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College of Soil Physics

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Factors affecting the water erosion process.

Donald Gabriels

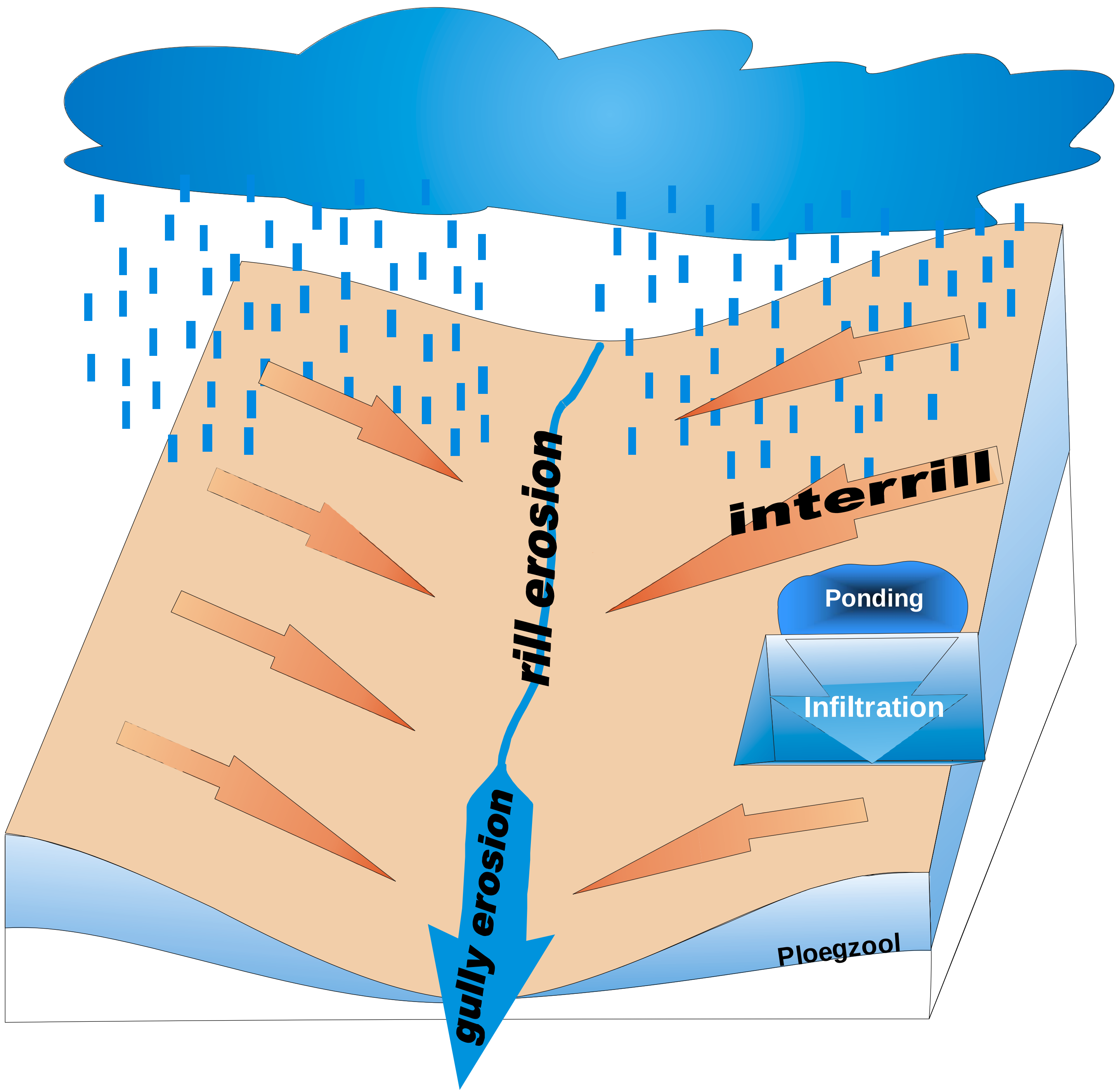
Dept. Soil Management
Ghent University
Belgium

COLLEGE ON SOIL PHYSICS

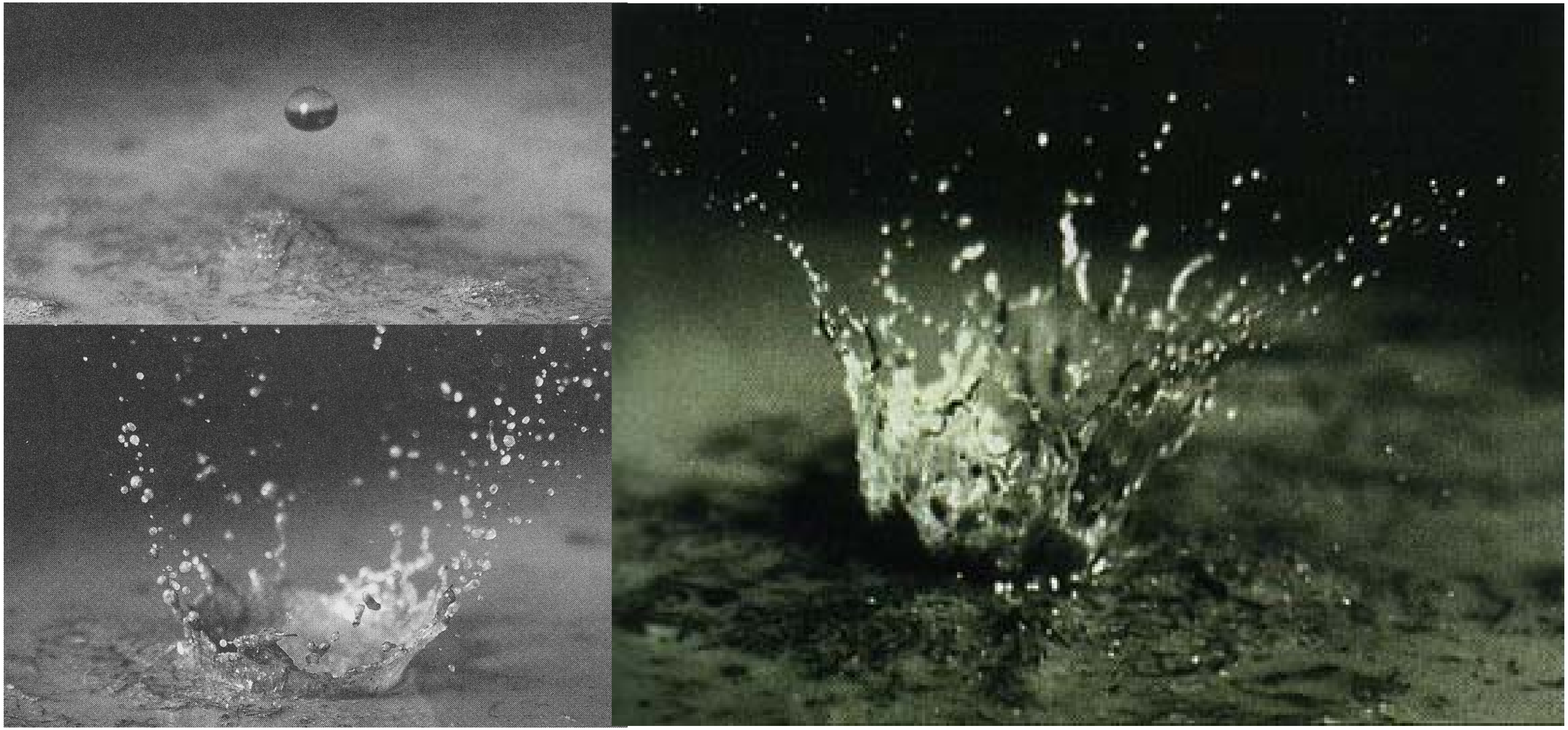
WATER EROSION: FACTORS

Donald Gabriels
Research group
Soil erosion and Soil conservation
Ghent University, Belgium

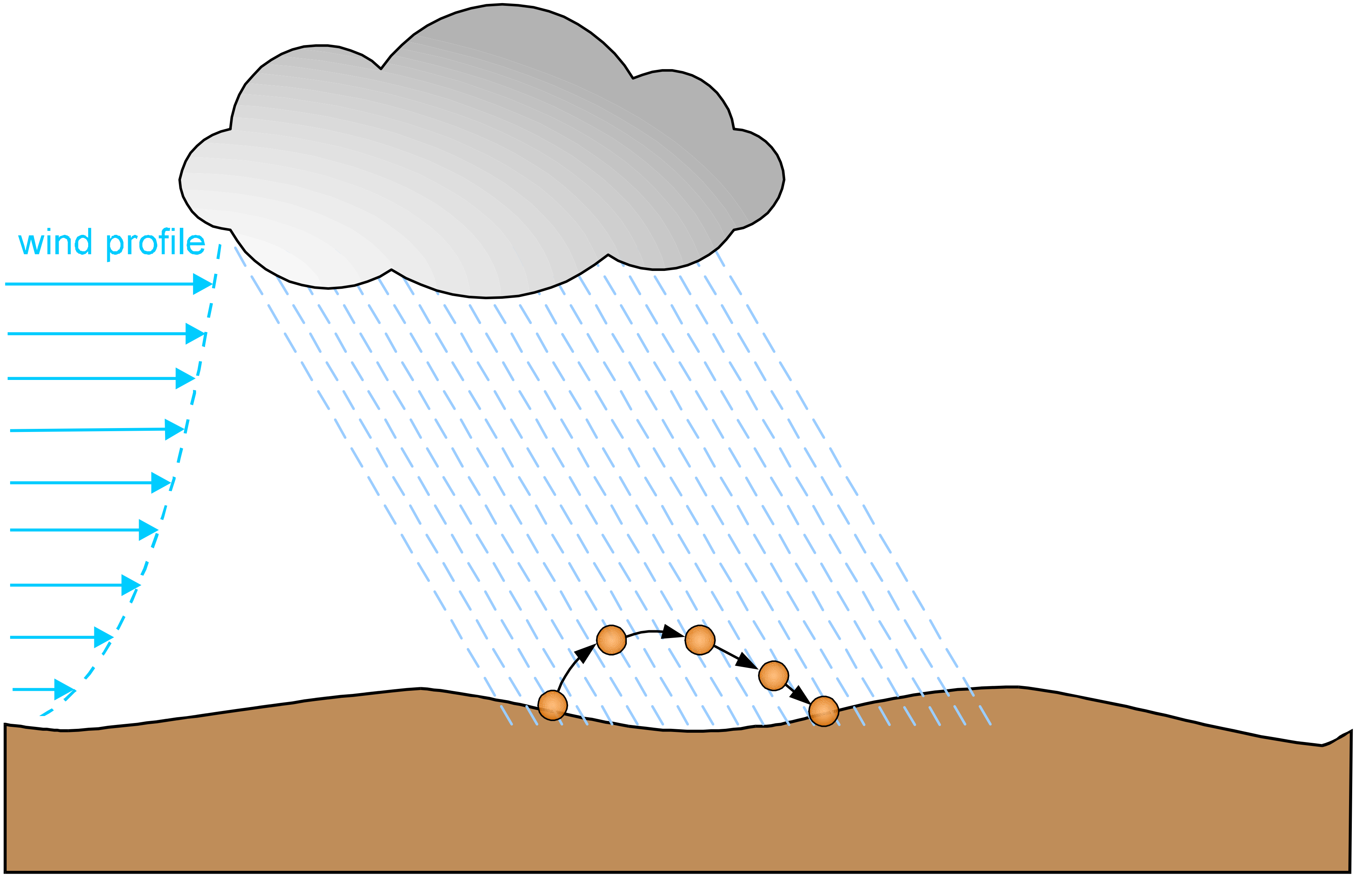
UNIVERSITEIT GENT


rill erosion
interrill
Ponding
Infiltration
gully erosion
Ploegzool

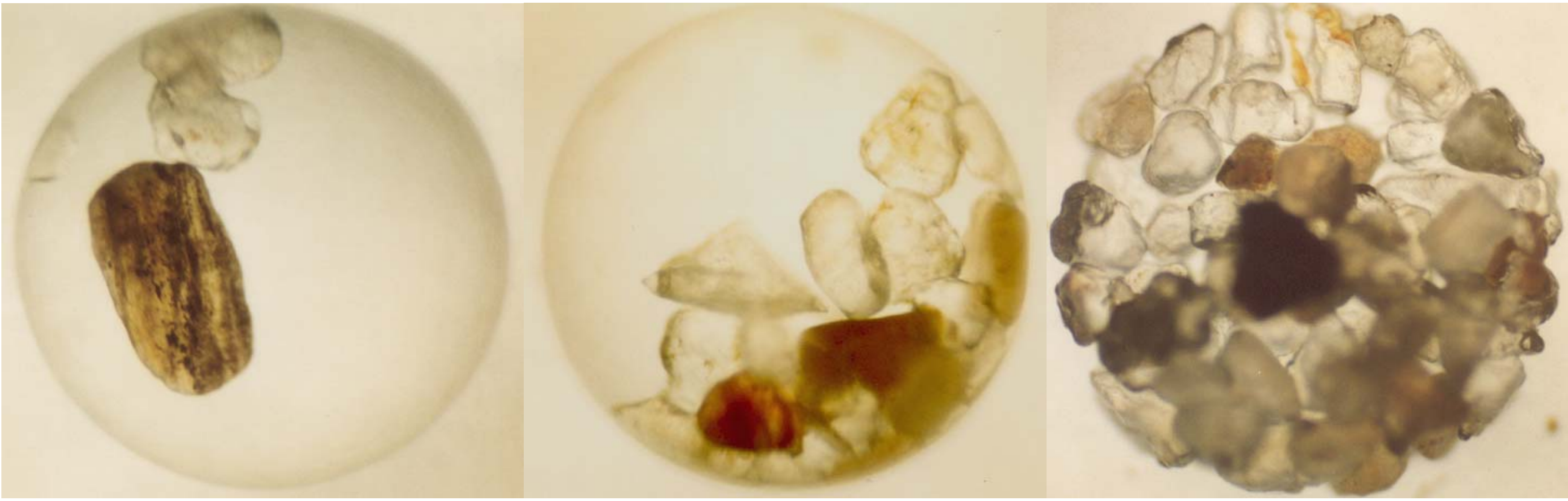
Sheet erosion (splash erosion and overland flow)



