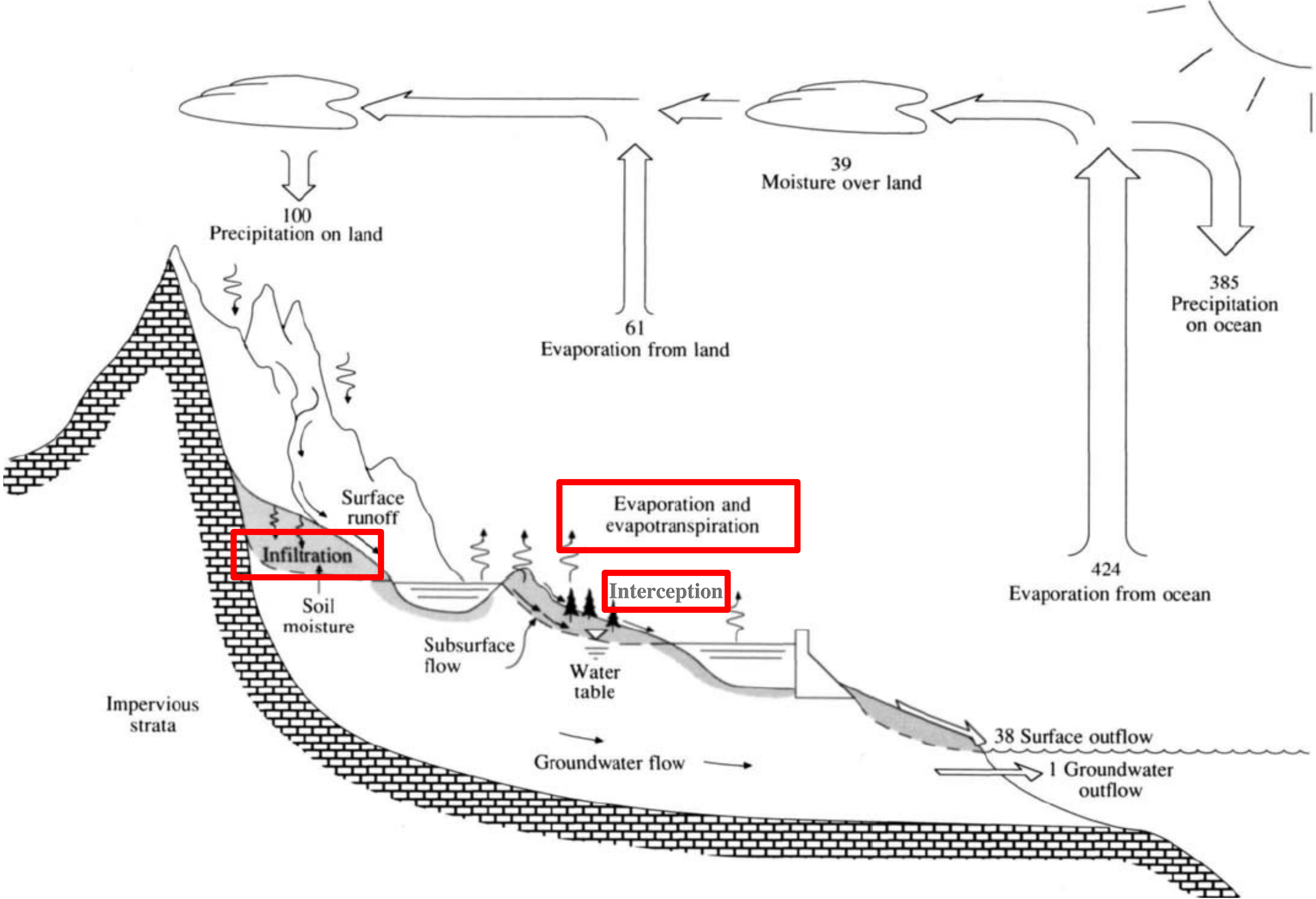
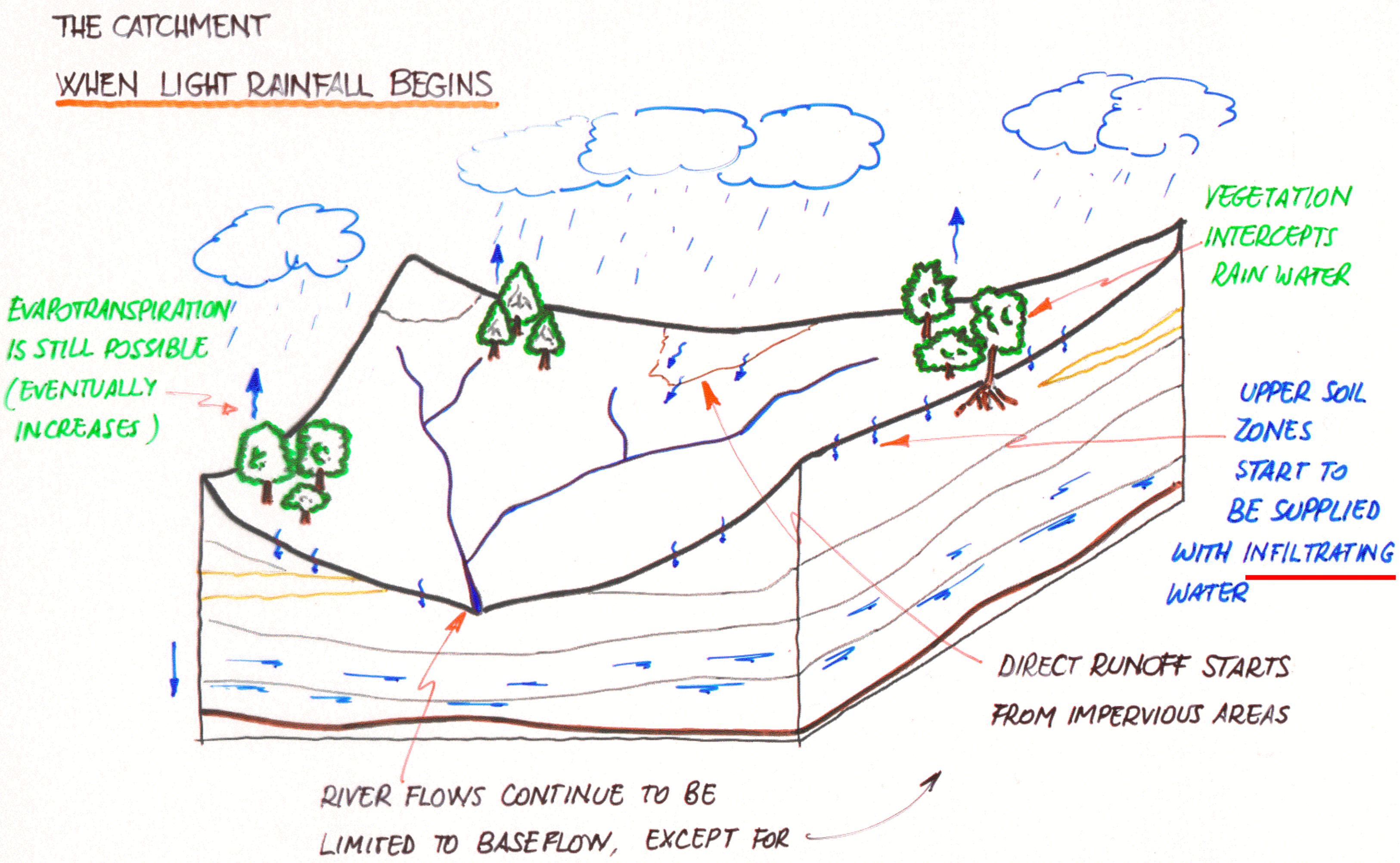
Land processes: soil vegetation atmosphere transfer

② *Infiltration and Runoff Generation Mechanisms*



Land processes: soil vegetation atmosphere transfer

② *Infiltration and Runoff Generation Mechanisms*



Mass conservation: $P = I + E + ET + \boxed{F} + R$

Infiltration → *Runoff Generation*

Land processes: soil vegetation atmosphere transfer

② *Infiltration and Runoff Generation Mechanisms*

Lecture content

Skript: Ch. IV.5

Ch. VI § 2.3

2.3.2

2.3.4 (including sub-sections)

- Infiltration
  - *relevance of the process*
  - *influencing factors (soil characteristics)*
  - *measurement*
    - ☐ infiltration vs soil water content
  - *infiltration and runoff generation mechanisms*
  - *mathematical models of infiltration*
    - ☐ physically based vs empirical/conceptual

