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WATER EROSION

Soil erosion by water is the detachment and transport of soil particles by rainfall or runoff. Several mechanisms contribute to both processes.

Detachment

Detachment can occur through the rapid wetting or by the forces exhibited by raindrops and runoff. The rapid, mainly one-sided wetting causes air entrapment within and differential swelling of the aggregates. The pressure of the entrapped air or the shear forces resulting from anisotropic swelling produce (micro-) fissures weakening the aggregates. Especially a fast procession of the wetting front increases the extent of these processes. Hydrophobicity caused by organic substances may, therefore, stabilize the aggregates. The disintegration of the aggregate along these fissures leads to micro-aggregates that range in size, mainly from 0.2 to 1 mm. This process is called slaking. The micro-aggregates can be divided further into smaller particles down to primary particles by dispersion. The low electrolyte content of the rain water compared to the electrolyte content of the soil solution increases hydration of ions in the diffuse double layer after wetting and disperses primary particles. This is especially pronounced in soils containing monovalent cations that do not form bridging bonds and that have a large hydration energy. In arid and semi-arid regions dispersion increases mainly because of sodium, whereas in areas of intensive agriculture the heavy use of fertilizer potassium can have a similar effect.

The aggregates weakened by slaking and dispersion are further disintegrated by the forces of the raindrops. For short moments of about 50 μs, high pressures up to 10^6 Pa occur when the raindrop hits a rigid soil surface (Ghadiri and Payne, 1981). On a deformable soil surface the pressure is still in the order of 10^5 Pa with its maximum about 2 mm from the center of impact for a 5.6 mm drop (Nearing et al., 1987). The water of the raindrop cannot infiltrate the soil at the same velocity with which it is supplied to the soil surface. It must disperse radially along the soil surface. The velocity of the radially flowing water can be twice as high as the falling velocity of the drop. For a 4 mm drop, terminal falling velocity would be 9 ms^{-1}. The high flow velocity in a very short distance to the soil surfaces causes a high shear rate in the order of 10^5 s^{-1}. Except for cemented soil, the soil shear strength is often smaller than the resulting shear stress of the drops. Thus, the raindrops produce smaller, more easily transported particles and a puddled, sealed surface that reduces infiltration and increases runoff.

The runoff also produces shear stresses that can further loosen soil particles. Its stresses are lower than those of the drops (range of Pa) but as those stresses act on larger areas, they may loosen larger particles. In addition, they act over longer times. They therefore can loosen soil, which exhibits a Bingham fluid behavior that is common in soils. For short moments or in some places, eddies or turbulent burst stochastically can produce even higher stresses that override soil shear strength (Nearing, 1991).

Concentrated runoff loosens soil particles by additional mechanisms. Under supercritical flow conditions (Froude number >1), a hydraulic jump occurs that releases much of the energy of the runoff at the spot where it occurs. The concentrated release of energy detaches soil and produces a small headcut. The changing flow pattern at the headcut causes the hydraulic jump always to occur at this position. Thus the headcut increases in size and slowly advances upslope. Additional material is detached by scour hole formation, rill side sloughing and undercutting of the sidewalls in rills.

Transport

Detached material can be transported by the drop impact through splashing or by flowing water. Although splashing occurs randomly, a net transport downhill results because of the longer splashing distances downslope than upslope. The amount of transport and the direction of splash transport can be strongly influenced by wind (Erpul et al., 2002). Splashing decreases with increasing depth of the water layer on the soil surface. Detachment and transport also depends on the water layer thickness. The highest rates occur with very shallow water depths of about 1/10–3/10 of a drop diameter (Mutchler and Larson, 1971). Splash becomes small when the water layer thickness is more than 2–3 drop diameters.

Where the water concentrates to linear flows, the main transport is achieved by the runoff. The forces of the flowing water can be strong enough to carry even stones, whereas splash only transports particles up to 1–2 mm in size. The effectiveness of the runoff increases with flow velocity and therefore, with increasing flow thickness and slope steepness and with decreasing roughness.

At the transition between splash and flow transport, where water depth is already too thick for high splash rates but still too shallow for high flow velocities, a type of transport occurs that is called raindrop induced flow transport, RIFT (Kinnell, 1990). Soil particles that are too heavy to be transported by the runoff are entrained and kept in motion by raindrop forces. The random raindrop forces are superimposed on the weak flow forces downslope. A high net transport downslope results. This type of transport dominates on short slopes and on the interrill areas that deliver soil into the rills.