Transport due to wind-driven rain



Transport due to wind-driven rain



u_* *and* KE_z or M_z

Sheet erosion

Interrill erosion

Rill erosion

Gully erosion

Natural factors influencing soil erosion (by water)

- rainfall erosivity
  - intensity
- soil erodibility
  - particle size (silt and fine sand)
  - clay content
  - organic matter content
  - (embedded) stones
- topography
  - slope steepness
- vegetation
  - surface cover
  - canopy cover
  - roots

clay content, organic matter content → **aggregate stability**

surface cover, canopy cover → **reduce rainfall erosivity**

roots → **reduce soil erodibility**

→ **Erosion by water is a natural process ...**

…but can be influenced by human practices

Human factors

- harvest of vegetation
  - loss of soil cover
- soil tillage
  - decrease in organic matter and biological activity
  - compaction of subsurface layers
- surface sealing (e.g. roads, pavement)
  - increase of overland flow

Erosion > soil loss tolerance

Soil loss tolerance value:

depends on the on and off site effects of soil erosion

- *on site*: depth of fertile soil layer
  → values proposed by the Soil Conservation Service (Logan, 1982)

soil depth (cm)	soil loss tolerance (t/ha yr)
< 25 till solid rock	2.2
< 25 till sand	4.5
25 to 50 till solid rock	4.5
25 to 50 till sand	6.7

- *off site*:
  - water quality (e.g. eutrophication risk)
  - silting up of reservoirs and ditches
  - risk of flooding

What are the consequences?

- On site
  - decrease of soil quality
  - filling up of gullies
  - loss of yield, nutrients, pesticides
- Off site
  - mudflows
  - silting up of reservoirs
  - deterioration of water quality

Loss of soil quality


Formation of gullies

Loss of yield

Mudflows

Silting up reservoirs

Deterioration of water quality (eutrophication)



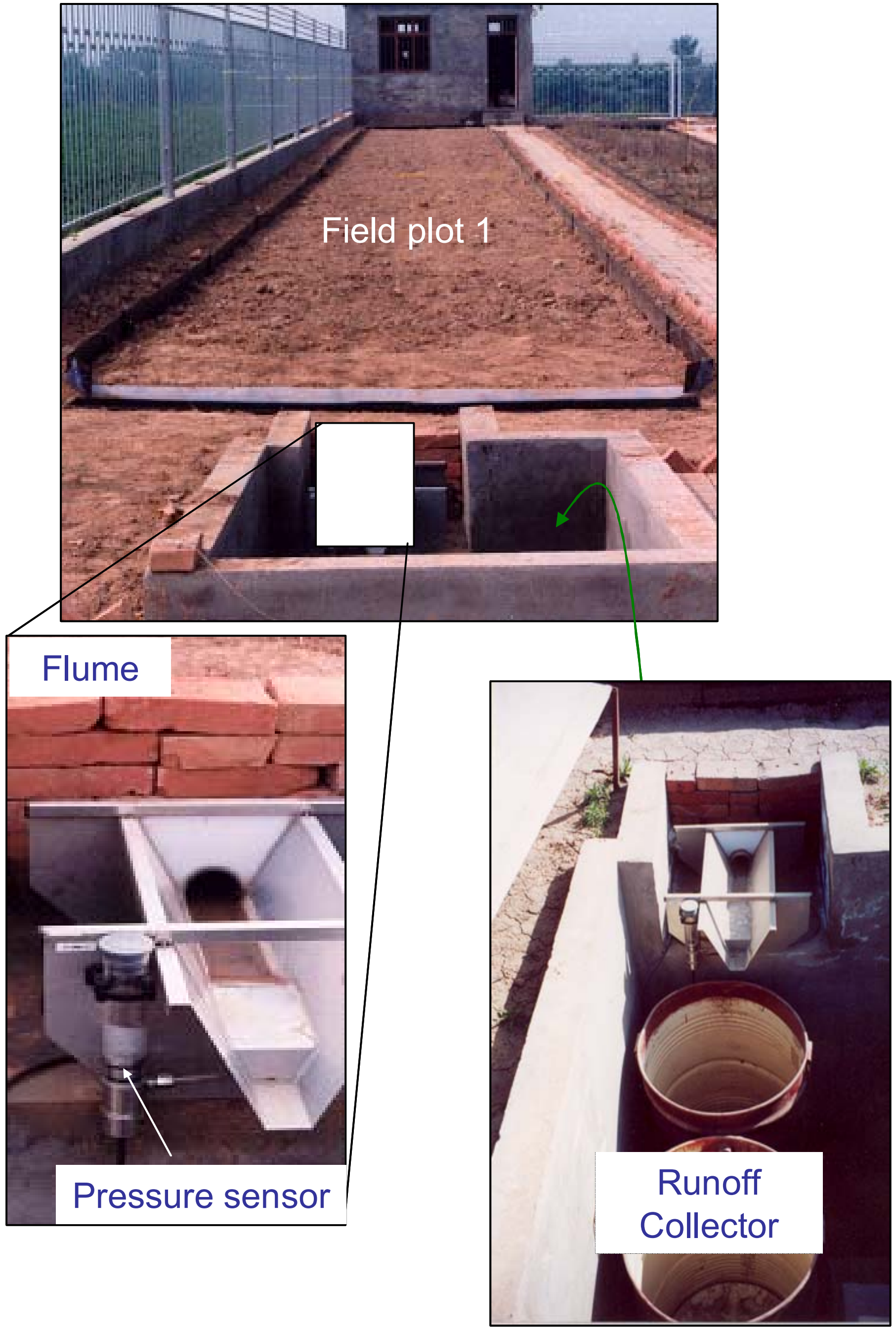
How can we measure it?

- Laboratory:
    - soil pans
    - rainfall simulations
    - flume experiments
- Field
    - erosion plots
    - rainfall simulations
    - flume experiments
- Watershed
    - deposition in reservoirs
    - sediment discharge at the outlet

- Laboratory rainfall simulation

- Field rainfall simulation

- Field plot
  (flume with pressure transducer + collector drum)



- Watershed

  (ultrasonic sensor to determine the water level)

- Watershed
  (sampling device)

- Watershed
  (turbidity sensor)

Universal Soil Loss Equation – USLE (1978)
Revised USLE – RUSLE (1997)

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

A = soil loss (sediment yield) per unit area ($Mg\ ha^{-1}\ year^{-1}$)

R = rainfall-runoff erosivity factor ($MJ\ mm\ ha^{-1}\ h^{-1}\ year^{-1}$)

K = soil erodibility factor ($Mg\ ha\ h^{-1}\ MJ^{-1}\ mm^{-1}$)

LS = slope-length factor

C = cover-management factor

P = supporting practices factor

R – Rainfall-runoff erosivity factor

- Potential of rain to detach and transport sediment

- Rainfall is characterised by

  - amount of rainfall (precipitation)
  - duration of rain storm
  - intensity of rainfall
  - momentum or kinetic energy of raindrops

- Wischmeier and Smith (1958): $R = E\ I_{30}$

Kinetic energy E

- KE of single raindrop

$$E_i = ½\ m_i\ v_i^2$$

- KE of rainstorm

$$E = \sum E_i$$

impossible → group raindrops into classes of equal size (and hence m and v)

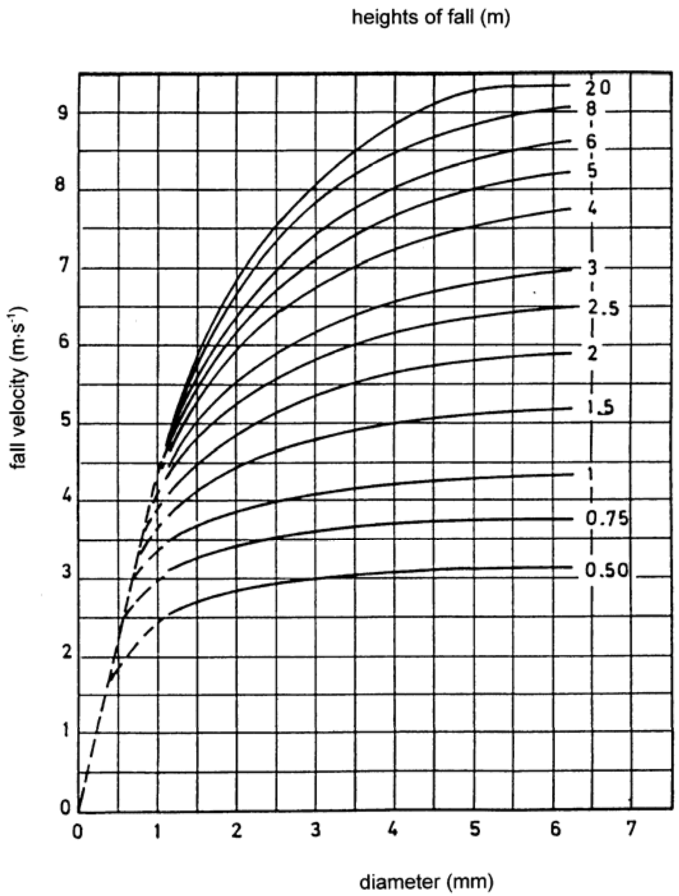
- Determine raindrop-size distribution

– stain technique: paper + appropriate dye
– photographic methods
– immersion method: heavy grade oil
– flour pellet: flour on plate
– impact assessment: tension balance, acoustic device, pressure transducer (distrometer)
– optical spectro-pluviometer: laser technique

Drop-size distribution depends largely on intensity (!!!), origin of raindrop, type of cloud – max. 7 mm

For each drop size (class): calculate $m = 1/6\ \pi\ d^3\ (\rho_w - \rho_a)$

determination of v: from Laws (1949)



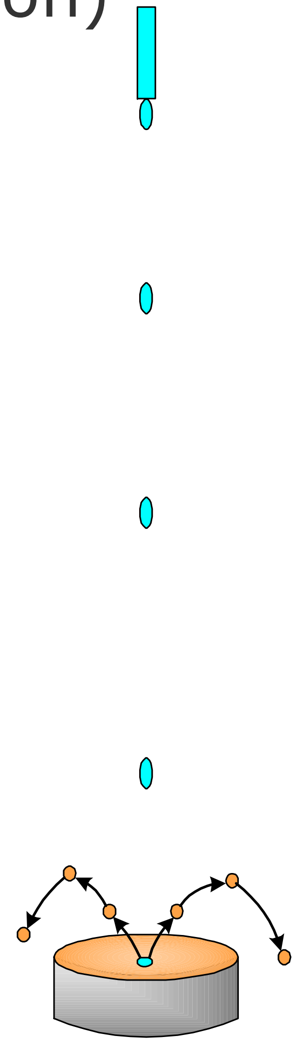
$\rightarrow$ m + v $\rightarrow$ E

very labor intensive

•"Direct" measurement of KE (needs calibration)

– Ellison splash cups (1947)

– Sensit KE meter: piezo-electrical crystals



still too labor intensive for practical purposes

• Indirectly from intensity: Renard et al. (1991)

KE of pluviophase j

$$E_{pj} = 0.29\ [1 - 0.72\ \exp(-0.05\ I_j)]\ \Delta P_j$$

E_{pj} = KE of pluviophase j (MJ ha^{-1})
I_j = rainfall intensity of pluviophase j (mm h^{-1})
ΔP_j = depth of rainfall of pluviophase j (mm)