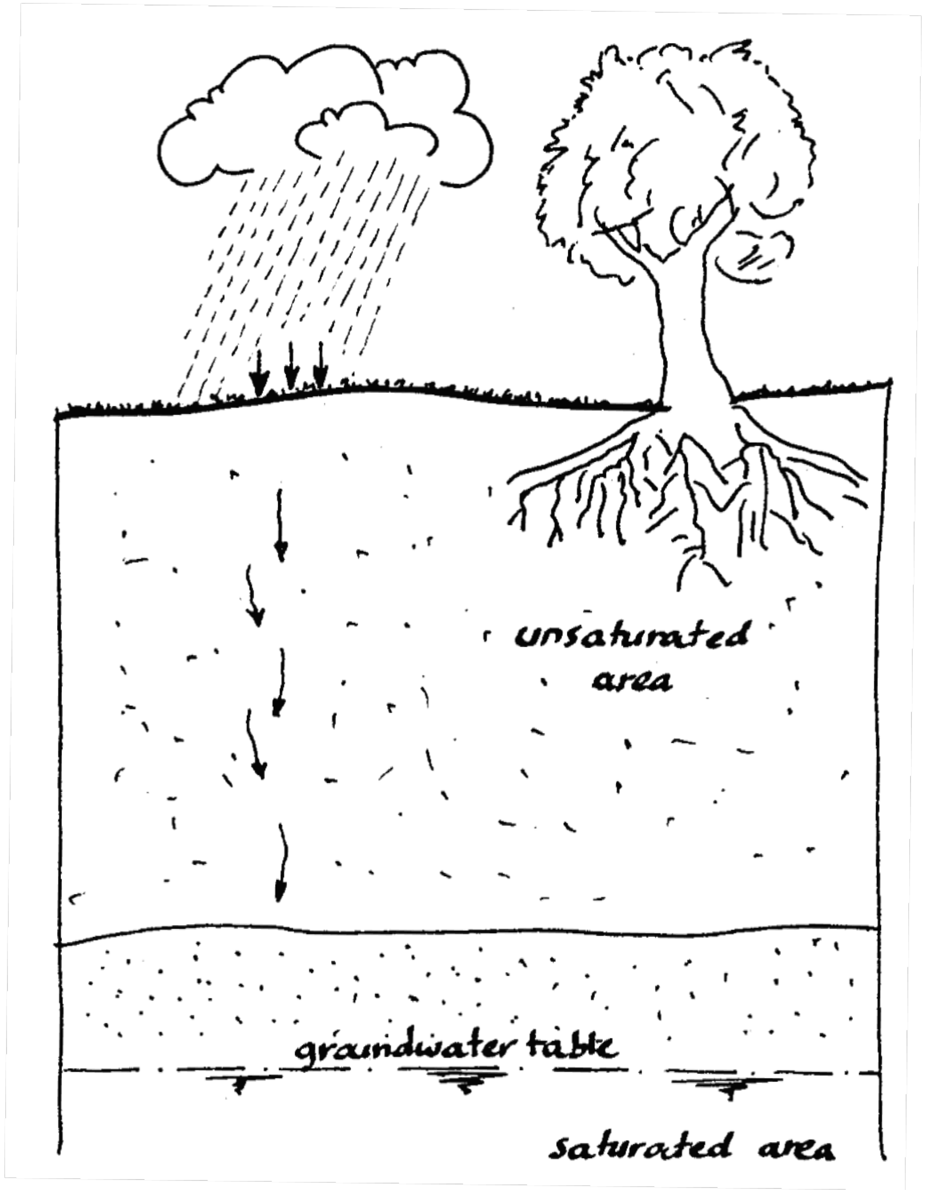
Infiltration

Definition:

Infiltration is the process of water penetrating from the ground surface into and through the soil

it depends on properties of the medium where it takes place, which are

- static/intrinsic
  - ↳ ***land/ground cover***
  - ↳ ***soil properties***
- or time variable
  - ↳ ***soil water content***



Infiltration is a flux (per unit area) → [L][T]$^{-1}$ → [mm/h], [cm/s], …

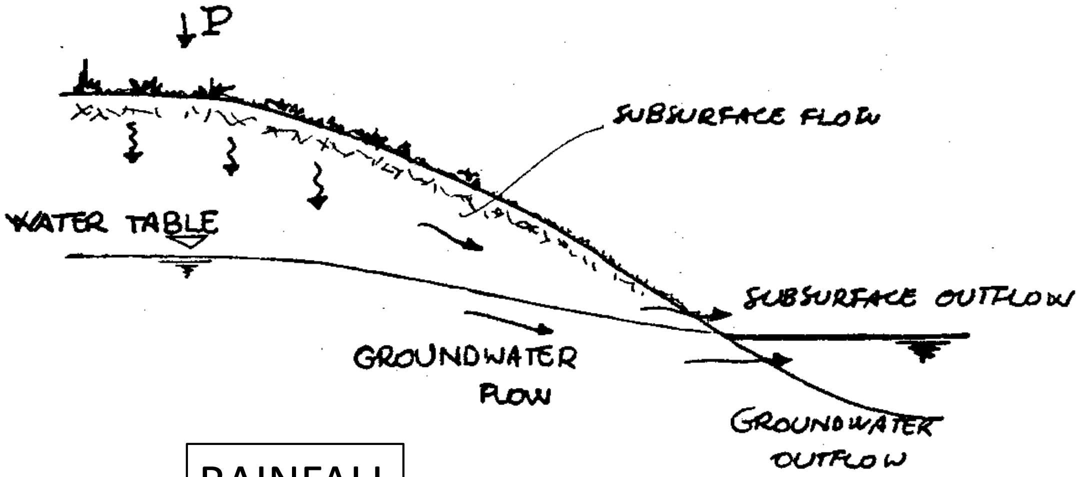
infiltration rate ←→ infiltration capacity

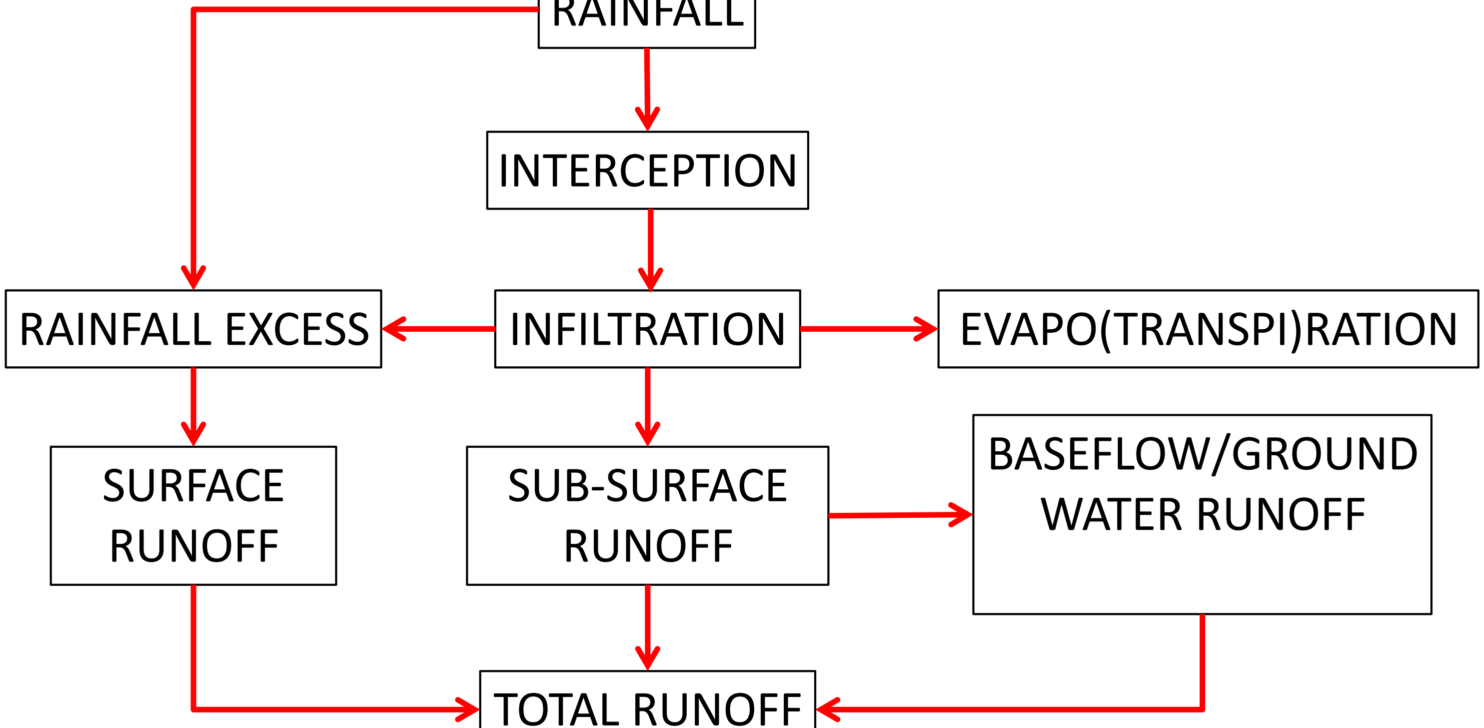
Relevance of infiltration in the transformation of rainfall into runoff

infiltration controls

↳ ***the generation of surface runoff (overland flow) by modulating the partitioning of precipitation into the three runoff components***

- surface runoff
- interflow
  (sub-surface runoff)
- baseflow
  (groundwater runoff)




RAINFALL

INTERCEPTION

RAINFALL EXCESS

INFILTRATION

EVAPO(TRANSPI)RATION

SURFACE RUNOFF

SUB-SURFACE RUNOFF

BASEFLOW/GROUND WATER RUNOFF

TOTAL RUNOFF

Infiltration controlling factors

land/ground cover controls the **permeability** *at the ground surface and below (effects of roots)*