Types of erosion

Slaking, dispersion and raindrops act evenly on an unprotected soil surface. Soil is detached and transported, more or less evenly, where these mechanisms prevail. The resulting type of erosion is called *sheet erosion*. The forces of the runoff tend to occur locally and lead to an incision into the soil surface and to linear types of erosion. Where many linear elements develop, they are shallow (about 10 cm) because the runoff is dispersed. This type of erosion is called *rill erosion*. The distance from the interrill area to the rill is small. In models, often a distance between rills of 1 m is assumed. Sheet erosion on the interrill areas still contributes a significant amount to the total soil loss. Sheet and rill erosion are governed by similar principles and transitions between both forms are common. Therefore, both types are often addressed together.

The detachment by flowing water gains importance with increasing concentration of the overland flow. This increases the depth of the linear erosion elements. As long as the linear element is not deeper than the plowing depth, it can be filled in by cultivation. This type of erosion is called *ephemeral gully erosion*. It mainly occurs along slope concavities where tillage accumulated rich but loose topsoil material and where surface and subsurface runoff concentrate. Exfiltrating subsurface runoff or shallow ground water (seepage) initiates or fosters this process because the soil at the surface looses the stabilizing water menisci, which depend on air-filled pores (Römkens et al., 2002).

With permanent *gully erosion*, the linear element cannot be removed by cultivation. Raindrop impact is unimportant for soil detachment. The main effect of the raindrop impact is to seal the soil surface of the contributing watershed and thus increase surface runoff that concentrates in the gully.

The fourth type of erosion is *tunnel erosion* (pipeflow), where raindrops have lost all their importance. Tunnel erosion mainly occurs where a stable soil surface covers unstable subsoil. The stability of surface soil could come from an extensive root network or a cementation, by lime or Fe oxides for instance. The low stability of the subsoil, with a high potential for slaking and dispersion, could be caused by less organic matter, less structure formation or high exchangeable Na. However, also an impermeable layer underneath the subsoil like hard rock or permafrost is conducive to piping (Carey and Woo, 2002). Under those circumstances, infiltrating rainwater may flow laterally underneath the soil surface and remove the unstable subsoil. Pipes of several meters in diameter can develop (Zhu et al., 2002).

Erosion factors

The amount of soil loss is determined by rain characteristics, soil cover and their interactions, as well as by drainage area per unit width, slope steepness and soil properties. The ability of a rainstorm to create runoff increases with rain intensity. Also, its ability to detach increases because of growing raindrop size. Rain erosivity, therefore, increases with about the power of two of intensity.

The soil is protected from the action of the raindrop where it is covered. A mulch or low growing vegetation cover is especially effective by additionally retarding runoff and creating small water pools, which dissipate raindrop energy. Soil loss decreases exponentially with increasing coverage and a reasonable protection is achieved often with a 30 to 50% mulch cover (Figure W5). The protective action of the cover decreases with increasing height because the drops dripping off the leaves gain more kinetic energy. Tall crops like hops or maize are less protective than small grain or sugar beet. The coverage decreases for a given leaf area with increasing distance between the plants. Therefore, crops in wide rows and with low seeding density are less protective than crops with a narrow, random seeding distance.

Under most climates, rain erosivity varies seasonally. Crops and cultivation methods that provide an insufficient cover during high erosivity periods increase erosion, whereas only minor erosion occurs on uncovered surfaces (seedbed) in periods of low erosivity. Especially crops with slow initial growth that are planted in wide rows late in the growing season like cotton, maize or soy-bean, are prone to erosion. Minimum, reduced or mulch tillage are techniques to provide sufficient mulch cover also when the crop is young.

In climates with ground frost during the dormant season snow-melt erosion can occur. The precipitation accumulated within the snow cover over a long period of time may be released within a few days causing long-lasting and strong runoff on the soil surface. Snow-melt erosion may even occur where only little snow cover has been accumulated given that deep-reaching ground frost restricts infiltration or that the soil surface has been destabilized by freezing processes.

The erosive power of the runoff increases with slope steepness and size of the contributing area per unit width at the lower end of the eroding area. While slope steepness cannot be changed usually, many conservation measures like contouring, terracing, drainage ditches or strip cropping can decrease the amount and velocity of the runoff.