KE of rainstorm

$$E = \sum E_{pj}$$

R – Rainfall-runoff erosivity factor

- Potential of rain to detach and transport sediment

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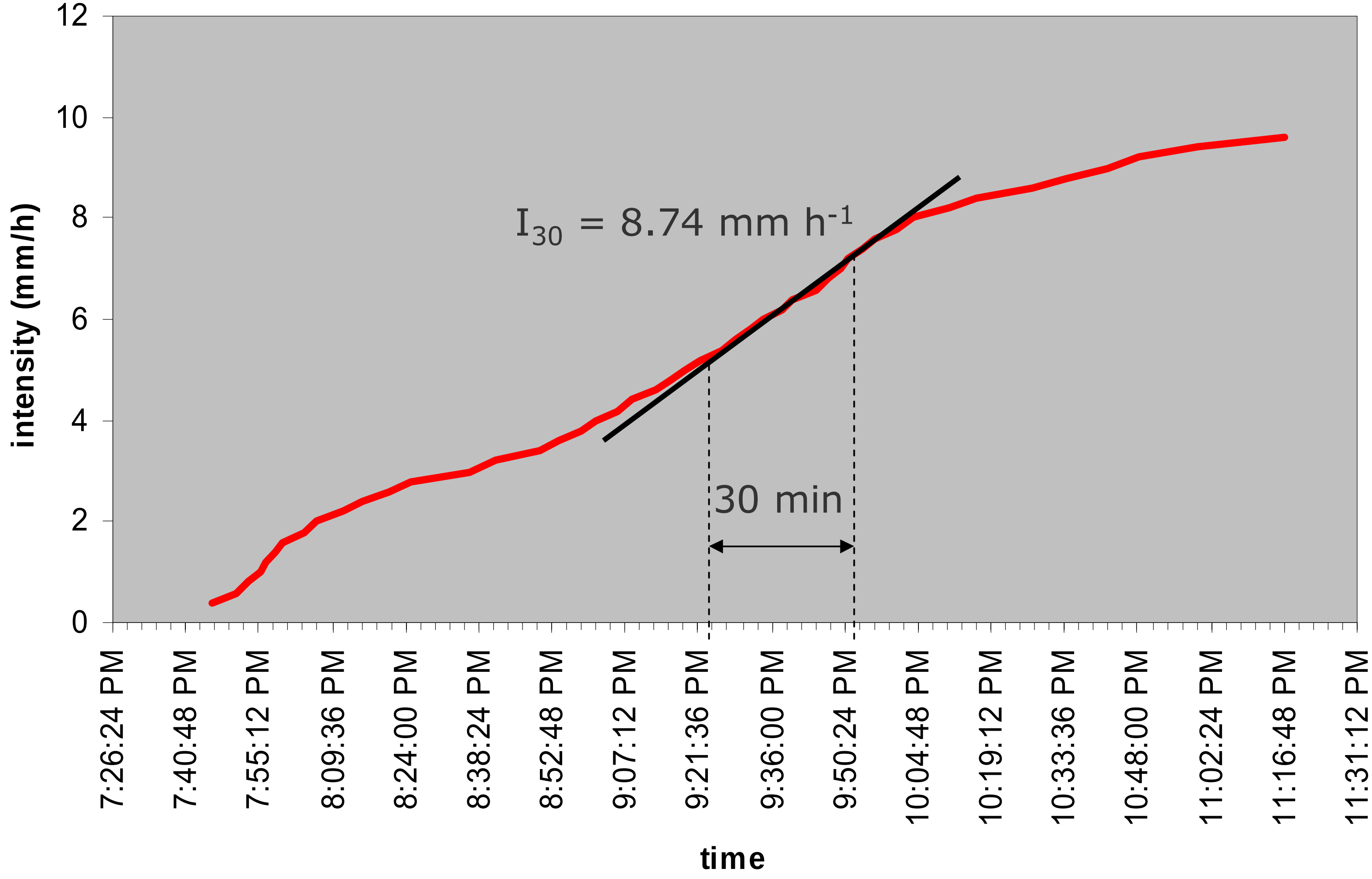
  - amount of rainfall (precipitation)
  - duration of rain storm
  - intensity of rainfall
  - momentum or kinetic energy of raindrops

- Wischmeier and Smith (1958): $R = E\, I_{30}$

I_{30} = maximum rainfall intensity in a 30 minute period within the rainstorm (mm h^{-1})

- pluviograph
- tipping bucket pluviometer (rain gauge)



I30 = 8.74 mm h-1
30 min
intensity (mm/h)
time
0
2
4
6
8
10
12
7:26:24 PM
7:40:48 PM
7:55:12 PM
8:09:36 PM
8:24:00 PM
8:38:24 PM
8:52:48 PM
9:07:12 PM
9:21:36 PM
9:36:00 PM
9:50:24 PM
10:04:48 PM
10:19:12 PM
10:33:36 PM
10:48:00 PM
11:02:24 PM
11:16:48 PM
11:31:12 PM

R – Rainfall-runoff erosivity factor

- Potential of rain to detach and transport sediment

- Rainfall is characterised by

  - amount of rainfall (precipitation)
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  - momentum or kinetic energy of raindrops

- Wischmeier and Smith (1958): $R = E\ I_{30}$

Experimental models: USLE

- Calculation of mean annual rainfall erosivity

  method 1: $R = 0.5\ P$

  with P = mean annual rainfall

  remark: outcome is in american units

  $\rightarrow R' = 17.3 \times R$ (Mg mm ha^{-1} h^{-1})

  method 2 (for KE > 25):

  $E = 9.28\ P - 8.838$

  $R = EI_{30}/100$

Experimental models: USLE

- Exercise: Calculate R if the mean annual precipitation P equals 2695 mm.

  method 1: $R = 0.5 \times P$

  method 2 (for KE > 25): Use $I_{30} = 75$ mm h^{-1}

  $$E = 9.28 \times P - 8.838$$

Experimental models: USLE

- Exercise: Calculate R if the mean annual precipitation P equals 2695 mm.

  method 1: $R = 0.5 \times 2695$

  $= 1347.5$

  $= 1347.5 \times 17.3$

  $= 23\,311.8$

  method 2 (for KE > 25): Use $I_{30} = 75$ mm h^{-1}

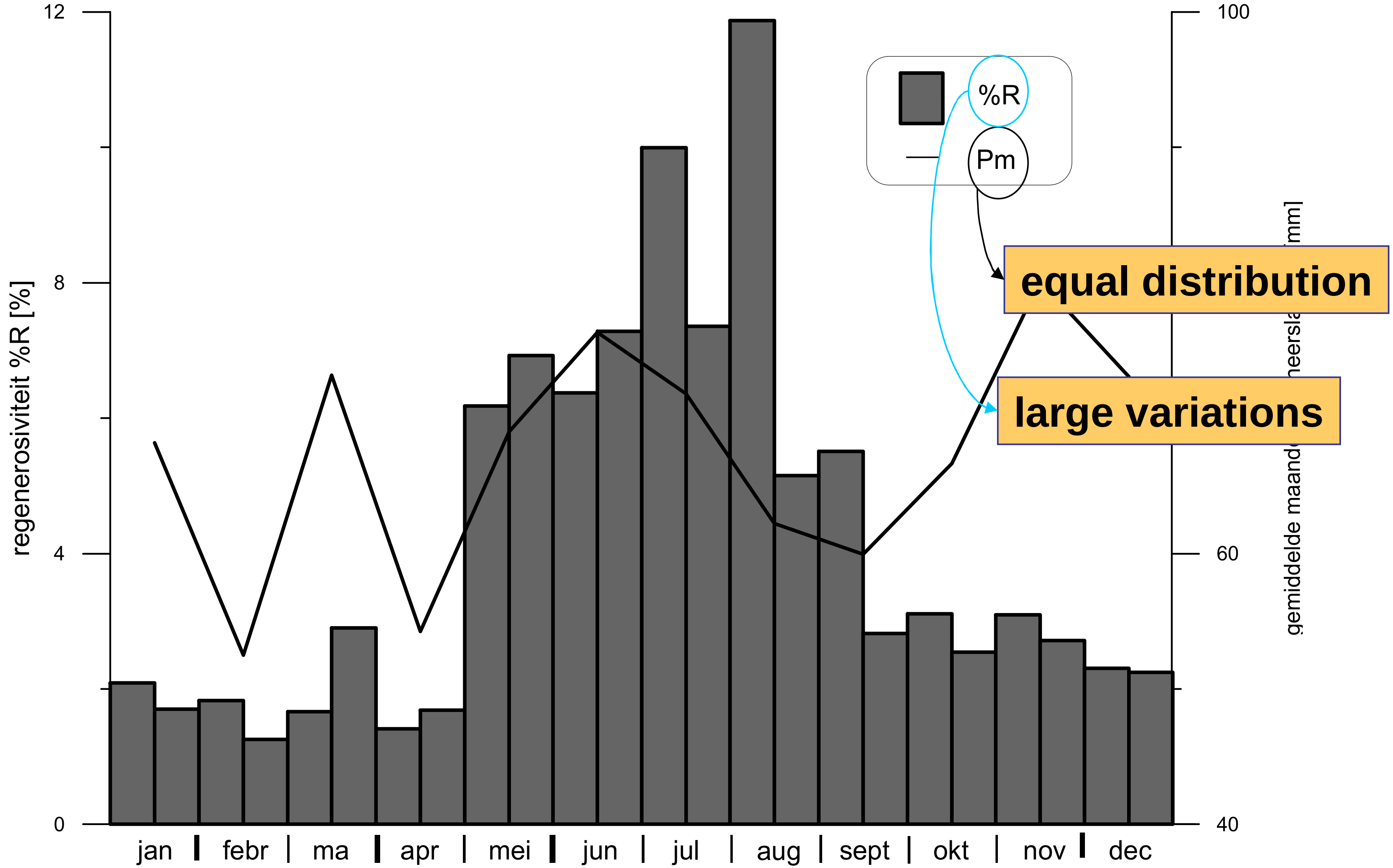
  $E = 9.28 \times 2695 - 8.838$

  $= 16\,171$ J m^{-2} $= 16\,171.6$ Mg ha^{-1}

  $R = (16\,171.6 \times 75)/100$

  $= 12\,128.7$

Monthly rainfall Pm and rainfall erosivity R at Ukkel (Belgium, period 1967- 1993)



problem: many weather stations do not have pluviograph or tipping bucket pluviometer

e.g. Belgium (Michiels and Gabriels, 1993)

$$R = 11.55 \exp(0.0254 \text{ MFI})$$

MFI = Modified Fournier Index

$$= \sum_{i=1}^{i=12} \frac{p_i^2}{P}$$

p_i = mean monthly rainfall in month i
P = mean annual rainfall

e.g. Belgium (Michiels and Gabriels, 1993)

$$R = 11.54 \exp(0.00215\ P)$$

e.g. Ethiopia (Hurni, 1985)

$$R = -8.12 + 0.562\ P$$

K – Soil erodibility factor

- Vulnerability or susceptibility of soil against erosion

- Erodibility depends on

  - soil texture (silt + very fine sand fraction)
  - organic matter content
  - soil structure
  - permeability – hydraulic conductivity

  - initial soil-water content

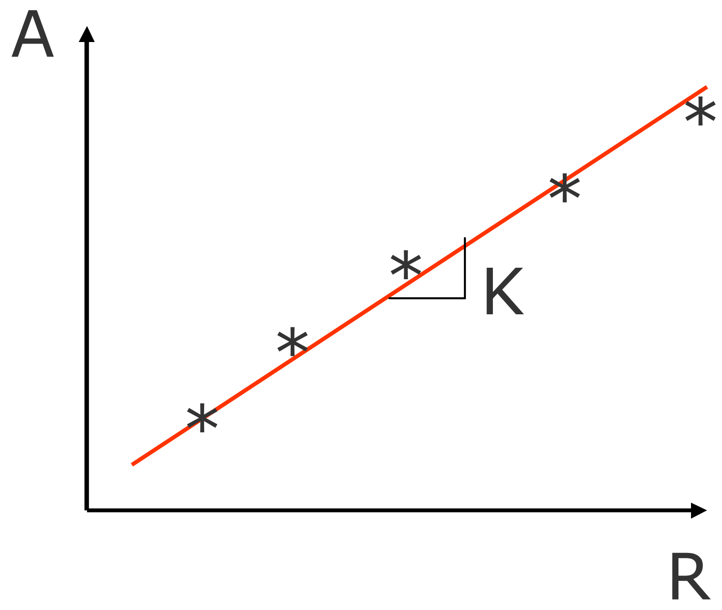
- K = soil loss (sediment yield) per unit of R on a standard plot (22.1 m long; 9% slope), continuous fallow for 2 years, tilled up and down the hill

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

$\longrightarrow K = A/R$

$LS = C = P = 1$

- from erosion plots



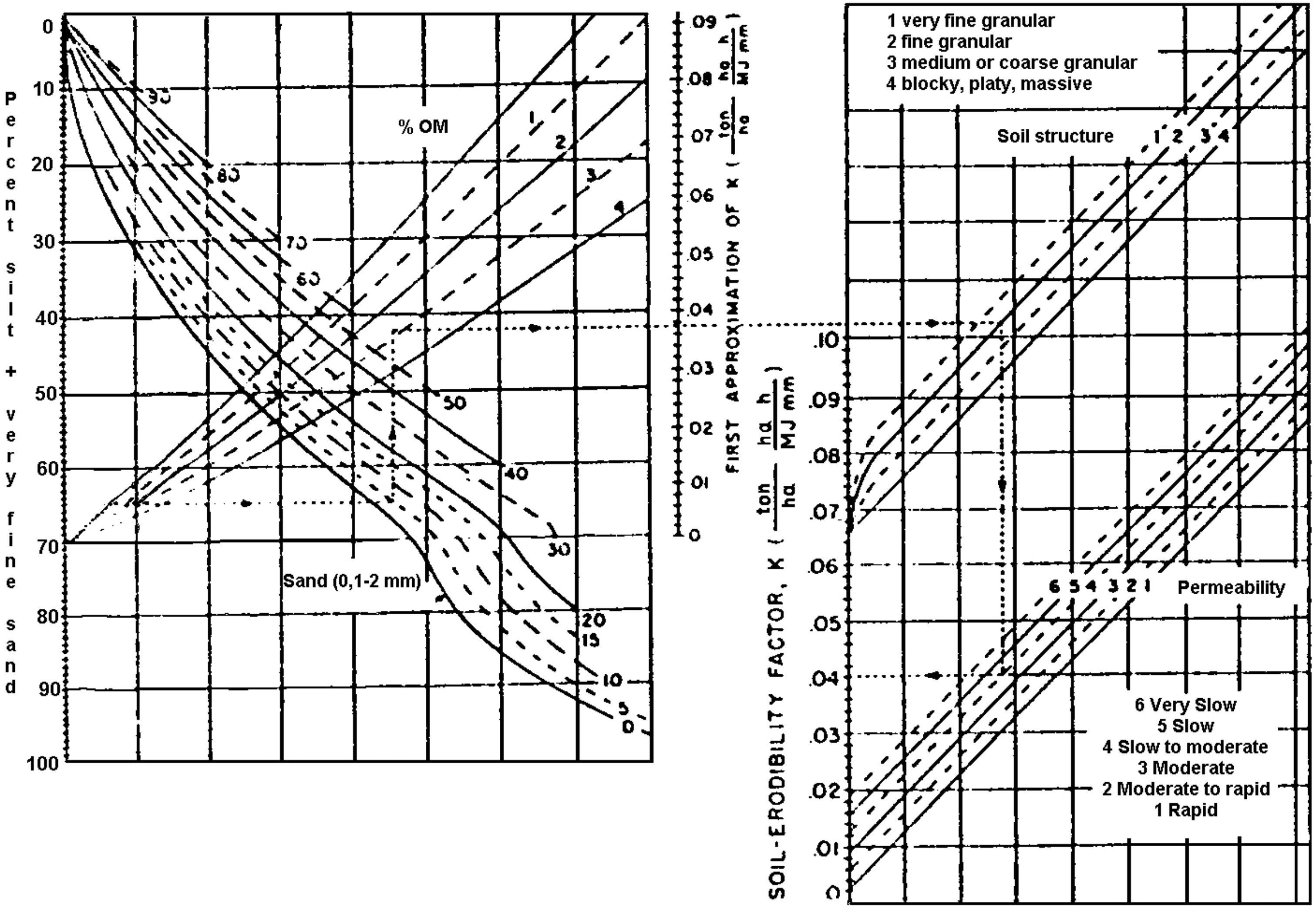
- <u>in practice (RUSLE):</u>

(1) via "nomogram"

