

Overland Erosion: From Rainfall Impact to Watershed Sediment Yield

Executive Summary

Overland erosion represents the critical bridge between hydrology and sediment transport, completing the systemic cycle of rainfall, runoff, and eventual deposition. This document synthesizes the physical mechanics, empirical modeling frameworks, and watershed-scale dynamics of soil loss.

The central conceptual framework for modern erosion science is the **Detachment–Transport model**, where erosion is governed by the lesser of two processes: rainfall-driven detachment (D_c) or flow-driven transport capacity (T_c). On a practical level, the **Universal Soil Loss Equation (USLE)** remains the empirical baseline for estimating annual soil loss, though modern process-based models such as **WEPP** allow for more detailed, event-based simulations.

Key Takeaways

- **Scale Dependency**
Erosion processes evolve across scales—from splash and sheet flow at the plot scale, to rill and gully formation at the hillslope scale, and ultimately to watershed-scale routing and deposition.
 - **Sediment Delivery Ratio (SDR)**
Not all eroded soil reaches a downstream outlet. The SDR typically decreases with increasing watershed area due to intervening deposition.
 - **Climate Sensitivity**
Climate change acts as a force multiplier for erosion, increasing both rainfall erosivity (detachment) and runoff-induced shear stress (transport).
-

1. Physical Processes and Typology

Overland erosion occurs through a sequence of physical interactions, beginning with raindrop impact and ending with sediment deposition.

1.1 The Erosion Sequence

Rainfall → Infiltration → Runoff → Erosion → Transport → Deposition

1.2 Classification of Erosion Types

Erosion can be categorized based on the mechanism of soil disturbance and the geometry of the resulting flow:

Splash Erosion

- **Description:** Detachment of soil grains from the soil structure
- **Mechanism:** Occurs when:

$$\text{Kinetic Energy} > \text{cohesion} + \text{adhesion}$$

- Highly dependent on rainfall intensity and soil type
-

Sheet Erosion

- **Description:** Selective removal of fine soil grains by shallow overland flow
 - **Mechanism:**
 - Transports detached particles
 - Coarser particles remain, forming an **armor layer**
-

Rill Erosion

- **Description:** Formation of small, well-defined channels
 - **Mechanism:**
 - Caused by concentrated runoff
 - Intermediate stage between sheet and gully erosion
 - Can be corrected by normal tillage
-

Gully Erosion

- **Description:** Deep, steep-sided channels causing severe land degradation

- **Mechanism:**
 - Occurs when rills deepen beyond ~300 mm
 - Triggered by heavy rainfall on poorly covered soil
 - Prevention requires >70% ground cover and reduced flow velocity
-

2. The Detachment–Transport Framework

The modern conceptual framework defines erosion as:

$$E = \min (D_c, T_c)$$

2.1 Process Definitions

- **Detachment (D_c)**
Rainfall-driven process where kinetic energy breaks soil bonds
- **Transport Capacity (T_c)**
Flow-driven process governed by shear stress:

$$\tau = \rho ghS$$

2.2 Limitation Dynamics

- **Transport-limited (capacity-limited)**
Available sediment exceeds flow transport capability
 - **Detachment-limited (supply-limited)**
Soil resistance or availability limits erosion despite sufficient flow
-

2.3 Mathematical Relations

- **Raindrop Terminal Velocity**

$$V_t = 20d^{0.35} \text{ (d in ft)}$$

- **Rainfall Kinetic Energy**

$$KE = 916 + 331 \log i \text{ (i in in/hr)}$$

- **Ellison (1945) Relation**

$$G = b_0 V_t^{4.33} d_r^{1.07} i^{0.65}$$

where:

- G = weight of detached soil
- d_r = raindrop diameter
- i = rainfall intensity

Primarily valid for bare soil conditions

3. Empirical Modeling: The Universal Soil Loss Equation (USLE)

The USLE is the standard empirical model for estimating annual soil loss, primarily applicable to sheet and rill erosion on agricultural lands.