Soils high in silt and very fine sand are especially prone to water erosion because of their low structural stability, the low density of the aggregates and the good transportability of silt-sized particles. With increasing content of clay and organic matter, the aggregate stability increases and detachment decreases. Except for soils with very high contents of clay (>40%) or organic matter (>6%), the erodibility of the soil decreases with increasing clay and organic matter content. A stone cover also lowers detachment. This makes stony soils often less erodible, but cases are also reported where stones had no effect or even accelerated erosion because of restricted infiltration (Poesen et al., 1994). Transportability decreases with increasing effective particle size. Especially for sheet erosion, the erodibility decreases with an increasing medium to coarse sand and gravel content.

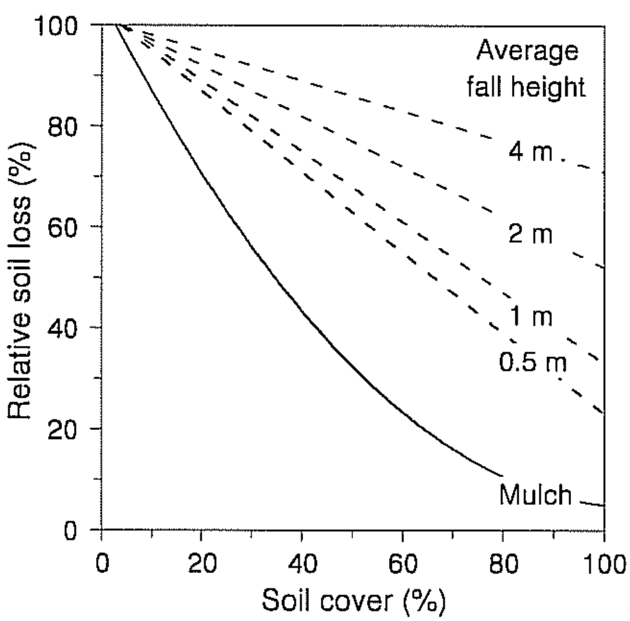

Figure W5 Influence of mulch cover and plant cover of various height on soil loss as it is considered in the models USLE/RUSLE, EPIC and WEPP.

Erosion rates

The natural erosion, sometimes called geologic erosion, depends mainly on the climate and slope steepness. Maximum rates occur in semi-arid to arid areas with sparse, natural vegetation cover and rare, but sometimes severe, rainstorms or in mountain areas with steep slopes. Except for these two conditions, erosion is mainly caused human activities, cultivation for example, which creates bare soil. This accelerated erosion is recognized as the greatest threat to the soil resource. Globally 1 094 million ha are affected by water erosion (Lal, 2003).

The reported erosions rates on arable land vary to a large extent, depending on the combination of influencing factors and on the time and spatial scale. For single events, soil losses up to several hundreds of t ha^{-1} have been measured. On a long-term average soil losses of up to 200 t ha^{-1} yr^{-1} for single fields have been quantified in temperate areas by using tracers (Schwertmann and Schmidt, 1980). The highest long-term average erosion rates are likely to occur in Southeast Asia. Annual losses of up to 1 000 t ha^{-1} are reported for Thailand and up to 1 500 t ha^{-1} for Java (Dregne, 1992). High erosion rates in tropical areas are especially reported for Parana and other regions of central Brazil, for alfisols in West Africa and Vertisols in central India and eastern Africa (Lal, 1990). In temperate countries, like the USA and Germany, long-term erosion rates of sheet and rill erosion were averaged to be about 10 t ha^{-1} yr^{-1} under the present soil management systems (Auerswald, 1991) but can be lowered to 1 t ha^{-1} yr^{-1} or less with conservation management systems.

The loss of soil material from a watershed is smaller than the total losses from the individual fields within the watershed. A significant proportion settles on the footslopes and in the riparian areas. With increasing watershed size, the sediment delivery ratio (= proportion of soil loss reaching the water course) decreases. For a 10 km^2 watershed, the expected sediment delivery is about 20%, whereas it decreases to almost 10% at the outlet of a 100 km^2 watershed.