$$K = 0.1317\ [2.1\ 10^{-6}\ (12 - OM)\ M^{1.14} + 0.0325\ (S - 2) + 0.025\ (P - 3)]$$

M = (% of 2-100 µm fraction) x (100 - % of < 2 µm fraction)
OM = % of organic matter
S = structural class
P = permeability class

valid for % of 2-50 µm fraction < 70%



aggreg. size
< 1 mm
1-2 mm
2-10 mm
-

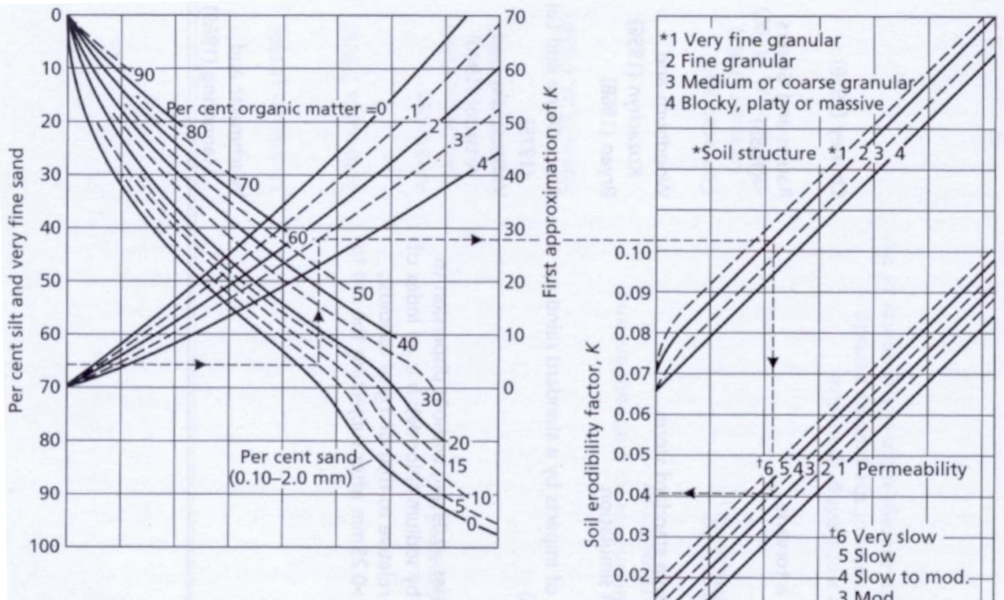
Ks (cm h^{-1})
< 0.125
0.125-0.5
0.5-2
2-6.25
6.25-12.5
>12.5

Experimental models: USLE

- Exercise:

  70 % silt + fine sand, 20 % coarse sand, OC = 1 %, medium granular structure, slow to moderate permeability

  K-Value = 0.62



Procedure. With appropriate data, enter scale at left and proceed to points representing the soil's % sand (0.10–2.0 mm). % organic matter, structure and permeability, *in that sequence*. Interpolate between plotted curves. The dotted line illustrates procedure for a soil having: sf + vfs 65%, sand 5%, OM 2.8%, structure 2, permeability 4. Solution: K = 0.041.

(2) via mean weighted diameter Dg (Declercq and Poesen, 1992)

$K = 0.0035 + 0.0388 \exp[-0.5((\log(Dg)+1.519)/0.7584)^2$

$Dg = \exp[0.01 \sum(f_i \ln(m_i))]$

Dg = mean weighted diameter (mm)
f_i = fraction of particles belong to diameter class i (mass%)
m_i = mean diameter of diameter class i (mm)

USLE: considers K is constant over season

RUSLE: considers seasonal variation (structure, antecedent soil-water content, frost, …)

by weighing instantaneous estimate of K in proportion to EI (the percent of annual R) for 15-day intervals

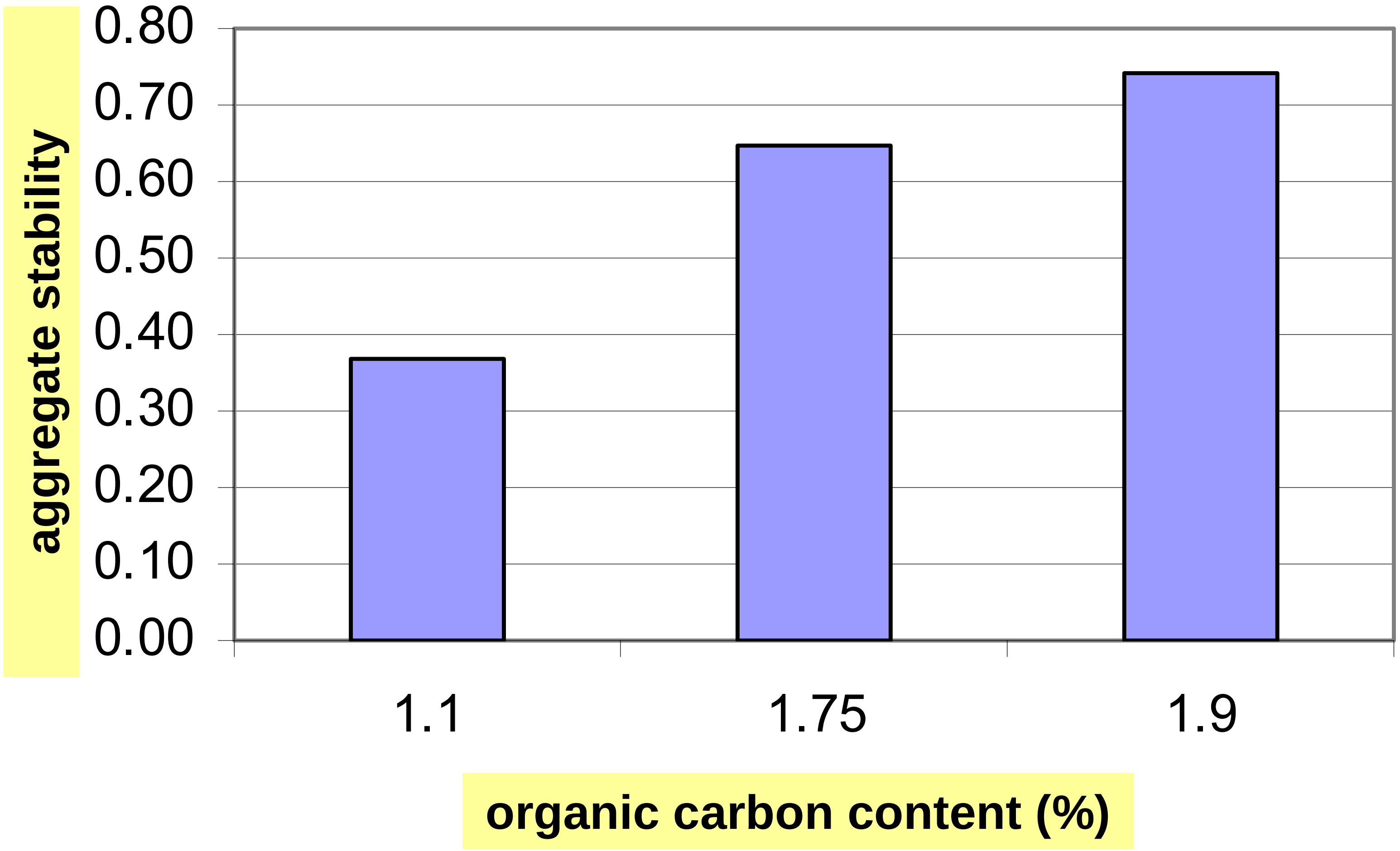
- soil structure
  - organic matter
  - soil conditioners

  ⇒ increase of aggregate stability against raindrop impact

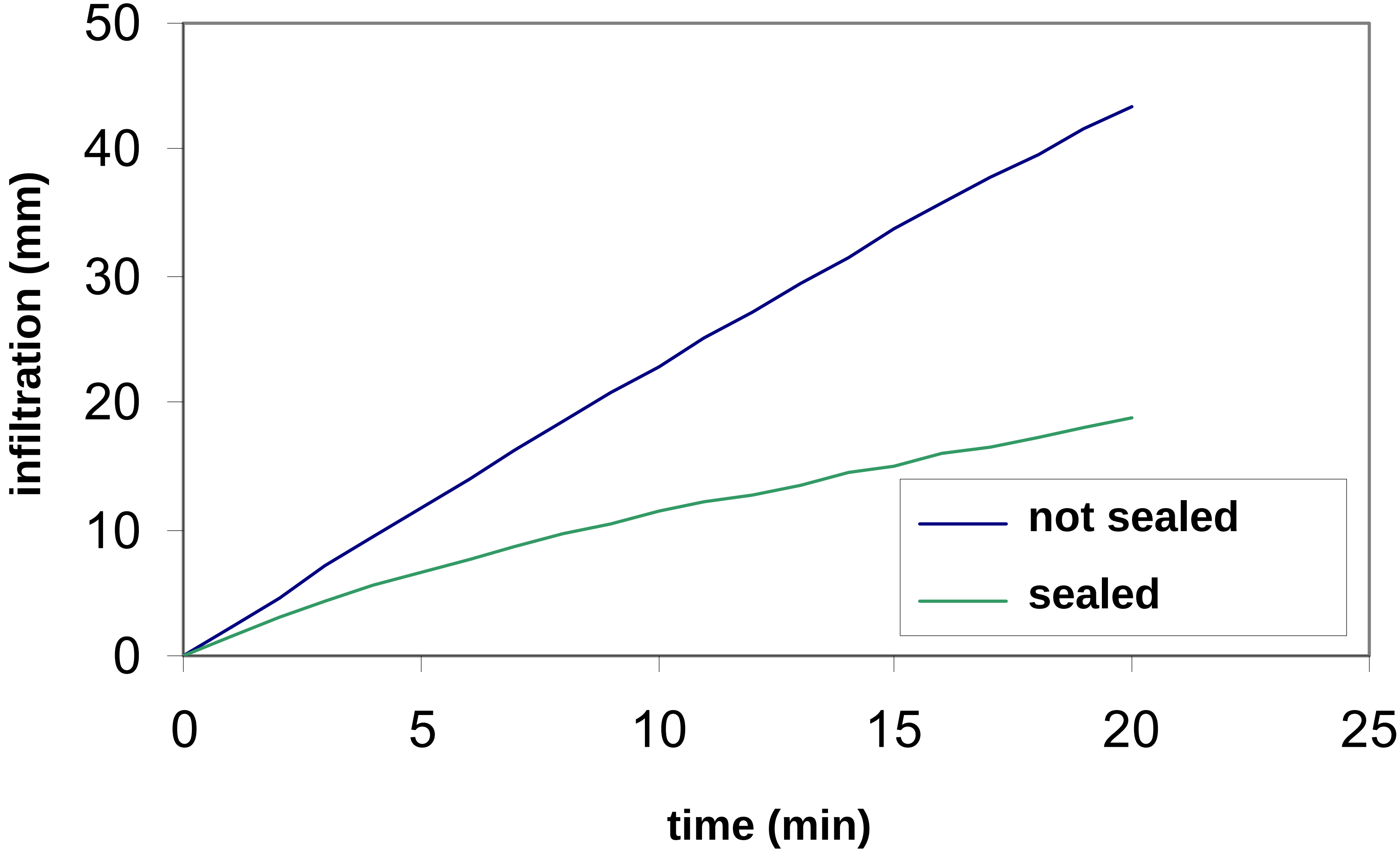
  ⇒ more infiltration

  - breaking of compacted ploughsole
  - controlled traffic

- aggregate stability at different organic carbon contents (clay content = 19 %)