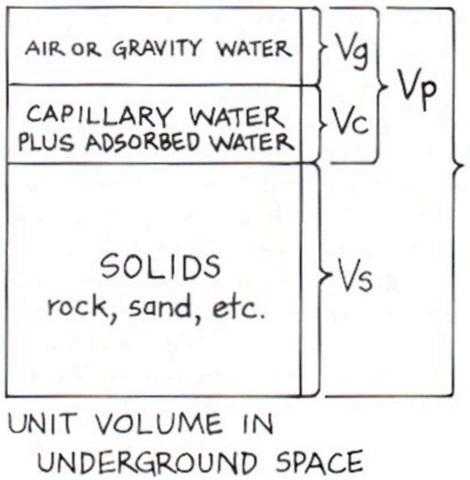
↳ i.e. controls the *ability of the soil to let water infiltrate e.g.:*

- rock → *impermeable (unless fractured)*
- bare soil →*permeability depends on soil material (sand/lime/clay), generally does NOT favour infiltration*
- vegetated cover (grassland, forest,…) → *permeable, favours infiltration*

Infiltration controlling factors

soil properties control the **permeability and the hydraulic properties** *of the porous medium, through which water flows*:

↳ ***porosity*** ------------------------------------>



WHERE: V = TOTAL VOLUME
Vs = VOLUME OF SOLIDS
Vp = VOLUME OF PORES
Vc = VOLUME OF CAPILLARY WATER PLUS ADSORBED WATER
Vg = VOLUME OF AIR AND/OR GRAVITY WATER (PORE VOLUME MINUS CAPILLARY WATER)

THEREFORE: $V = V_s + V_p$
$V_p = V_c + V_g$

AND: POROSITY $= \frac{V_p}{V}$

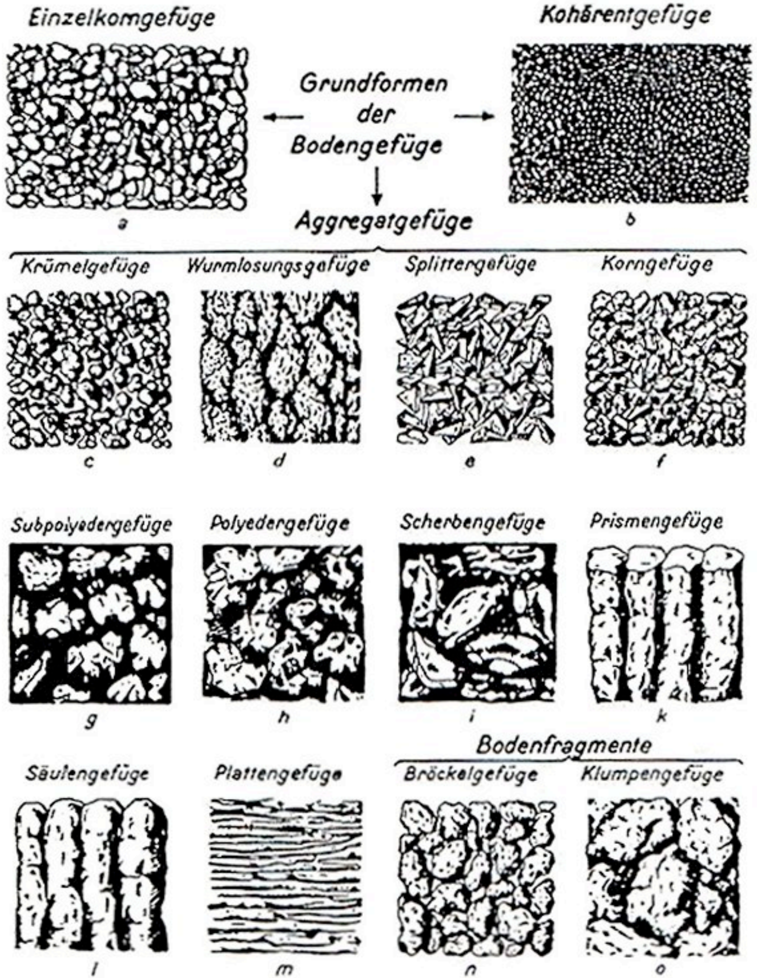
FIELD CAPACITY $= \frac{V_c}{V}$ (APPROXIMATE)