Damages

Damages are manifold (Pimentel et al., 1995). Water erosion can decrease crop yields by the unproductive loss of rain through runoff, by nutrient loss and imbalances because of the nutrient dislocation, by pesticide concentrations that are too low at the eroding site and too high where runoff and sediment accumulates. It causes difficulties in crop management because of an uneven crop development and because of rills and gullies. Besides these short-term damages, soil erosion leads to long-term damages. These are more critical, because they increase slowly and are often undetectable for the farmer but accumulate with time and are almost irreversible due to the much slower soil formation rate. Those damages are caused by a decrease in soil depth and a loss of nutrient and water holding capacity. They are especially severe where a fertile but shallow soil material like loess covers a poor material like gravel, hard rock or an acid subsoil. Although any soil loss of more than 1 t ha^{-1} yr^{-1} can be considered to cause irreversible damages within the time span of 50–100 years, it is commonly accepted that agricultural soil can "tolerate" a certain amount of erosion, which typically ranges from 1 t ha^{-1} yr^{-1} on shallow sandy soils to 5 t ha^{-1} yr^{-1} on deeper soils (OECD, 2001).

Besides the on-site damages on the eroding areas, off-site damages occur where the runoff and sediment accumulates. Examples are the flooding of roads and houses, the undercutting of roads, the siltation of water reservoirs, and the input of nutrients, pesticides, heavy metals and other pollutants into streams. Those damages can be followed by many others like a decreased recreational value of water bodies or increased fish mortality. Off-site effects are especially harmful to society today whereas the loss of productivity mainly affects future generations. Today, transfer of nutrients especially phosphate to surface water bodies including marine systems is a main concern in many countries with intensive agriculture where (eroding) topsoils have been enriched by heavy fertilizer input in the past (OECD, 2001).

In some cases, soil erosion also may have beneficial effects. It can remove a depleted or very acid topsoil and uncover a more fertile subsoil. In alfisols, the loss of parts of the poorly structured eluvial horizon leads to an incorporation of the clay-enriched Bt horizon into the plow layer. This increases structural stability and nutrient holding capacity of the top layer. The input of eroded soil into streams acts as an adsorptive sink and may lower the concentration of dissolved nutrients or pollutants where heavy input from point sources exists.

Erosion control

Figure W6 provides a conceptual overview of the different types and targets of erosion control. The most important measure to lower soil loss is to provide more soil cover in time and space. This can efficiently be achieved by zero, reduced or mulch tillage. Ley-based arable systems especially increase soil stability, which can additionally be used to lower soil loss in periods of insufficient soil cover. Further methods decrease the size of the contribution watershed, e.g., diverting fields or creating terraces, or decrease flow velocity (rough surface; contour tillage). Grassed waterways, retention ponds with controlled outlets and filter strips reduce damages downslope and the input into downslope terrestrial or aquatic ecosystems.

Models

The extent of soil erosion is highly variable in space and time. Commonly, 50% of the total soil loss is caused by less than 1% of the erosive rains and less than 0.1% of all rains. This extreme variability complicates the quantification of damages and the planning of protection measures. Therefore, a large variety of prediction models has been developed. One of the oldest, best known and most widely used is the Universal Soil Loss Equation, USLE, (Wischmeier and Smith, 1978). Due to its universality and calibration to many regions it is recommended by the OECD (2001) to indicate erosion. The USLE computes the long-term annual soil loss A from eroding sites:

$$A = RKLSCP$$

Only six site-specific factors are necessary, the average annual rainfall and runoff erosivity R, the soil erodibility K,