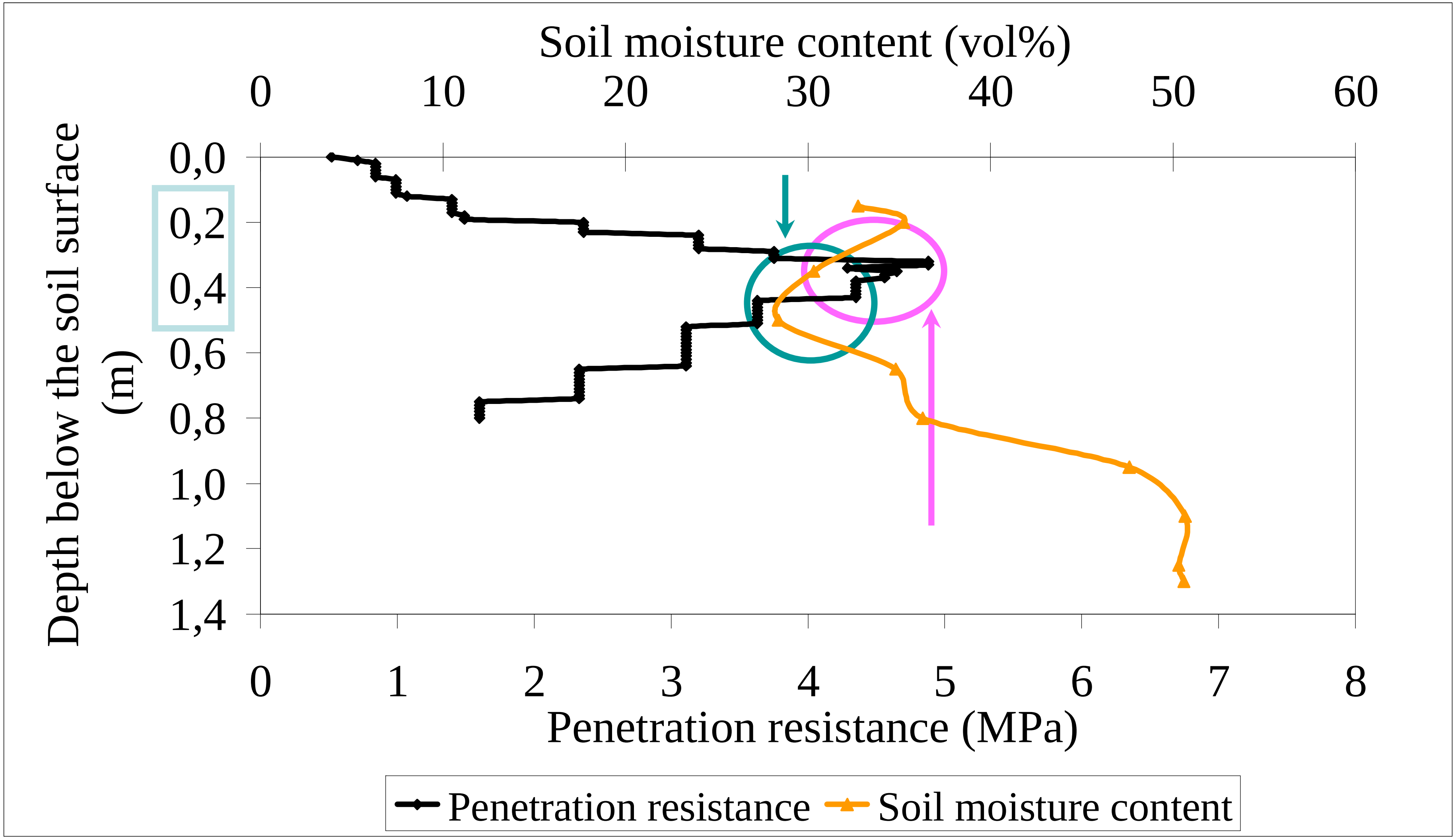


- infiltration with and without soil sealing (resp. low and high aggregate stability)



– soil compaction:

- at 30-40 cm depth



soil compaction hampers infiltration to deeper soil layers

⬇

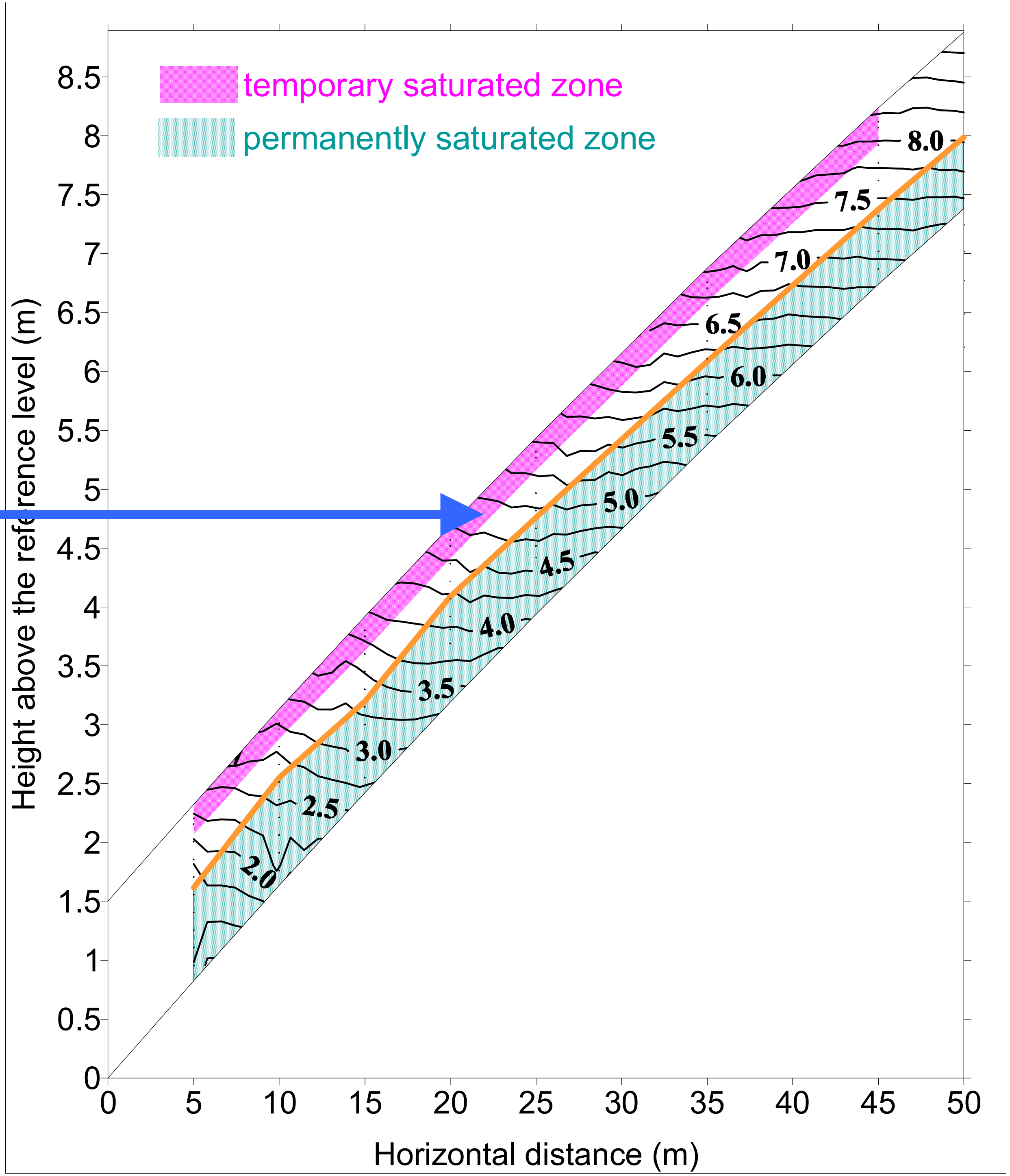
saturation of topsoil

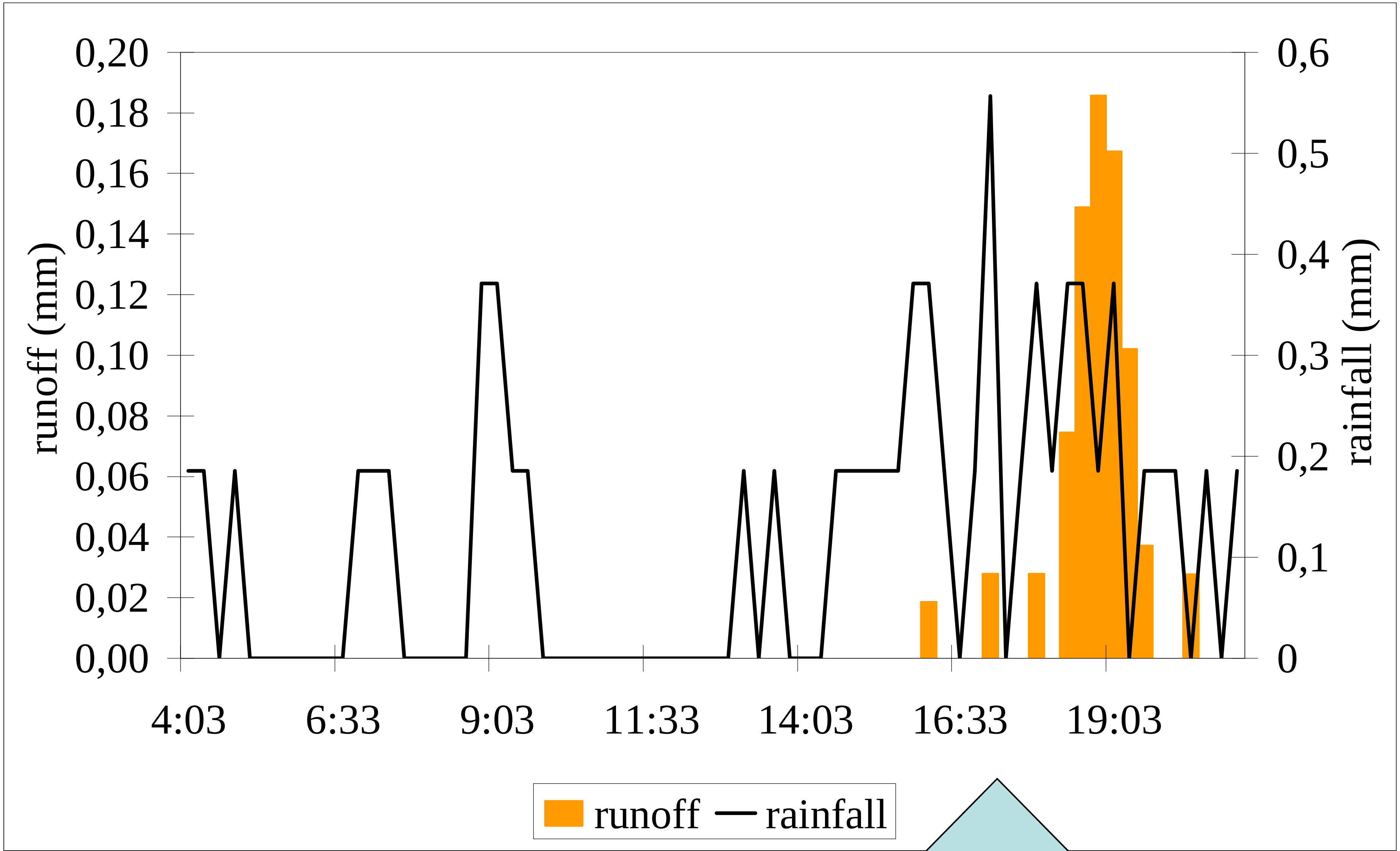
⬇

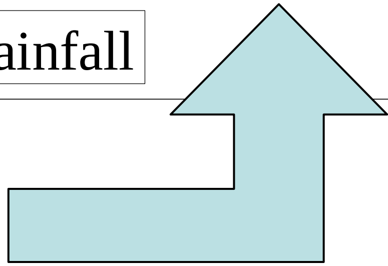
runoff

⬇

erosion



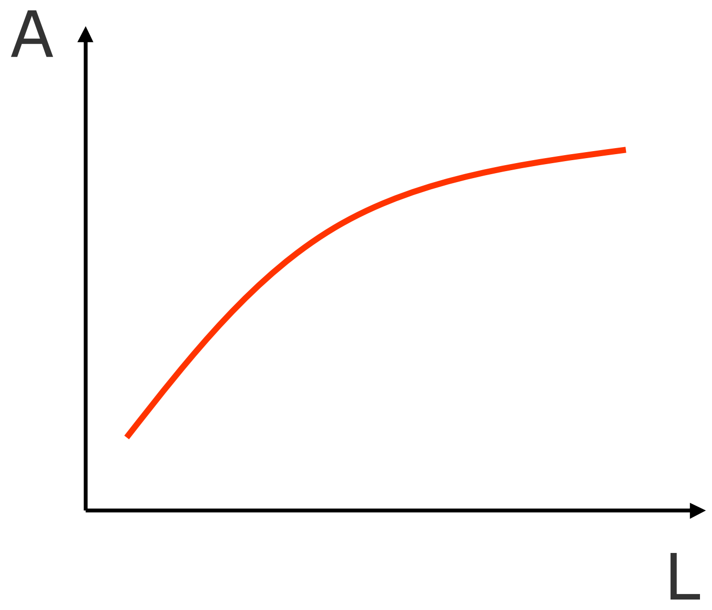


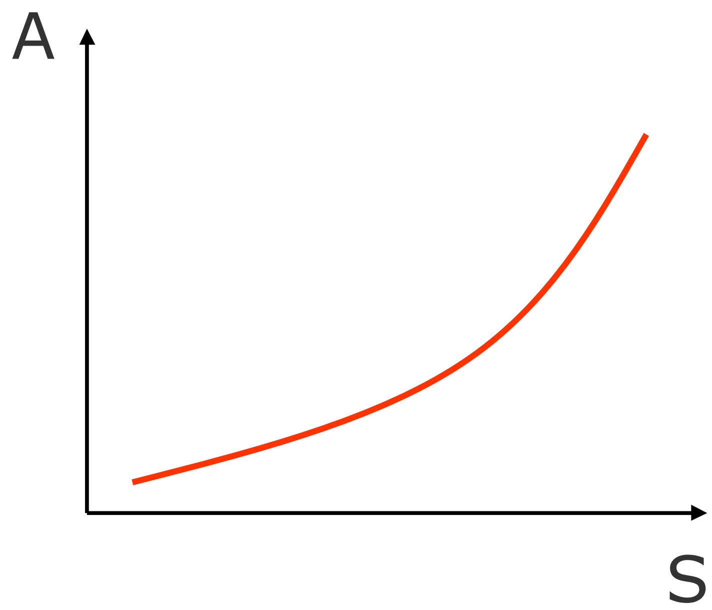


saturation of topsoil

LS – Slope-length factor

- expresses the effect of topography





USLE:

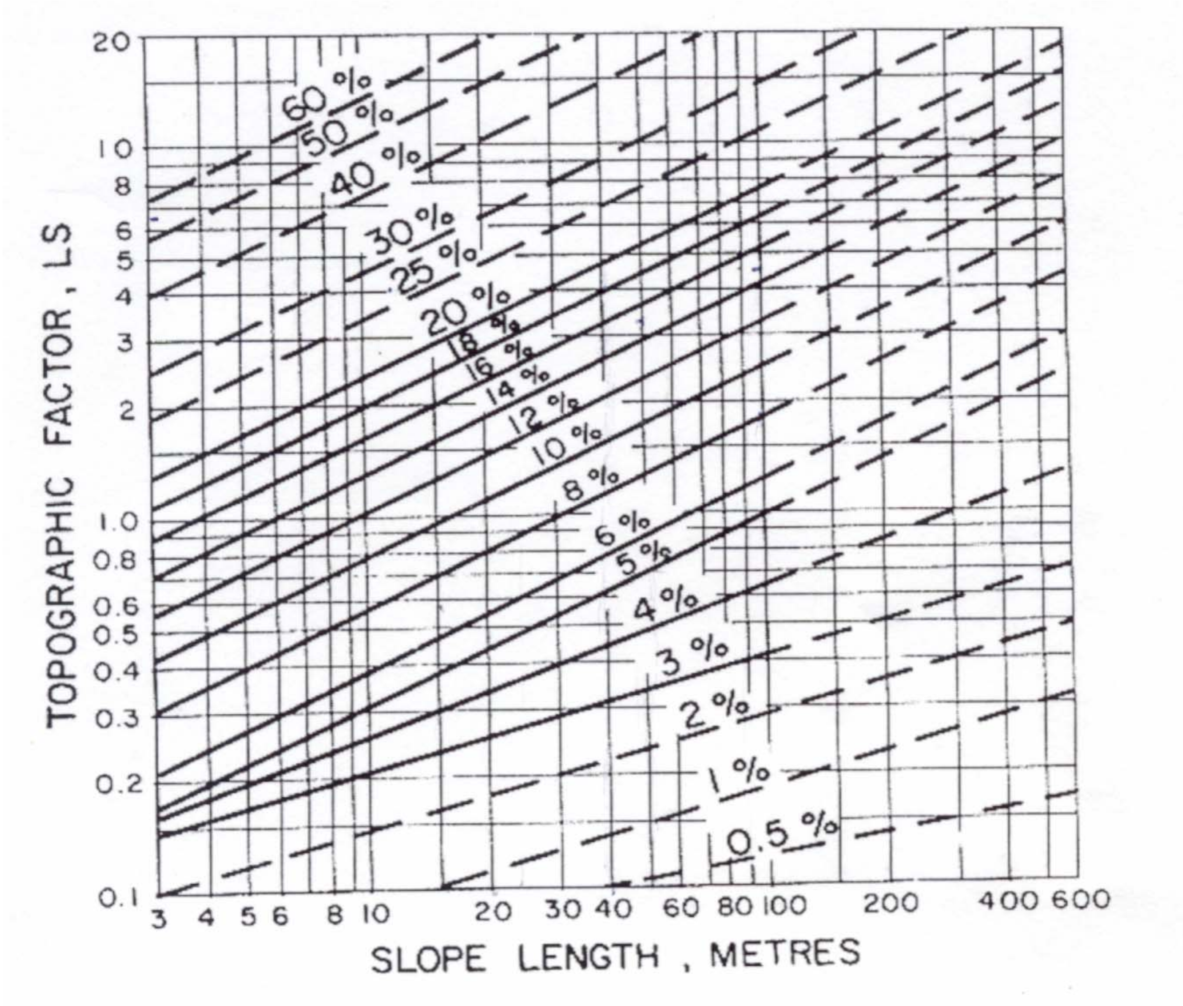
$$LS = (\lambda/22.1)^m \, (65.41 \sin^2\theta + 4.56 \sin\theta + 0.065)$$

λ = slope length (m)
θ = angle of slope
m = 0.5 if percent slop is < 5%, 0.4 on slopes of 3.5-4.5%, 0.3 on slopes of 1-3% and 0.2 on slopes < 1%

RUSLE: uses four separate slope length relationships

Experimental models: USLE

- Value obtained from nomograph



Experimental models: USLE

- Non-uniform slopes:
  - Slope is divided in *n* segments with uniform slope
  - For each segment: topographic factor calculated
  - Total topographic factor:

$$L \cdot S = \left(1/L_n\right) \cdot \sum_{i=1}^{i=n} (L_i / 22.13)^{m_i} \cdot S_i \cdot (L_i) \cdot (1 - (L_{i-1} / L_i)^{m_i + 1}$$

with $(L_i/22,13)^{mi}.s_i$ = topographic factor

$(L_i)(1-(L_{i-1}/L_i)^{Mi+1}$ = weight factor

Experimental models: USLE

- After re-arranging:

$$L \cdot S = \left(1/L_n\right) \cdot \sum_{i=1}^{i=n} S_i \cdot (L_i^{m_i+1} - L_{i-1}^{m_i+1})(22.13^{m_i})$$

$$S_i = 0.0065 s_i^2 + 0.0454 s_i + 0.065$$

with L_n = total slope length

L_i = length from top of slope to bottom of segment i

l_i = length of segment i

S_i = slope factor of segment i

s_i = slope of segment i (%)

m_i = slope length exponent

Experimental models: USLE

- Exercise:

  Calculate LS for a uniform slope of 12 % and contour bunds at 20 m spacing.

  Formula:

$$LS = \left(\frac{x}{22.13}\right)^n \left(0.065 + 0.045s + 0.0065s^2\right)$$

Experimental models: USLE

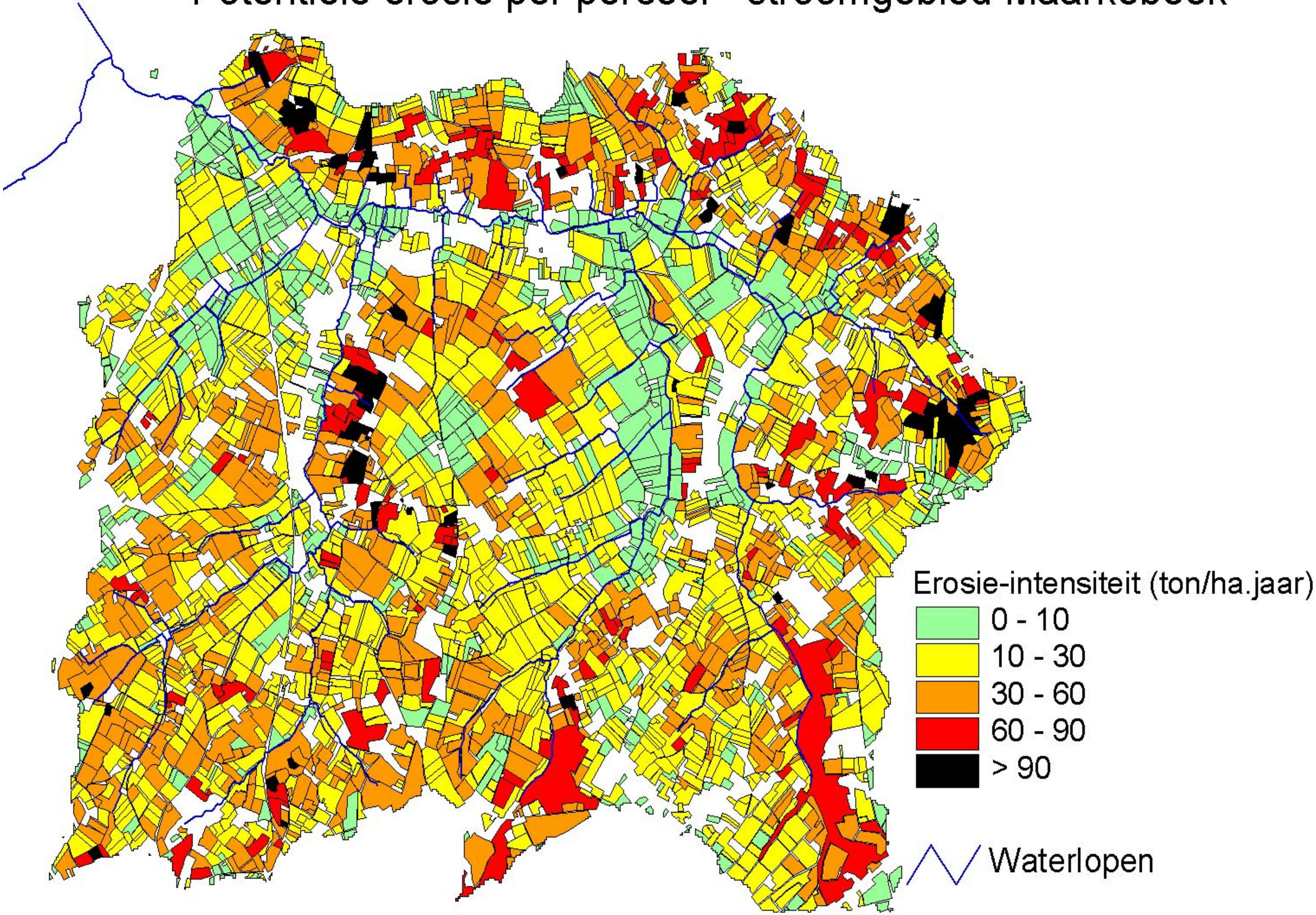
- Exercise:

  Calculate LS for a uniform slope of 12 % (= 7°) and contour bunds at 20 m spacing.

$$LS = \left(\frac{x}{22.13}\right)^n \left(0.065 + 0.045s + 0.0065s^2\right)$$

LS = 1.46

Potentiële erosie per perceel - stroomgebied Maarkebeek

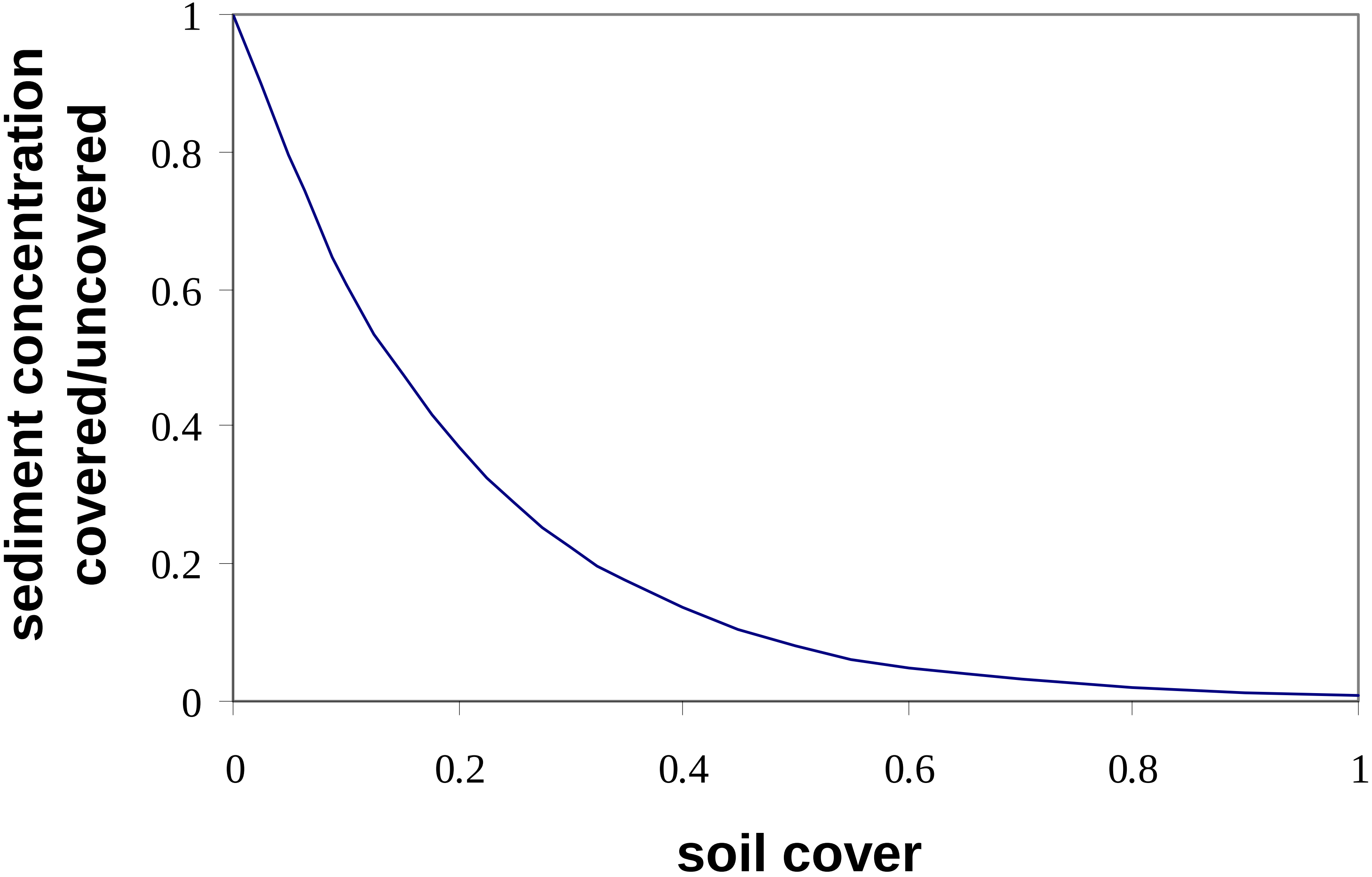


C – Crop-management factor

- expresses degree of soil loss compared to clean-tilled fallow

- varies from near 0 (very well protected soil) till 1.5 (finely, tilled fallow surface)
  for clean-tilled fallow surface: C = 1