3.1 USLE Formula

$$E = R \times K \times LS \times C \times P$$

3.2 Factor Definitions

- **R — Rainfall Erosivity**
Represents rainfall intensity and frequency
- **K — Soil Erodibility**
Higher values indicate greater susceptibility to erosion
(e.g., Dunkirk silt loam ≈ 0.69 vs. Albia gravelly loam ≈ 0.03)
- **LS — Topographic Factor**
Combines slope length (λ) and slope steepness (θ)

- **C— Cropping-Management Factor**
Depends on vegetation cover, crop stage, and residue (e.g., matured grass: $C \approx 0.004$)
 - **P— Conservation Practice Factor**
Accounts for contouring, terracing, strip cropping, etc.
-

3.3 Limitations of USLE

- Empirical and plot-scale
 - Does not account for deposition
 - Based on annual averages (no event dynamics)
 - Does not model sediment routing within watersheds
-

4. Modern and Process-Based Models

To address USLE limitations, more advanced models have been developed:

RUSLE / RUSLE2

- Updated empirical formulations
 - Applicable to a wider range of land uses (e.g., construction sites, rangelands, disturbed lands)
-

WEPP (Water Erosion Prediction Project)

A process-based, continuous simulation model that represents:

Rainfall → Infiltration → Runoff → Shear → Detachment → Transport → Deposition

Key Features

- Sub-models for:
 - soil
 - climate (CLIGEN)

- management
 - hydrology
 - plant growth
 - residue decomposition
 - Simulates:
 - hillslope erosion
 - sediment delivery to slope outlet
-

5. Watershed Sediment Yield and Delivery

Sediment yield represents the portion of eroded material that reaches a downstream control point.

5.1 Key Definitions

- **Gross Erosion**
Total soil eroded from watershed surfaces
- **Sediment Yield (Y)**
Sediment mass reaching the watershed outlet
- **Sediment Delivery Ratio (SDR)**

$$SDR = \frac{Y}{\text{Gross Erosion}}$$

5.2 Scaling Effects

$$SDR \propto A^{-n}$$

- **Small watersheds:** high SDR
 - **Large watersheds:** low SDR due to deposition in channels and floodplains
-

5.3 Estimation Methods

1. **Rating Curve Method**

$$Y = \int Q_s(Q) f(Q) dQ$$

2. Reservoir Method

$$Y = \frac{A_t/t}{E_f}$$

3. USLE + SDR Method

$$Y = E \cdot SDR$$

6. Urban and Construction Site Erosion

Construction sites typically exhibit high erosion rates due to disturbed soil conditions.

6.1 Practice Factors (P) in Urban Context

- **High erosion ($P \approx 1.30$):**
 - smooth, compacted soil (bulldozed)
 - **Lower erosion ($P \approx 0.80$):**
 - rough, loose soil (>12 in depth)
 - **Structural controls:**
 - sediment basins: $P = 0.30-0.50$
 - advanced basins with flocculants: $P \approx 0.10$
-

6.2 Buildup and Washoff (SWMM Framework)

- **Buildup:** accumulation of pollutants during dry periods
- **Washoff:** rapid removal during rainfall events

$$\text{Washoff} \propto q^m \cdot B$$

where:

- q = runoff rate
- B = buildup

👉 Unlike USLE, this is **event-based modeling**

7. Climate Change Implications

Climate change amplifies erosion by affecting both detachment and transport processes:

$$\text{Climate Change} \Rightarrow R \uparrow, \tau \Rightarrow E \uparrow$$

Key Effects

- **Increased rainfall intensity**
 - $R \uparrow, D_c \uparrow$
 - **Increased runoff magnitude**
 - $h \uparrow, \tau \uparrow, T_c \uparrow$
 - **Soil and vegetation changes**
 - saturation \rightarrow more runoff
 - drought \rightarrow weaker soil structure
 - vegetation loss $\rightarrow C \uparrow$
-

Engineering Implications

- Increased sediment loads to:
 - reservoirs
 - stormwater systems
- Reduced storage capacity
- Need for:
 - updated design storms
 - enhanced erosion control practices