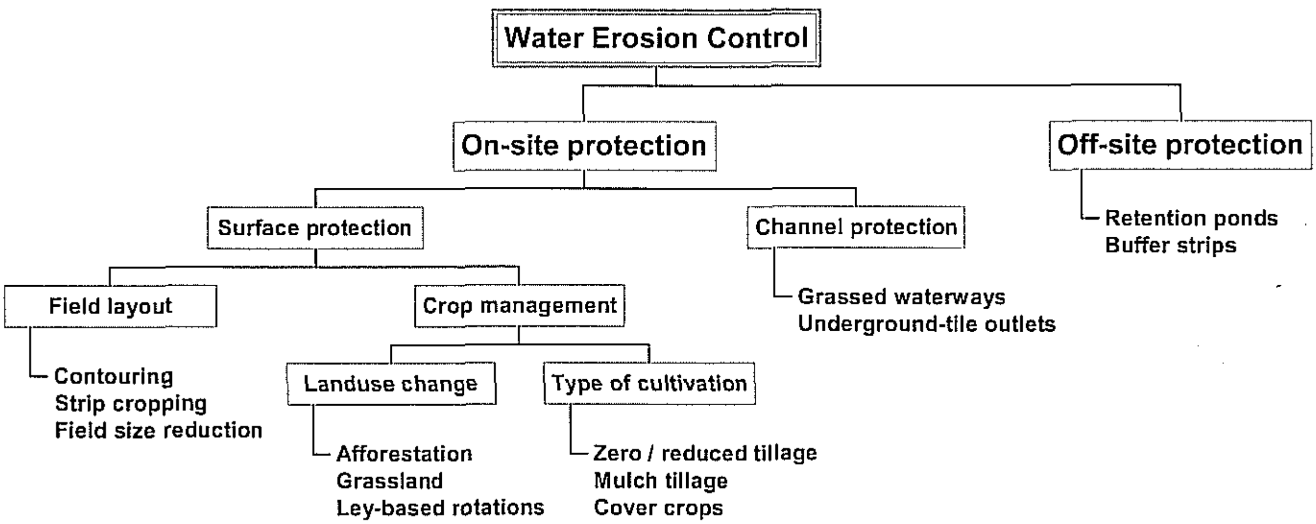

Figure W6 Conceptual framework of water erosion control.

Table W1 Main areas of application for five most common erosion models (special adaptations were not considered; *brackets* show a restricted applicability; frequency of use gives percentage in water erosion modeling in scientific articles between 2000 and 2003 among 15 common models)

Model Frequency of use	USLE/RUSLE 51%	WEPP 16%	EPIC 13%	AGNPS 5%	EUROSEM 4%
Time scale					
Minute					x
Single event	(x)	x		x	x
Annual		x	(x)		
Long-term	x	x	x		
Spatial scale					
Field	x	x	x		x
Watershed	(x)	x		x	x
Soil use					
Agriculture	x	x	x	x	x
Rangeland	x	x		x	
Forests	x	x		x	
Construction sites	x	x		x	
Erosion control structures	x	x		x	
Types of erosion					
Gully erosion					
Ephemerial gullies		x	x	x	x
Sheet and rill	x	x	x	x	x
Snowmelt	(x)	x			x
Irrigation		x			
Wind erosion			x		
Sedimentation			x		x
Nutrient loss			x	x	
Pesticide loss					
Water movement (runoff, infiltration, percolation)		x	x	x	x
Weather generator		x	x		
Plant growth		(x)	x		
Economic evaluation			x		

Documentation:
USLE, Universal Soil Loss Equation: Wischmeier and Smith (1978).
RUSLE, Revised Universal Soil Loss Equation: Renard et al. (1997).
WEPP, Water Erosion Prediction Project: Flanagan et al. (1991).
EPIC, Erosion Productivity Impact Calculator: Sharpley and Williams (1990).
AGNPS, AGricultural Non-Point-Source pollution model: Young et al. (1995).
EUROSEM, EUROpean Soil Erosion Model: Morgan et al. (1998).

and factors that take into consideration slope length (L), slope steepness (S), crops and cover (C), and protective measures (P). The necessary factor values have been worked out for many situations and areas in the world. The USLE or parts of it are also included in many more recent models like AGNPS (Young et al., 1995) or WEPP (Flanagan et al., 1991). The estimation of all factors was improved and updated in the Revised Universal Soil Loss Equation RUSLE (Renard et al., 1997).

The variety of processes connected to erosion occur over a wide temporal scale from microseconds to centuries and on a wide spatial scale from aggregates to river basins and the global system. Hence a variety of erosion model exist, which differ in the processes that are included (sheet/gully erosion, rainfall/snowmelt erosion), in time scale (minutes to centuries), spatial scale (field/watershed) and modeling technology (lumped/mechanistic). Table W1 summarizes some common models. Especially the older models like the USLE have been modified or extended for the application in cases that were not intended originally. These extensions were not included in Table W1 because the modifications are often valid only under very special conditions. Every model has weaknesses and strengths. The selection of an appropriate model for a specific task is therefore essential to obtain reliable results. New technologies like digital elevation models, geographic information systems or remote sensing now allow to substantiate the models increasingly better.

K. Auerswald

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A C.I.P. Catalogue record for this book is available from the Library of Congress.

ISBN: 978-1-4020-3994-2 Springer Dordrecht, Berlin, Heidelberg, New York
This publication is available also as:
Electronic publication under ISBN 978-1-4020-3995-9 and
Print and electronic bundle under ISBN 978-1-4020-5127-2

Published by Springer
PO Box 17, 3300 AA Dordrecht, The Netherlands

Printed on acid-free paper

Cover photo: Mount Olga (Katatjula), 25 km west of Ayers Rock (reproduced courtesy of Getty Images, image 55862814, photographer: DAJ).

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