Influence of soil cover on sediment concentration (Rose, 1994)



- types of soil cover
  - protection of soil by potato, sugar beets and maize is rather limited due to the low amounts of crop residues and stem flow (maize)
  - sowing of grass under maize, double drilling, green manure
  - mulching

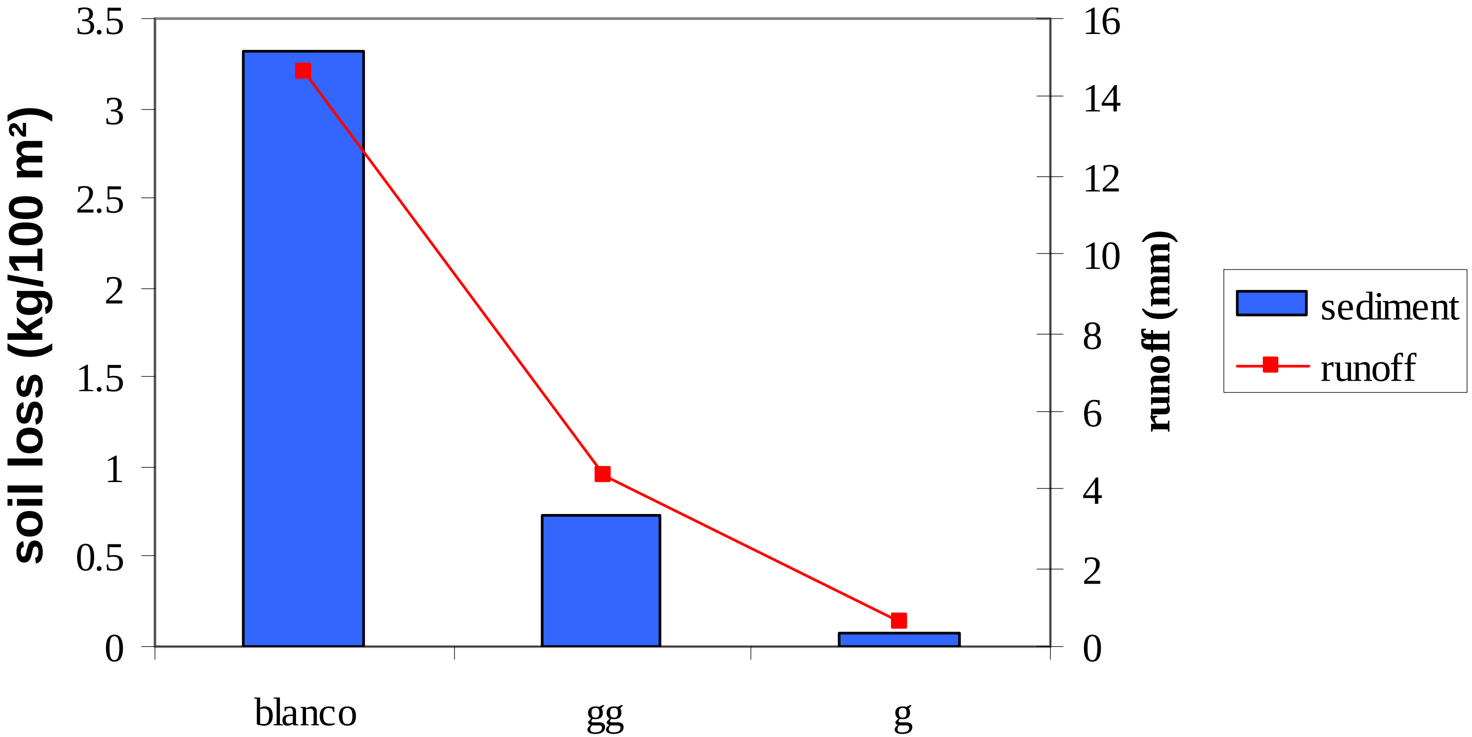
- USLE: distinction between
  - forest (e.g. C = 0.001 if 90% of soil surface covered by humus); values from tables
  - pasture (e.g. C = 0.003 for grass with 95% of cover); values from tables
  - cropland: different growth stages are considered; each with different % of surface cover and multiplied with the monthly fraction of annual R
    e.g. development stage is June:
    $C_{June} = 0.5 \times R_{June}$

mulch

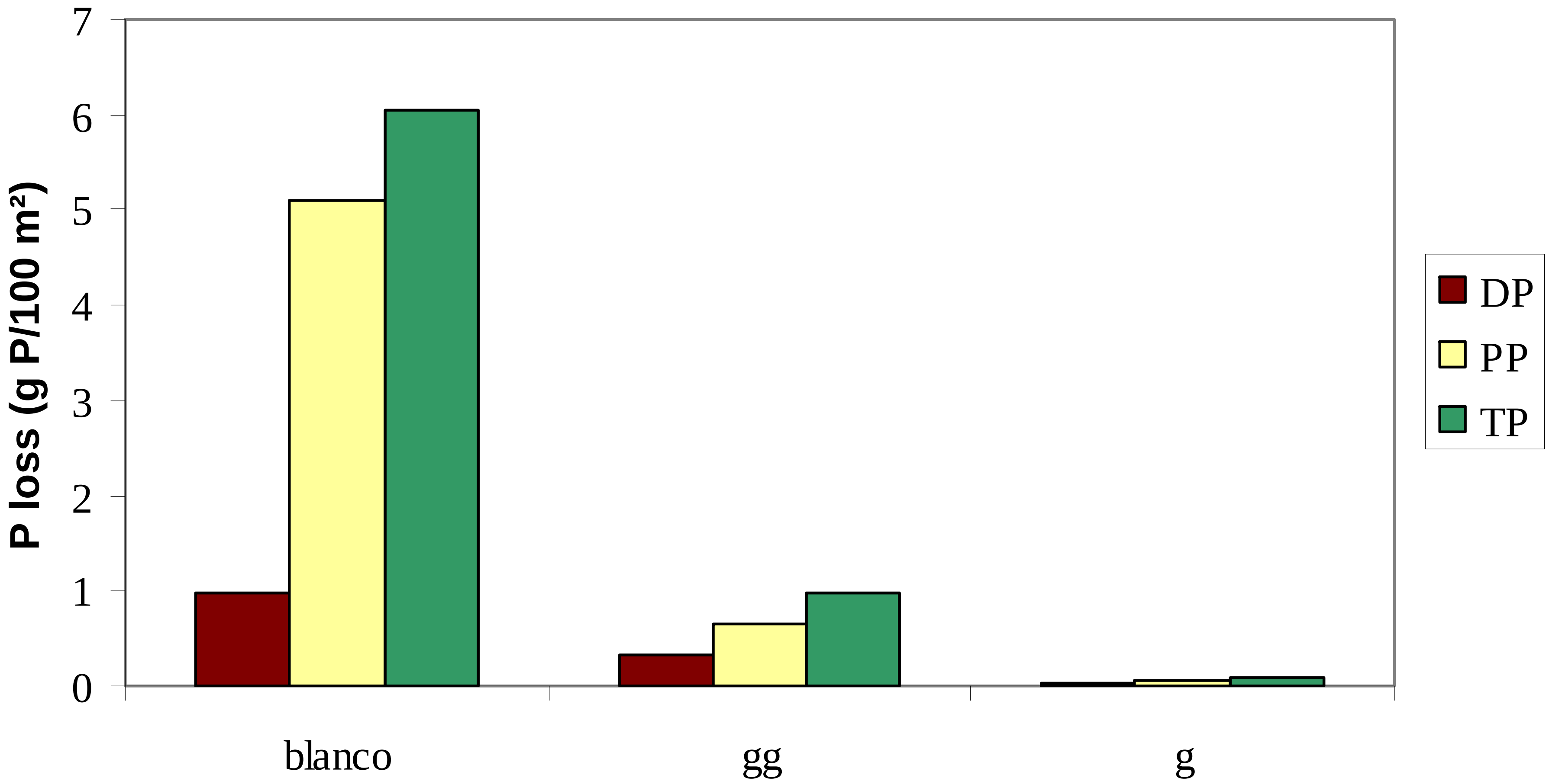
Mulching: crop residues corn

– Field plot measurements (Nukerke, Belgium):

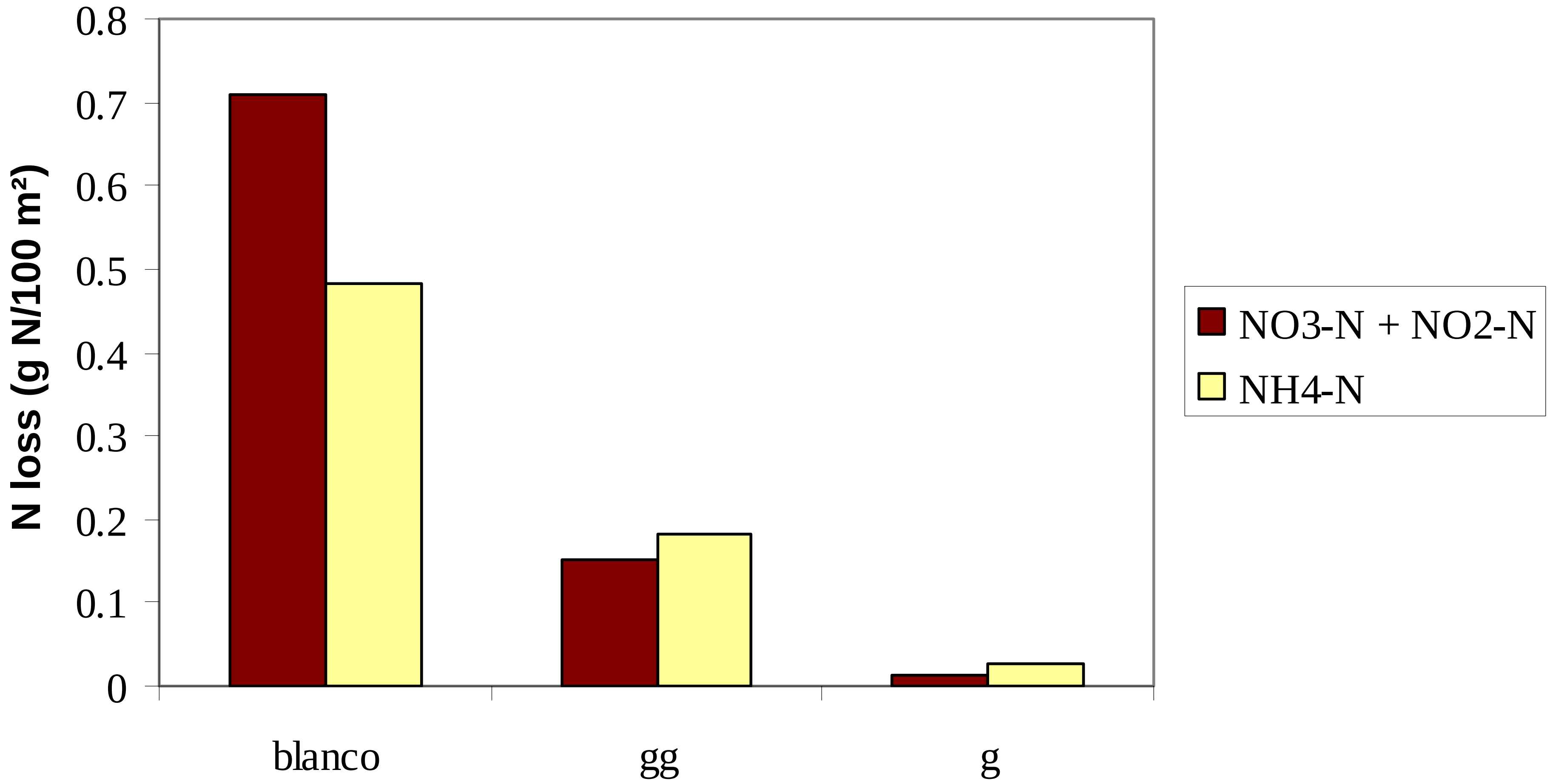
- 1 March -3 April 2001: 91 mm rain
- 98 % less soil loss by green manure (rye grass, 60 % cover)



- 84 to 99 % less total phosphorus losses by green manuring



- 79 to 98 % less nitrate losses (NO_3-N + NO_2-N) and 64 to 94 % less ammonium losses (NH_4-N)



- RUSLE:

  C = PLU x CC x SC x SR

  PLU = prior land use
  CC = crop canopy
  SC = surface cover
  SR = surface roughness

  C is calculated and weighted at 15-day intervals

P – Supporting practice factor

- expresses degree of soil loss compared to up-and-down-hill culture
- max. P-value = 1
- values for contouring, strip cropping, terracing, conservation practices, … from tables;