SPECIFIC RETENTION $= \frac{V_c}{V}$

SPECIFIC YIELD $= \frac{V_g}{V}$

↳ ***texture***

↳



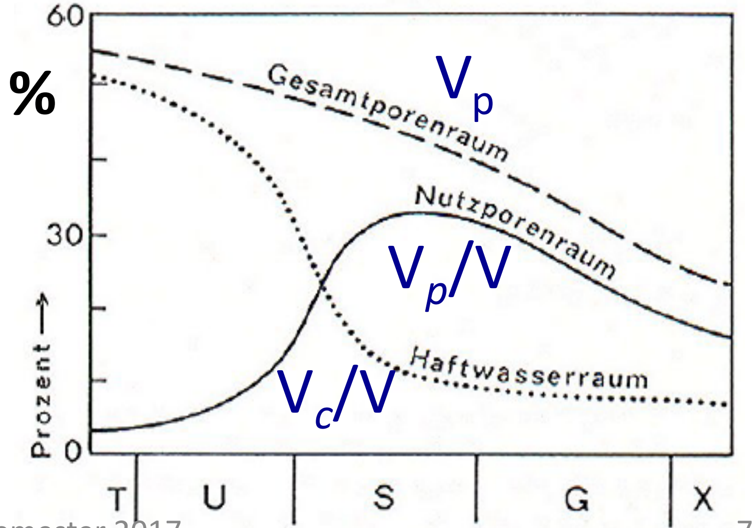
T = Clay

U = Silt

S = Sand

G = Gravel

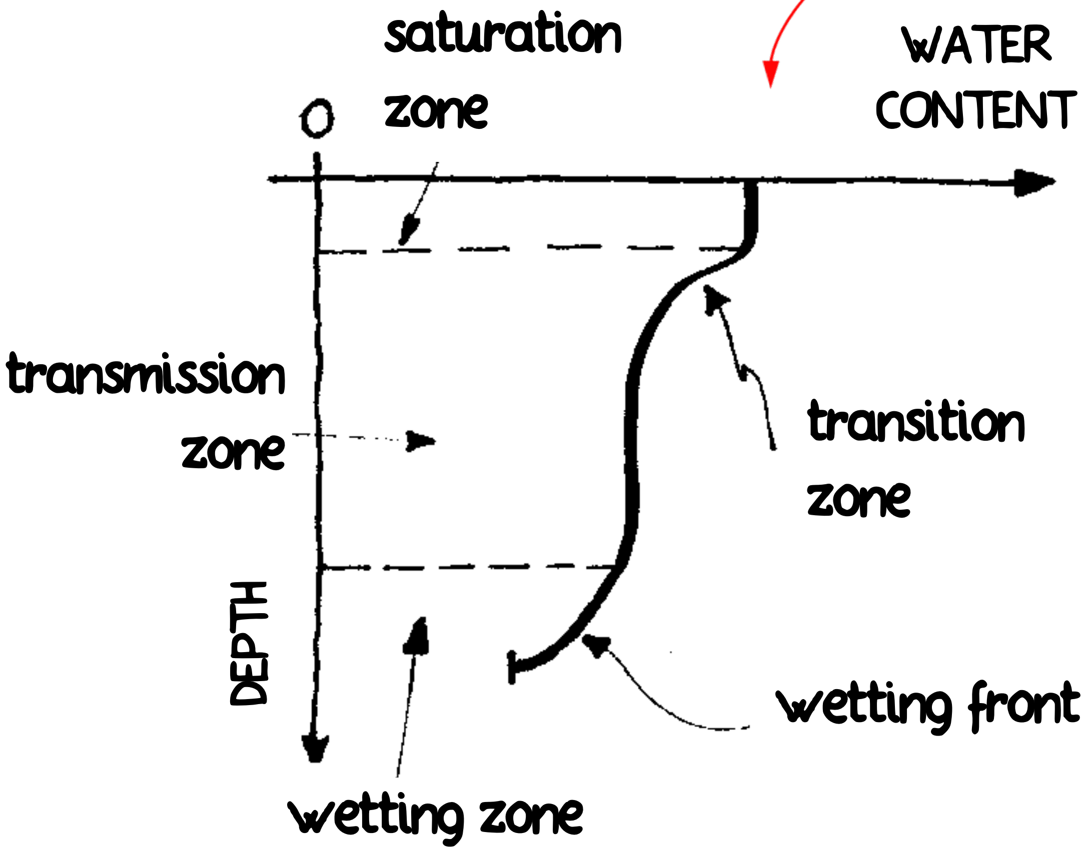
X = Pebbles



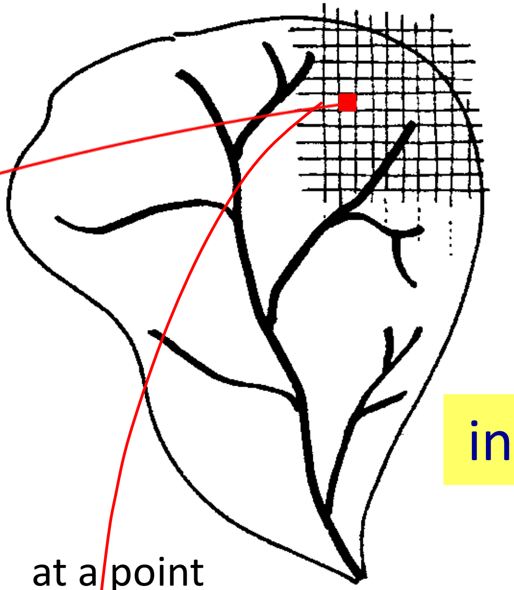
Infiltration – process characteristics

infiltration is variable

along ***the soil profile***

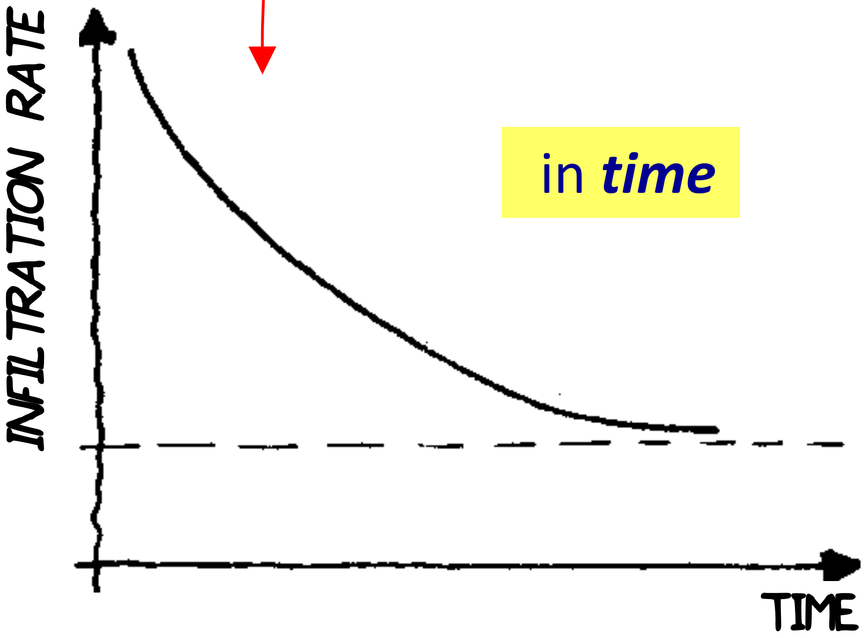


at a point
in space



in ***space***

at a point
in space



in ***time***

Measurement vs estimation of infiltration

Direct ***measurement*** of ***infiltration*** rate is carried out by means of

↳ ***infiltrometers***

↳ ***lysimeters*** *(water bal.)*

↳ ***experimental plot*** *(water bal.)*

http://en.wikipedia.org/wiki/File:Double_ring.JPG

Infiltration rate is ***estimated*** by equations, which express its temporal dynamics

↳ ***soil water content measurement*** (gravimetric sampling, tensiometers, neutron probes, time domain reflectometers)

Measurement of infiltration - Infiltrometers

Measuring principle:

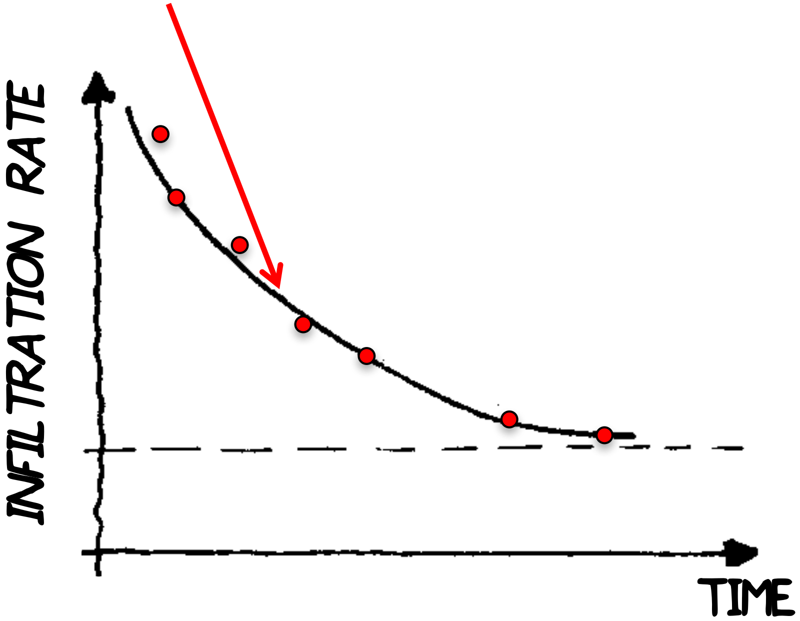
lowering of head in infiltrometer

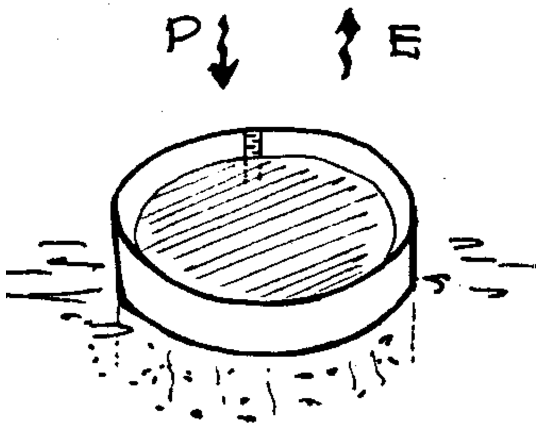
or

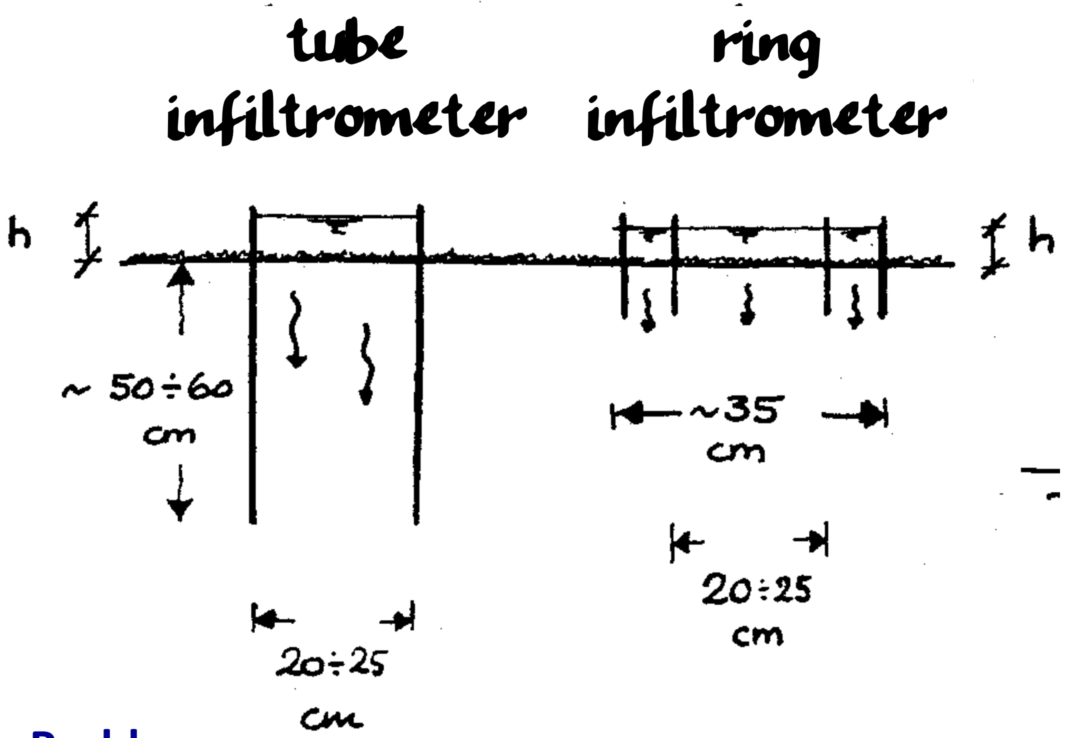
water refill to keep constant head

↓

breakthrough curve







Problems:

- *soil disturbance*
- *boundary effects*
- *lateral flow*
- *poor rainfall similitude*

Measurement of infiltration - plots

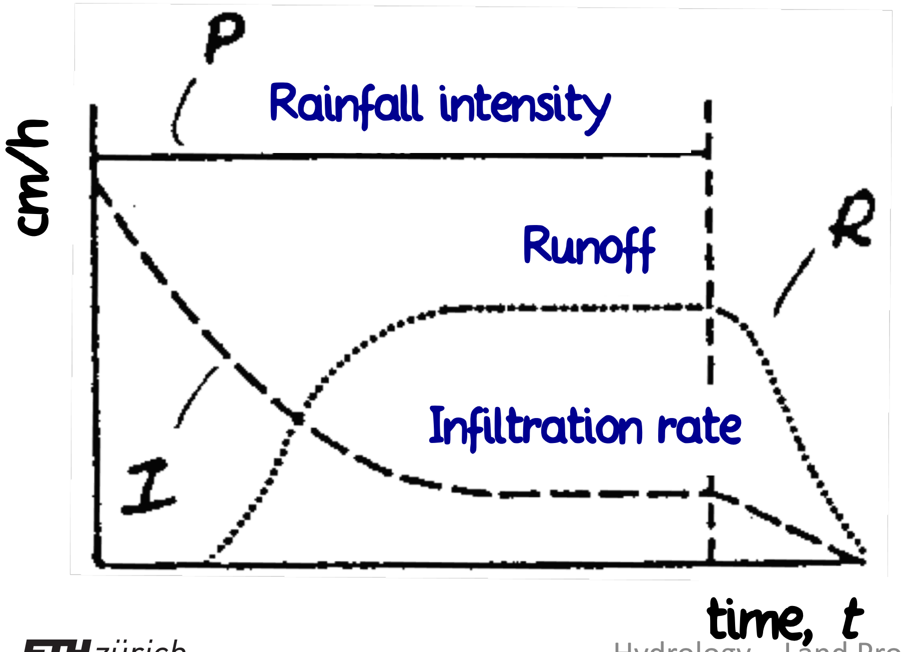
Measuring principle:

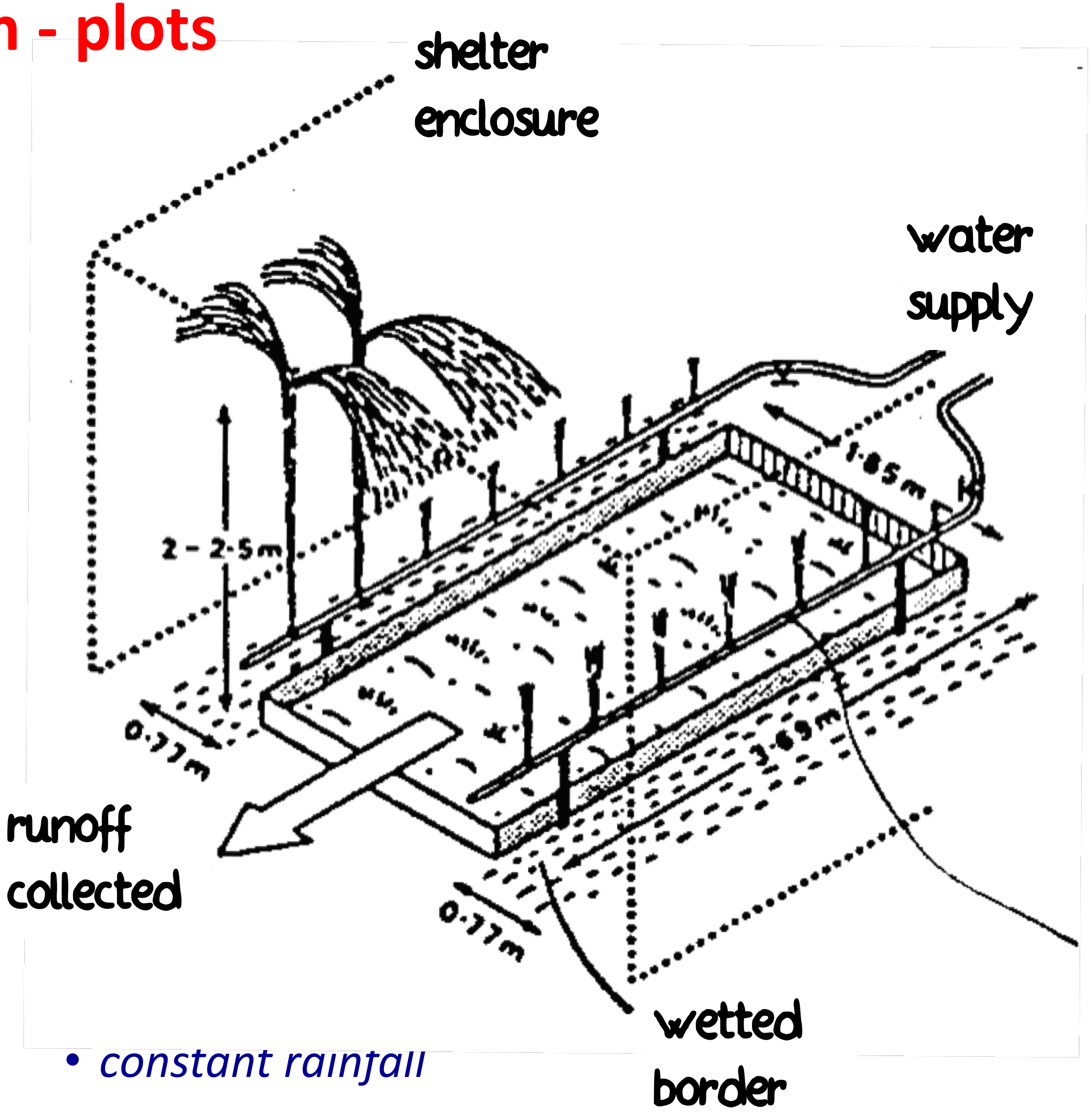
mass conservation at plot scale

🡇

water balance equation

$$I = P - R$$



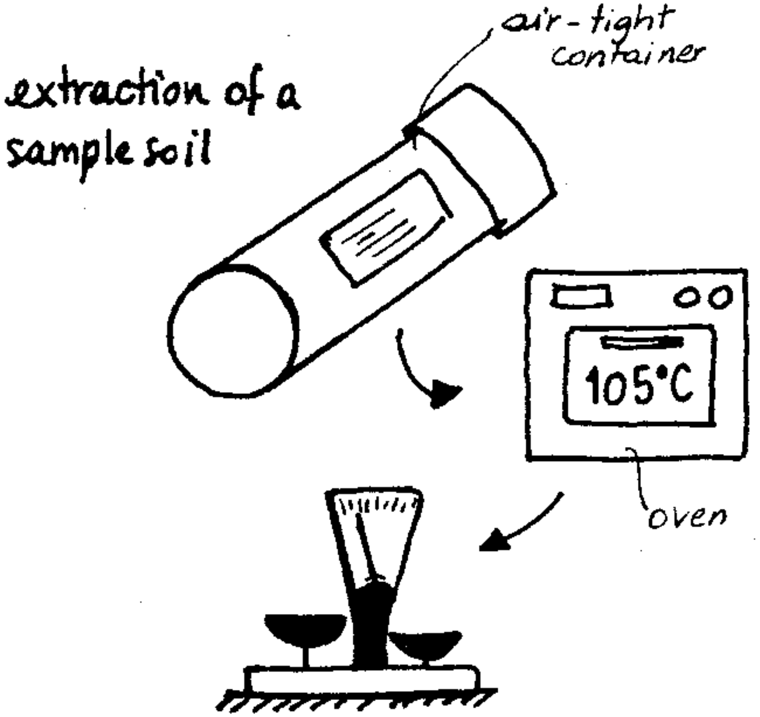


- *constant rainfall*
- *E, ET =0*

Measurement of soil water content – gravimetric sampling

Measuring technique:

- ***extraction of soil carrot in the field***
- ***lab analysis***
    - wet weighing
    - drying in oven
    - dry weighing



🡻

dry weight fraction $$M_{\text{dry}} = \frac{\text{weight of water expelled at 105°C}}{\text{overdry weight of soil}}$$

moisture volume fraction $$MVF = \frac{\text{volume of water expelled at 105°C}}{\text{volume of soil before drying}}$$

Measurement of soil water content – tensiometer

Measuring technique:

- ***water content equilibrium***

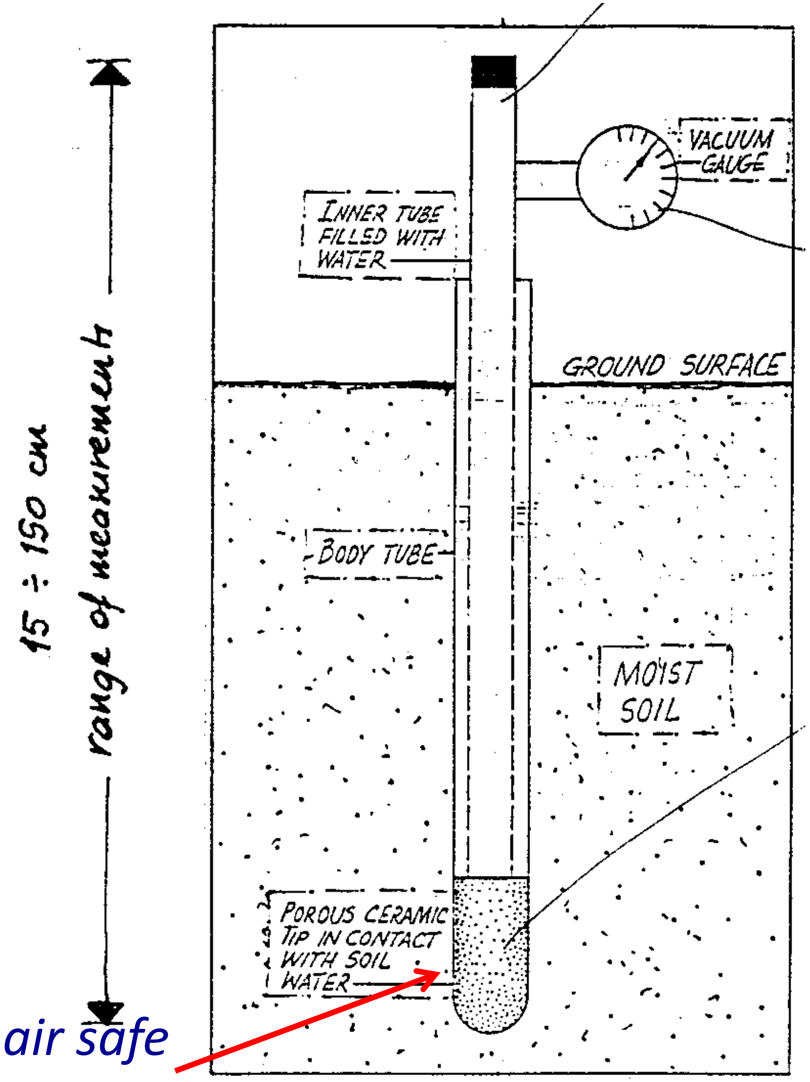
🡻

capillary flows through a porous ceramic tip from tensiometer to soil

proportional to the water content gradient

capillary flow generates a vacuum in the air safe tensiometer tube filled with water

air safe cover



vacuum range:

0.35÷0.85

[Manning, 1977]

Measurement of soil water content – neutron probe

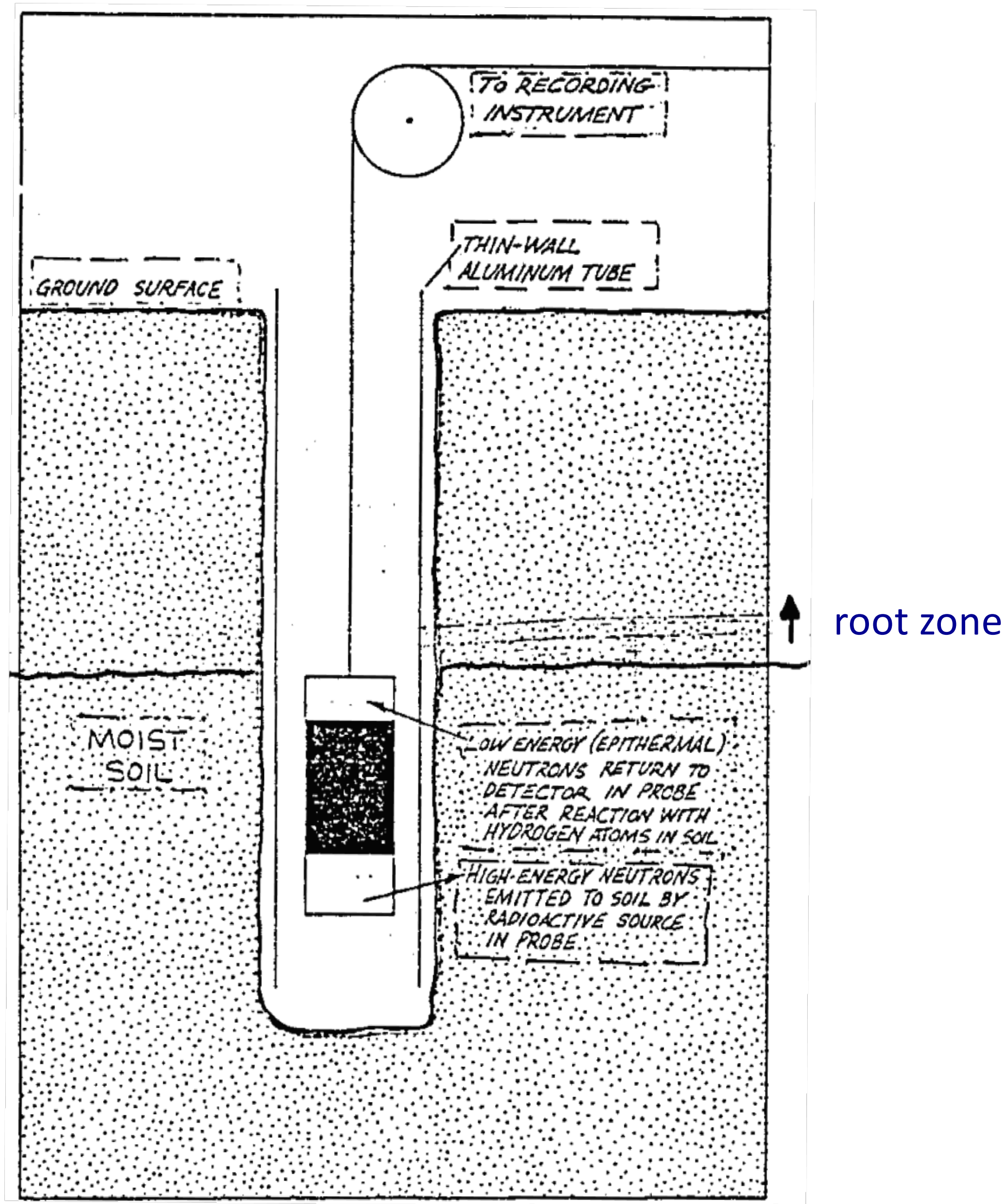
Measuring technique:

- ***attenuation of flux (or velocity) of radioactive neutrons***

↓

collision with hydrogen nuclei contained in soil water molecules

- *non disturbing measurements*
- *more accurate than tensiometers*



[Manning, 1977]

Measurement of soil water content – TDR

TDR = Time Domain Reflectometry

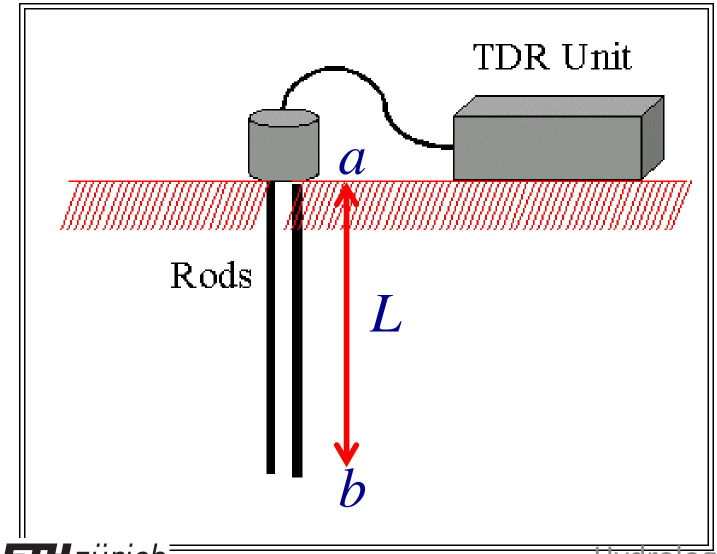
Measuring principle:

velocity of propagation of a high-frequency signal

↓

computation of the dielectric constant of the soil, which is related to its water content

water dielectric constant ≈80, solid soil components ≈2⇗7



$$K_{ab} = (c/v)^2 = (c \cdot t / 2 \cdot L)^2$$

K_{ab} = soil bulk dielectric constant

c = velocity of electromagnetic waves in vacuum ($3 \cdot 10^8$ m/s)

t = time required by the wave to travel from a to b and return (distance 2L)

