodged soil particles from one point to another. Function of the kinetic energy of raindrops and overland flow, land surface characteristics (cover, roughness), and sediment characteristics (particle size, density, shape, fall velocity).

**Deposition:** Process by which sediment is lost (settles out) from flowing water. Occurs when flow no longer has sufficient kinetic energy to transport the sediment load. The deposition rate will be heavily influenced by the fall velocity of sediment particles.

**Methods for Estimating Sediment Yield:**

1. Monitoring - very time consuming, expensive, and difficult to collect good data. How do you take a representative sample?

2. Reservoir sedimentation surveys (time consuming, expensive)

3. Sediment delivery ratio methods - both gross erosion and sediment delivery are difficult to estimate, considerable uncertainty in estimates.

4. Bedload prediction equations/models - assume an infinite supply of noncohesive material is available for bedload transport. Transport a function of transport capacity and sediment characteristics. Some researchers have correlated bedload transport with washload in an effort (poor) to simulate gross sediment transport. Does not consider upland landuse.

5. Cesium-137 testing. Amount of Cesium-137 (from atmospheric testing of nuclear weapons in the 1950's and 1960's) in the soil or sediment is a function of the amount of soil loss or deposition in an area. Reduced concentrations indicate erosion while higher concentrations indicate deposition of increased amounts of Cesium.

6. Empirical erosion equation/models - USLE, Negev equation, and other regression equations. Estimate sediment detachment, not delivery. Suitable for general planning purposes.

7. Watershed and field-scale erosion models - ANSWERS, STORM, ARM, NPS, CREAMS, HSPF, AGNPS, WEPP. Usually based upon the USLE, Negev, or other empirical erosion equations. Useful because they estimate sediment delivery.

**Factors Affecting Erosion and Sedimentation in Upland Areas:**

• Hydrology: precipitation rates, surface runoff, temperature

• Topography: slope, slope-length, slope shape

• Soil erodibility: Function(texture, chemistry, organic matter content, history)

• Soil transportability: Function(particle size, density, and shape)

• Cover: plant canopy and surface residue

• Incorporated residue: reduces rill erosion

• Residual land use: previous sod of no-till

• Subsurface effects: root channels, infiltration

• Tillage: reduces organic matter and compaction, exposes soil

• Soil roughness: affects surface retention and detention and resistance to overland flow

• Tillage marks: can induce rilling and subsequent gully formation, can increase surface roughness and thus reduce runoff

**Factors Affecting Channel and Gully Erosion Processes:**

• Runoff and sediment inflow from upland areas

• Channel erodibility

• Tillage: destruction of ephemeral drainage ways by tillage

• Non-erodible subsurface layers

• Cover: armoring, grassed waterways

• Channel slope, width, and roughness

• Structures: dams, reservoirs, drop structures, non-erosive linings

• Channel alignment

• Sediment transportability: Function(particle size, density, and shape)

**UNIVERSAL SOIL LOSS EQUATION, USLE**

Developed by USDA-Agricultural Research Service and Purdue University to predict water erosion. Involved cooperative research at 49 locations and produced more than 10,000 plot years of runoff and soil loss data beginning in 1954. In 1960 rainfall simulators were used to expand the database and fill in data gaps. Principal developers were Wischmeier and Smith. The model is "empirical" and was developed from regression analysis of the plot data. The USLE is the most widely used method for predicting soil loss in the world. Developed for soils and conditions in the US, however, so expect errors if applied in tropical areas. USLE is seriously inaccurate under many circumstances and is technologically obsolete. Temporarily replacement by the Revised USLE in 1991 which was supposed to be replaced by the WEPP models in 1995.

"The USLE was designed to predict long-term average annual soil erosion for alternative combinations of crop systems and management practices in association with specified soil types, rainfall patterns, and topography. The USLE does not predict deposition or sediment yield from gully or channel erosion. The USLE is not recommended for prediction of specific soil loss events." (Wischmeier and Smith, 1978. Predicting rainfall and erosion losses: A guide to conservation planning. Agriculture Handbook No. 537, USDA, Washington, DC.)

*A = C1 R K L S C P*

where:

A = Average annual soil loss, Mg/ha

R = Rainfall and runoff erosivity index factor, Mg-m/ha-cm

K = Soil-erodibility factor, Mg/ha (per unit of the erosion index)

L = Slope length factor, dimensionless

S = Slope factor, dimensionless

C = Cropping-management factor, dimensionless

P = Conservation practice factor, dimensionless

C1 = 1.0, 1.292, 1.735, or 2.242 depending on the units of the K and R factors)

If the USLE is in English units:

A = t/ac; R = ft-t/ac-in; K = t/ac; C1 = 1.0

In metric units:

A = Mg/ha; R = Mg-m/ha-cm; K = Mg/ha; C1 = 1.0

Units conversions:

1 unit of R (or EI) in metric units = 1.735 \* R in English units

1 unit of K in metric units = 1.292 \* K in English units

The value of the units conversion term, C1, can be defined as:

R K A C1

English English English 1.000

English English Metric 2.242

English Metric Metric 1.735

Metric English Metric 1.292

Metric Metric Metric 1.0

**Rainfall Erosivity Index, R or EI:**

Considers the affects of the energy of rainfall and overland flow on rill and interrill erosion. Found to be highly correlated with the product of the storm kinetic energy and the maximum 30-min storm intensity.



where:

Rr = rainfall energy factor for a single storm, Mg/ha

Ei = kinetic energy of rainfall during the I the portion of a storm, Mg-m/ha-cm

*Ei = 210 + 89 log10(Ii) for Ii [ 7.72 cm/hr*

*Ei = 289 for Ii > 7.72 cm/hr*

Ii = rainfall intensity during the I th period of the storm, cm/hr

Di = rainfall during time interval I, cm

I30 = maximum 30-min rainfall intensity for storm, cm/hr

I = rainfall hyetograph time interval

n = number of rainfall hyetograph time intervals

To get the average annual R value, individual Rr values are summed (USLE only uses storms with more than 12.7 mm of rainfall in a 6-hour period, unless more than 6.35 mm of rain fell in 15 min.

EI varies throughout the year.

**Soil Erodibility Factor, K** (ranges from 0 to 1 for US soils):

Experimentally determined from direct soil loss measurements on research plots in continuous fallow for 2 or more years, with uniform 9% slopes, and slope lengths of 22 m. Under these conditions L, S, C, and P = 1 and K can be calculated as: *K=A/EI*, where A is the measured soil loss from the plots and EI is determined from rainfall records at the research plots. K =f(soil texture, chemistry, and organic matter content) but the relationships are not yet fully developed. K also given in Soil Survey reports.

**Length Factor, L** (m 0)

Used to account for slope lengths other than 22 m (72.6 ft).

*L=( /22)m*

where:

** = actual slope length, m

m = slope factor which varies with field slope as follows:

Slope,% m

<1 0.2

1 to 3 0.3

3 to 5 0.4

>5 0.5

**Slope Factor, S** (m 0)

*S = (0.43 + 0.3s + 0.43s2)/ 6.574*

where s is the field slope in percent.

**Cropping and Management Factor, C** (ranges from 0 to 1)

Most difficult parameter to estimate because it varies throughout the year with changing crop/cover conditions and precipitation patterns. Defined as the ratio of soil loss for crops to that for continuous fallow. Includes the effects of cover, crop sequence, productivity level, length of growing season, tillage practices, residue management, and expected time distribution of erosive rainstorms. Determined by weighting the C-factor for different portions of the year with the rainfall energy occurring during each portion of the year.

**Conservation Practice Factor, P** (ranges from 0 to 1)

Ratio of soil loss from a given conservation practice to that for up and down slope farming. Practices that affect P slow runoff water and thus reduce sediment transport capacity. In other words, the P factor attempts to account for deposition caused by detention of surface runoff. The P factor includes the effects of: contouring, strip cropping, terracing (adjust slope length also to account for terraces)

**Conservation practice factors (original).**

Conservation Practice Factors, P

Slope, Contouring Strip Terracing &

% factor cropping contouring

(Max. slope length) factor factor

1.1-2 0.6 (150) 0.30 -

2.1-7 0.5 (100) 0.25 0.10

7.1-12 0.6 (60) 0.30 0.12

12.1-18 0.8 (20) 0.40 0.16

18.1-24 0.9 (18) 0.45 -

*Terraces* control erosion in three ways:

1. Terraces break long slopes into shorter segments, therefore, must also adjust the L factor if terraces are present. Terrace spacing equals L.

2. Terraces impound water temporarily behind them, decreasing transport capacity and allowing excess sediment to deposit.

3. Outflow from individual terraces is via non-erosive grass waterways or subsurface drainage pipes therefore, land above terrace doesn't contribute to erosion of land below the terrace unless the terrace fails.

*Contouring* reduces erosion by reducing runoff by impounding water in depressions. Water tends to flow in tillage channels along the contour which effectively decreases the slope as seen by runoff. Primary use in US is for moisture conservation rather than erosion control (reduces runoff 40-80%). Contouring in areas with steep slopes and large intense storms can increase erosion due to over topping of contour furrows which may cause severe gullying. See handout on new state standards for contouring.

*Strip cropping*: Practice of growing alternate strips of different crops in the same field. For control of water erosion, strips are on the contour. In the U.S. strip cropping is prevalent where wind erosion is a problem (Montana, North Dakota, Nebraska, Wyoming) and for wind erosion control, strips are laid out perpendicular to the prevailing wind directions.

*Buffer Strip Cropping*: Alternate strips of grass or legumes between other crops (normally in rotation). Often plant buffer strips on steep unfarmable portions of fields.

***MAJOR WEAKNESSES OF THE USLE***

• Empirically based equation which uses variables that are to a degree indices of factors that affect soil erosion.