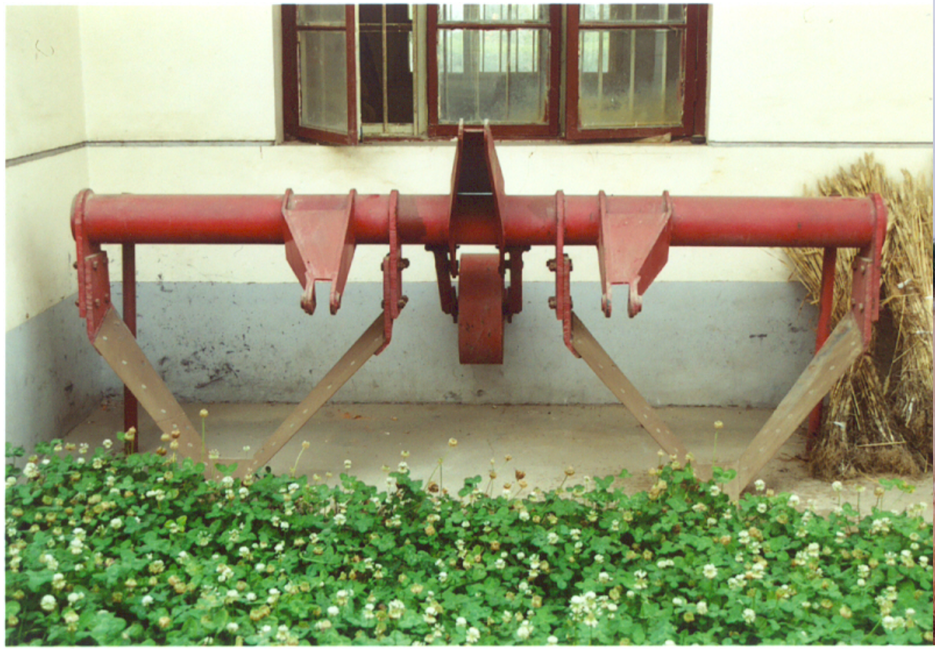
  e.g. contouring on 9 to 12 % slope: P = 0.60

- soil tillage
  - to retain crop residues at the surface
  - to increase soil biological activity
  - tillage practices:
    - conventional tillage
    - no tillage
    - reduced tillage
    - subsoiling
    - contouring

No tillage

Subsoiling

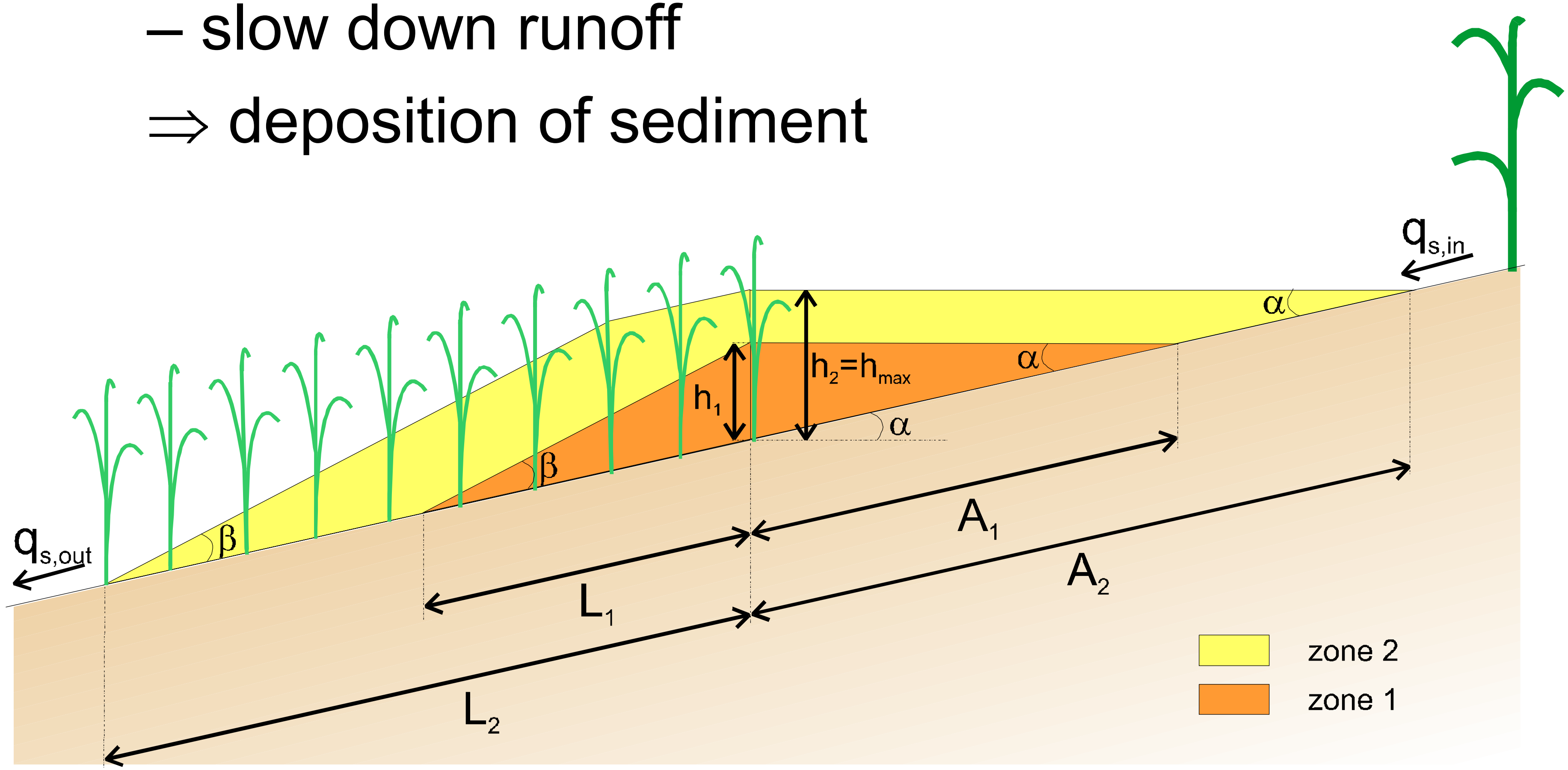
subsoiling



Difference in soil moisture content after conventional (left) and reduced tillage (right)

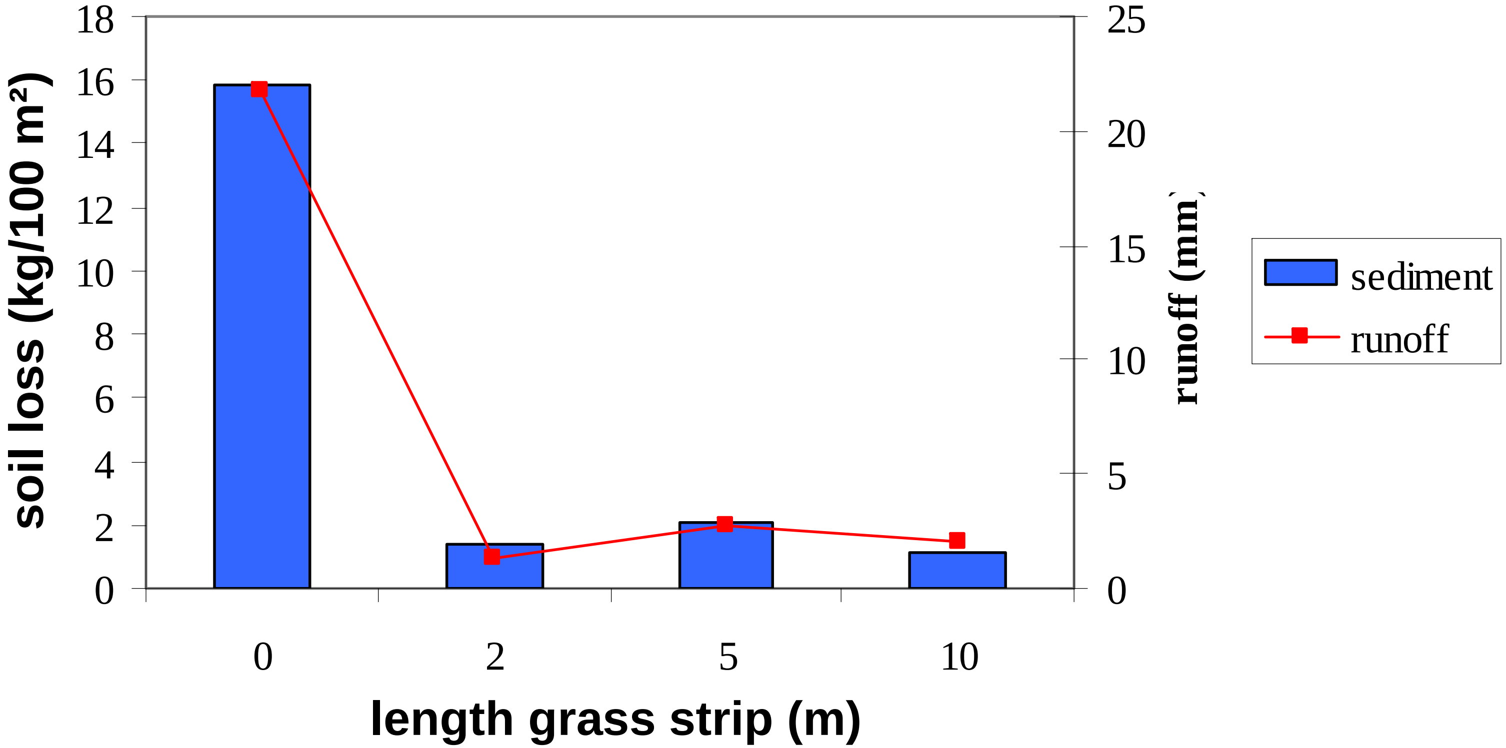
- grass buffer strips
  - do not prevent soil erosion on site but reduce off site effects
  - slow down runoff

  ⇒ deposition of sediment



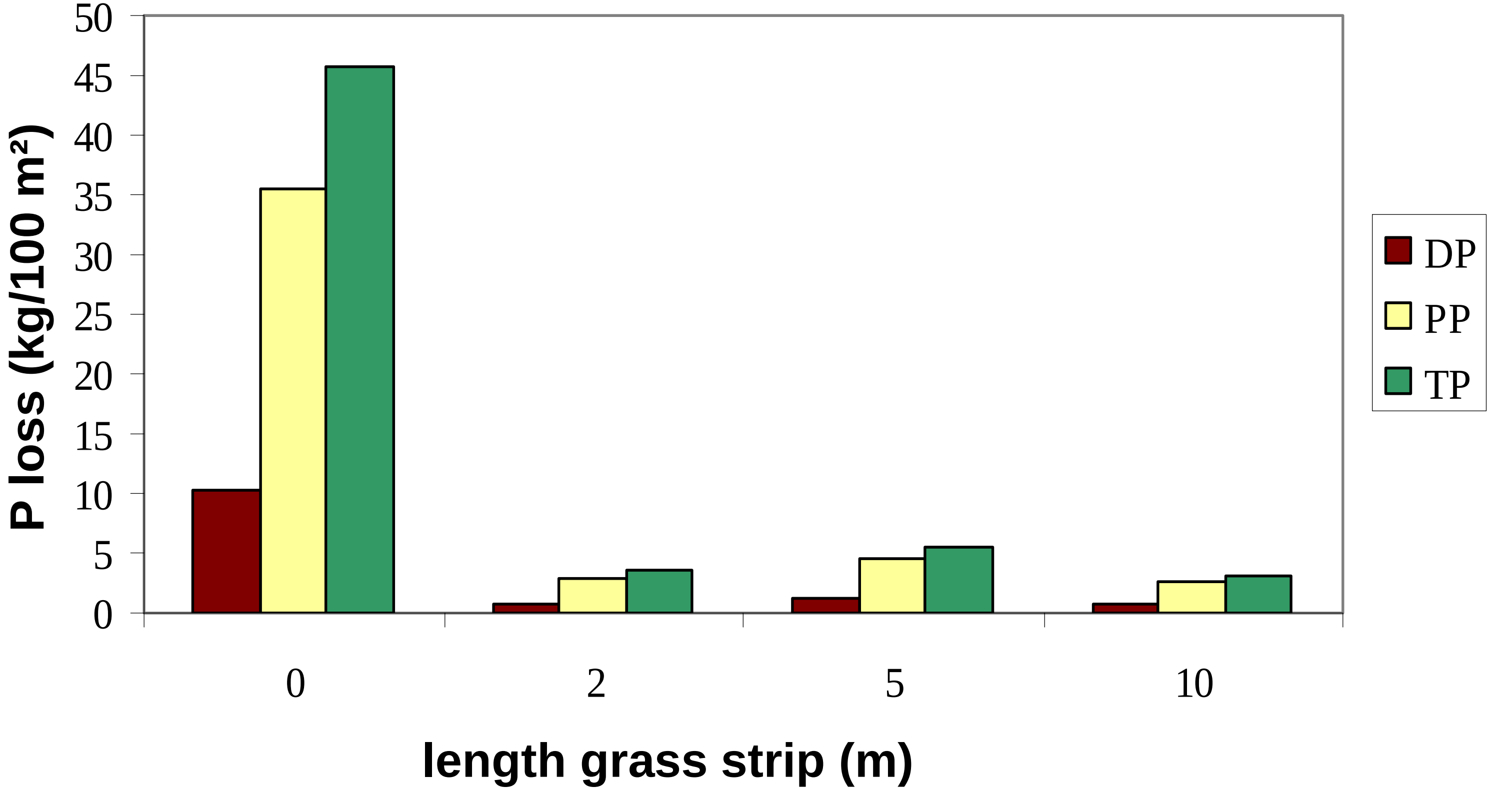
– Measurements on field plots (Nukerke, Belgium):

- 12 to 16 February 2001: 26,7 mm rainfall
- 94 % less soil loss
- 93 % less runoff



– Measurements on field plots (Nukerke, Belgium):

- 93 % less total P-losses



Small and large scale hydraulic structures

- terraces, dikes, reservoirs and retention ponds

$\rightarrow$ to protect villages, channels, ...

bunds

retention ponds


syncro