©Maja Krzic, University of British Columbia, Vancouver BC

Infiltration models – theoretical framework

θ = soil water content

q = flow

- ***1D flow***
- ***continuity equation***

$$\frac{\partial\theta}{\partial t}+\frac{\partial q}{\partial z}=0$$

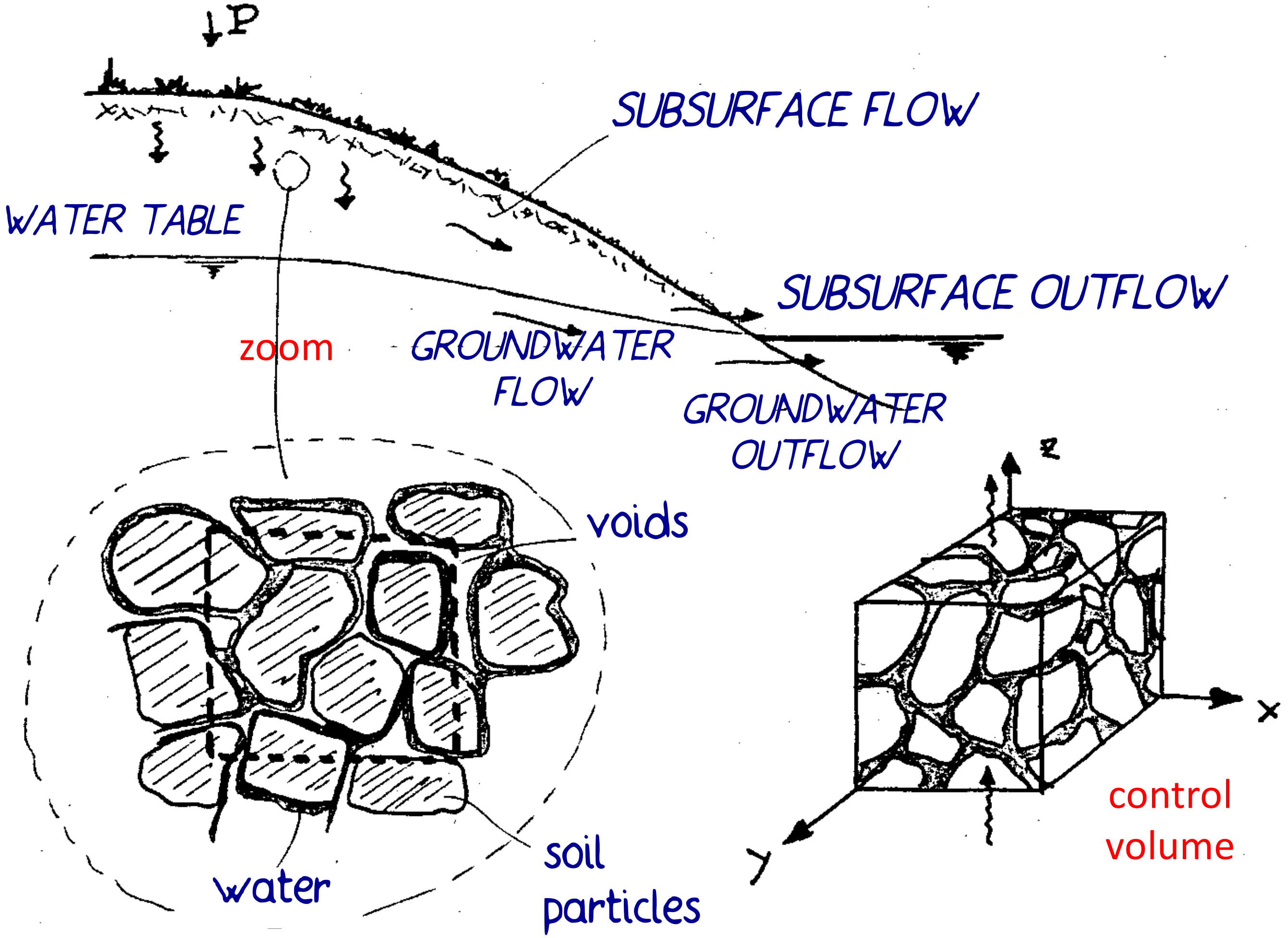
- ***momentum equation***

$$q=-\left(K+D\frac{\partial\theta}{\partial z}\right)$$

↓

Richards' equation

$$\boxed{\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial z}\left(D\frac{\partial\theta}{\partial z}+K\right)}$$



where:

- K = *hydraulic conductivity* [L][T]$^{-1}$
- D = *soil water diffusivity* = $K\cdot d\Psi/d\theta$ [L]^2[T]$^{-1}$
- Ψ = *suction head* [L]

↳ governing equation for 1D unsteady unsaturated flow in a porous medium [Richards, 1931]

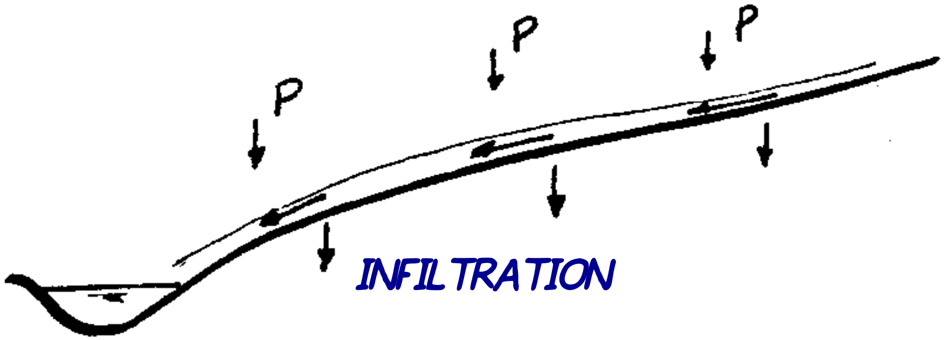
Infiltration models – runoff generation mechanisms

- ***Hortonian mechanism***

  → ***infiltration excess***

  - runoff generation occurs when the ***rainfall rate exceeds*** the ***infiltration capacity*** (rate)

more frequent
- in arid and semiarid environments
- where vegetation coverage is limited



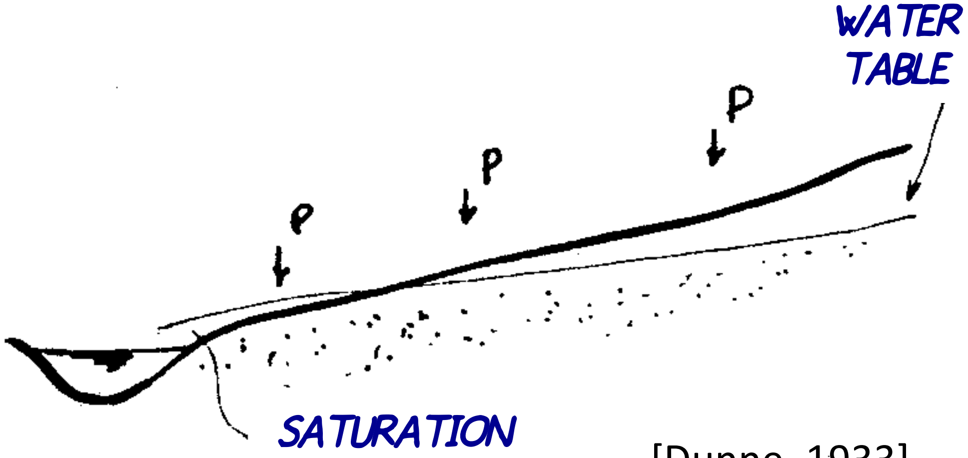
[Horton, 1933]

- ***Dunnian mechanism***

  → ***saturation excess***

  - runoff generation occurs when ***the unsaturated zone becomes saturated*** and the soil does not allow any infiltration

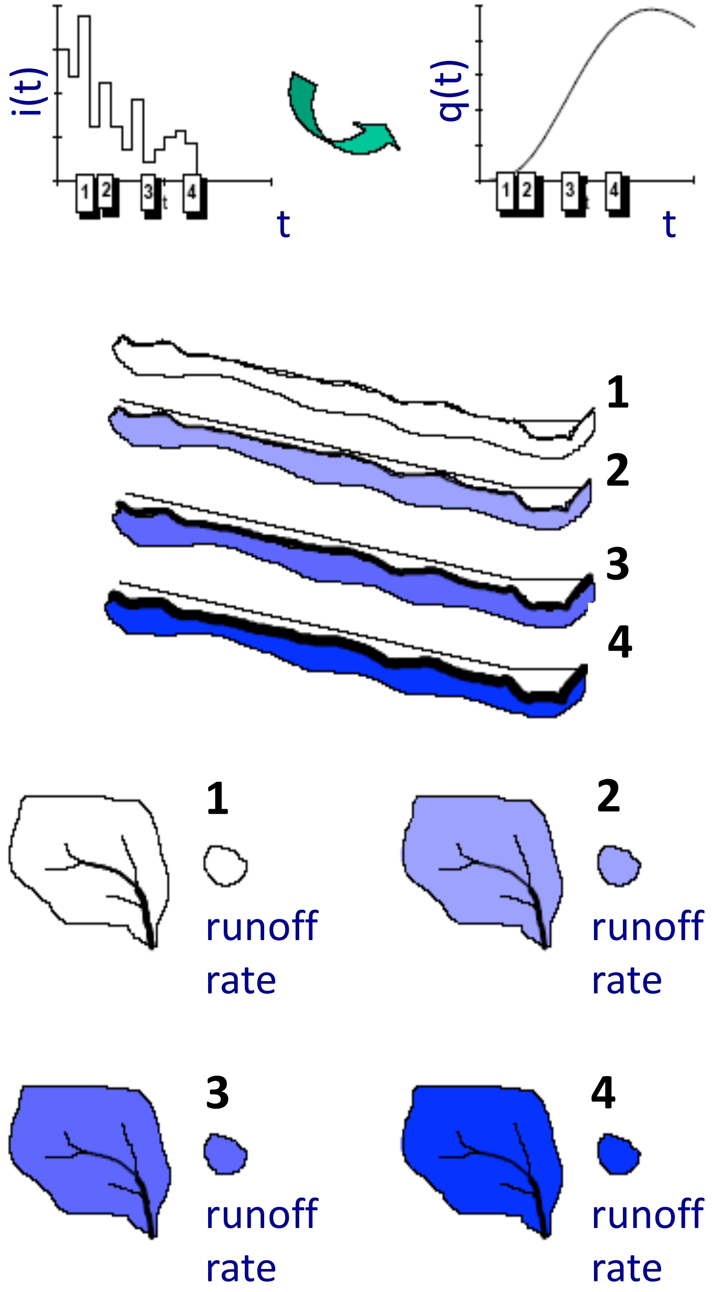
more frequent
- in humid environments
- where vegetation coverage is rich