• Erosion processes are not explicitly represented as physical processes in the USLE. Poor representation of erosion, infiltration, slope, slope length, and especially contouring.

• USLE is a regression equation developed from a limited data base. When the equation is applied to new situations, new experimental data are usually required.

• Most of the USLE data are from cropland. Extension of the USLE to range land, forest land, and construction sites without an extensive data base has been highly controversial.

• Not designed for individual storm analysis. Does not predict particle size distributions required for water quality work.

• Problems with contour tillage accurately representing field slopes.

**Problems with individual USLE factors:**

• EI - Does not accurately reflect rainfall characteristics in all regions.

• K - The more we study it, the less we seem to know (Romkens).

• S - Too large on steep slopes. The relationship is more linear on steep slopes.

• C - Canopy and soil roughness effects are not represented well.

• P - For contouring should vary with ridge height and EI of 10 year storm.

**Sediment Delivery Ratio Estimation Equations:**

*Roehl's Equation*: Roehl measured sediment delivery to 15 reservoirs in the Piedmont of Georgia and North and South Carolina and estimated erosion with the USLE to develop the following sediment delivery ratio equation:

*log10DR = 3.59 - 0.23 log10W + 0.51 log10(R/L) - 2.79 log10BR*

where:

DR = delivery ratio, %

W = watershed area, km2

R/L = watershed relief

BR = bifurcation ratio, ratio of number of streams of a given order to the number in the next higher order.

This equation has been simplified by many users, even as simple as: *DR = 10 R/L* by the EPA and the VirGIS project.

*Colorado Construction Site Method*: *DR = D-0.22* , where D is the distance between the sediment source and the stream in feet.

*Modified USLE - MUSLE (1976)*: Replaced rainfall energy term in USLE, EI30, with a runoff energy term. Developed from 778 storms on watersheds in Texas and Nebraska. Watershed areas ranged from 2.7 to 4380 acres, 0.9 to 5.9% slopes, and slope lengths of 258 - 470 ft. Storm sediment yield can then be expressed as (English units):

*Y = 95 (Q qp)0.56 K L S C P*

where:

Y = single storm sediment yield, tons

Q = runoff volume, ac-ft (from SCS method)

qp = peak runoff rate, cfs (SCS triangular hydrograph

*K L S C P* = area weighted USLE factors

MUSCLE can be combined with the USLE to estimate the DR as follows:

where W is the watershed area, acres. MUSLE is best for homogeneous watersheds in Texas and Nebraska.

**REVISED UNIVERSAL SOIL LOSS EQUATION (RUSLE)**

"RUSLE is a computerized update of the USLE. It also includes the analysis of research data not available at the time the USLE handbook was published in 1978. The basic USLE equation is retained, but the technology for evaluating the factor values has been altered and new data introduced to evaluate the terms for specific conditions.

RUSLE retains the six factors of the USLE and calculates average annual soil loss from a hillslope. The methodology is computerized to facilitate the calculations. Soil loss calculations can be made for conditions the USLE could not handle if information is available to create the three data files required by RUSLE:

1. **CITY**: contains monthly precipitation and temperature, frost free period, annual R, and 15-day distributions of EI

2. **CROP**: contains below-ground biomass, canopy cover, crop height at 15-day intervals, residue to yield conversion factors, carbon/nitrogen ratios of residues, stem characteristics

3. **FIELD OPERATION**: contains data reflecting soil and cover disturbances associated with typical farming operations (surface roughness, residue levels, etc.)

Residue decomposition is considered to be a function of the climatic data, field operation and crop files and is one of the most sensitive factors controlling the soil loss ratios for 15-day calculations. In the aggregate, these values multiplied times the 15-day EI values, produce the average annual cover-management factor (C).

Major changes between RUSLE and the USLE include:

1. Rainfall-runoff erosivity factor (R): database has been expanded in the western US and a correction developed for rain falling on ponded water conditions.

2. Soil erodibility factor (K): changed to reflect variability within the year due to freeze-thaw conditions and consolidation due to moisture extraction by growing crops; an alternative regression was developed for tropical volcanic soils; and a correction was developed for rock fragments in the soil profile.

3. Slope length (L) and steepness factors (S): revised to reflect the ratio of interrill/rill erosion

4. Cover-management factor (C): now calculated as the product of terms reflecting prior land use, surface cover, crop canopy, surface roughness, and in the Pacific Northwest small grain farming areas, soil moisture. C-factor is now a continuous function of the product of four subfactors: prior land use (PLU), surface cover (SC), crop canopy (CC), and surface roughness (SR). These subfactors include the effects of root mass in the upper 10 cm of the soil mass, changes in crop cover and root mass with time, tillage, and residue decomposition.

5. Supporting practice factor (P): changed to consider conditions for contouring, strip cropping, terracing, and subsurface drainage as well as for addressing conditions for rangeland and pastures.

Climatic data used by RUSLE include: monthly precipitation and temperature, the frost free period, and 15-day distributions for the EI (product of kinetic energy and maximum 30-min precipitation intensity)."