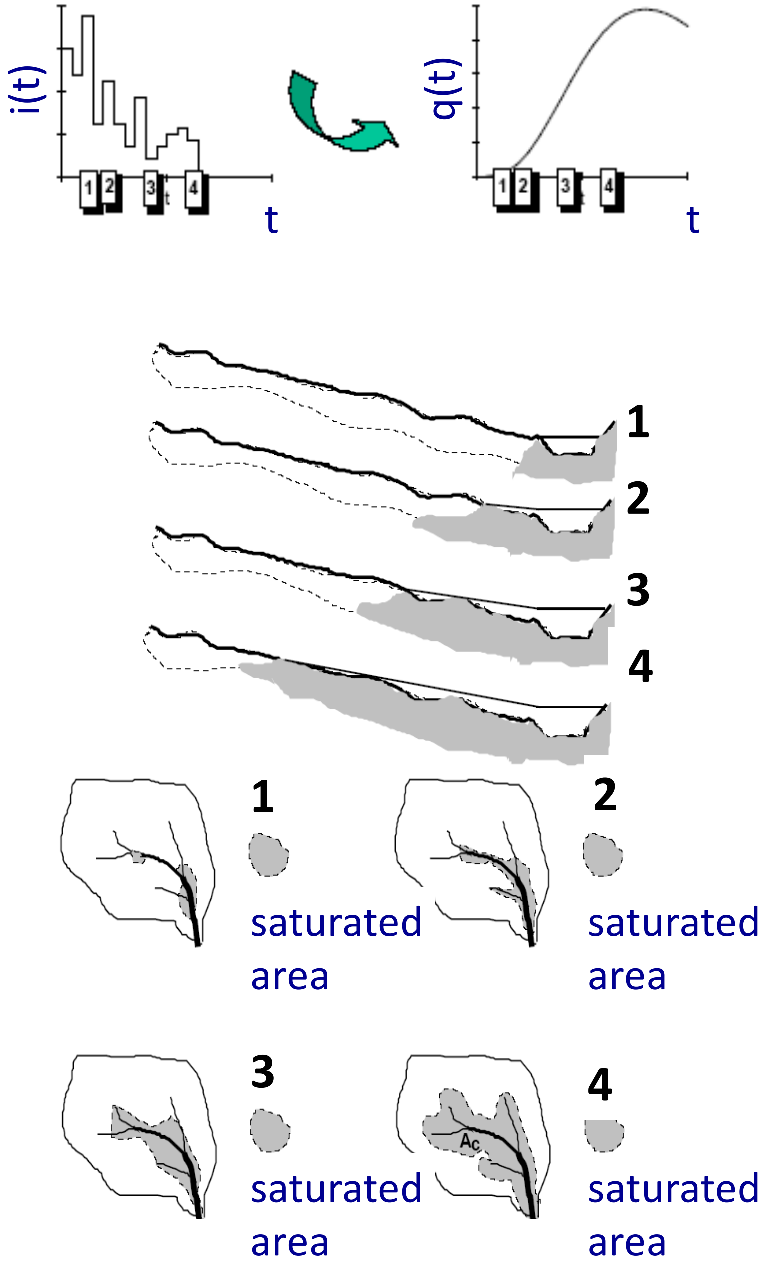
[Dunne, 1933]

Infiltration models – infiltration excess vs saturation excess

infiltration excess



saturation excess



Infiltration models – physically based vs empirical/conceptual models

Physically based models

Richards' equation

$$\boxed{\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(D \frac{\partial \theta}{\partial z} + K \right)}$$

numerical solution only

where:

- $K = K(\theta)$, $D = D(\theta)$

simplified physically based models → K , D = constant → Green-Ampt model (1911)

(analytical solutions) → K = constant, $D = D(\theta)$ → Philip's model (1957, 1969)

Empirical / conceptual models

- *derived from empirical investigations (e.g. Horton equation)*
- *based on conceptualisation*
  - e.g. storage + infiltration excess → *CN method*
  - e.g. constant infiltration rate → *Φ index*
  - e.g. infiltration rate variable and proportional to rainfall rate → *percentage method*

Infiltration models – Horton‘s equation

Horton’s equation was developed in the 1930’s from repeated observation of infiltrometer tests

Its shape reflects essentially the experimental breakthrough curve

Can be obtained integrating Richards’ equation for z= surface and K, D = constant

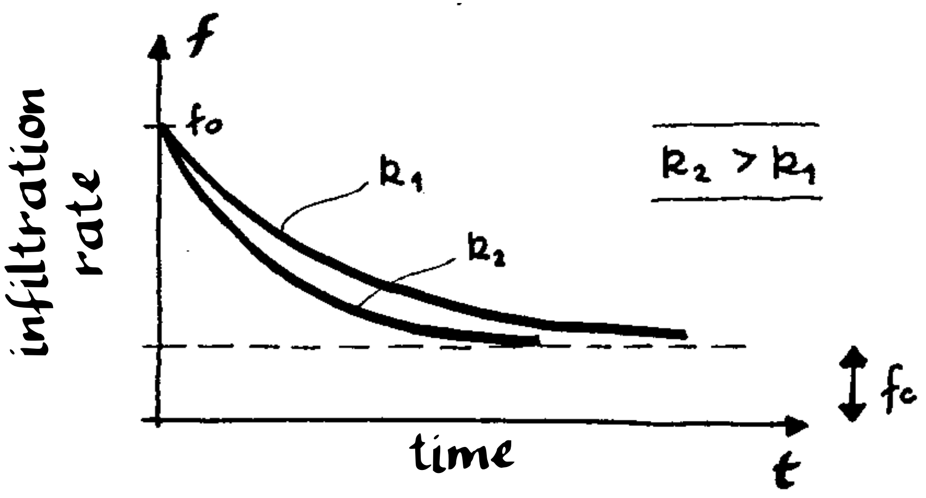
$$\Downarrow$$

$$-\frac{df}{dt} = k\left(f - f_c\right)$$

$$\Downarrow$$

$t = 0$ → $f=f_0$ → the ***infiltration rate*** f(t) is:

$$\boxed{f(t) = f_c + \left(f_0 - f_c\right)e^{-kt}}$$



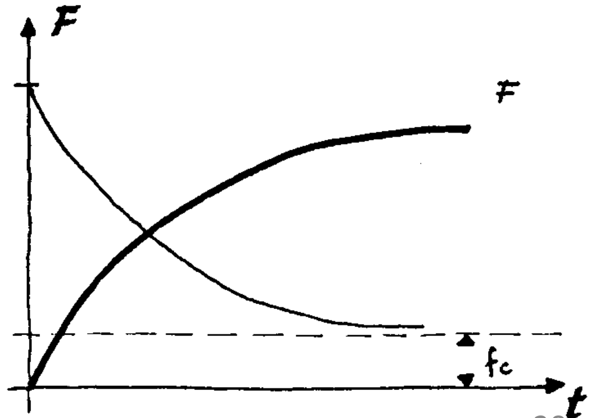
where k = decay constant $[T]^{-1}$ f_0 = infiltration rate at t=0

f_c = (saturated) infiltration rate at $t=\infty$

↳≈ K_s, saturated hydraulic conductivity

Cumulative infiltration (volume) →

$$F(t) = f_c t + \frac{\left(f_0 - f_c\right)}{k}\left(1 - e^{-kt}\right)$$



Infiltration models – Soil Conservation Service Curve Number (SCS-CN)

Conceptual model combining infiltration and saturation excess

Hypothesis: the ratio between ***actual, F,*** and ***potential, S, soil water content*** is equal to the ratio between ***actual, P_e***, and ***potential, P***, *runoff*

↓

$$\frac{F}{S} = \frac{P_e}{P - I_a} \quad (\bullet)$$

- if no infiltration is possible → *runoff = gross rainfall*
- with infiltration → *runoff = net rainfall*

where P = gross rainfall, P_e = ***rainfall excess*** → fraction of rainfall not infiltrated → ***net rainfall***

I_a = ***initial abstraction*** → water stored in depression storages

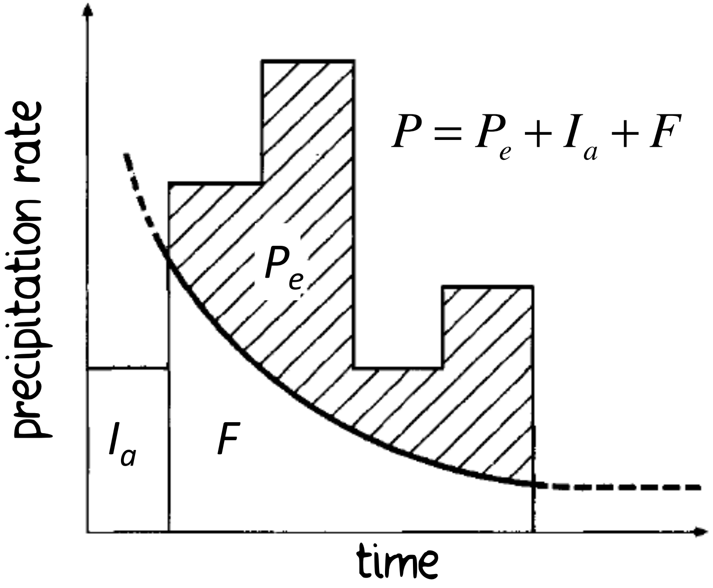
Obeying continuity $P = P_e + I_a + F \quad (\bullet\bullet)$

↓ (•) + (••)

$$P_e = \frac{(P - I_a)^2}{P - I_a + S} \quad (\bullet\bullet\bullet)$$

P_e = cumulative net rainfall

If $I_a = \alpha S$, (•••) is only **function of the parameter *S***



S is ***parameterised*** on the basis of ***hydrologic soil type***
land cover → ***CN***

Infiltration models – Soil Conservation Service Curve Number (SCS-CN)

S is ***parameterised*** through the ***Curve Number, CN***

$$S = S_0\left(\frac{100}{CN} - 1\right)$$ ①

S_o = 254 → S [mm]

CN is ***function of***

- ***hydrologic soil type***
- ***land cover***

→ ***CN tables***

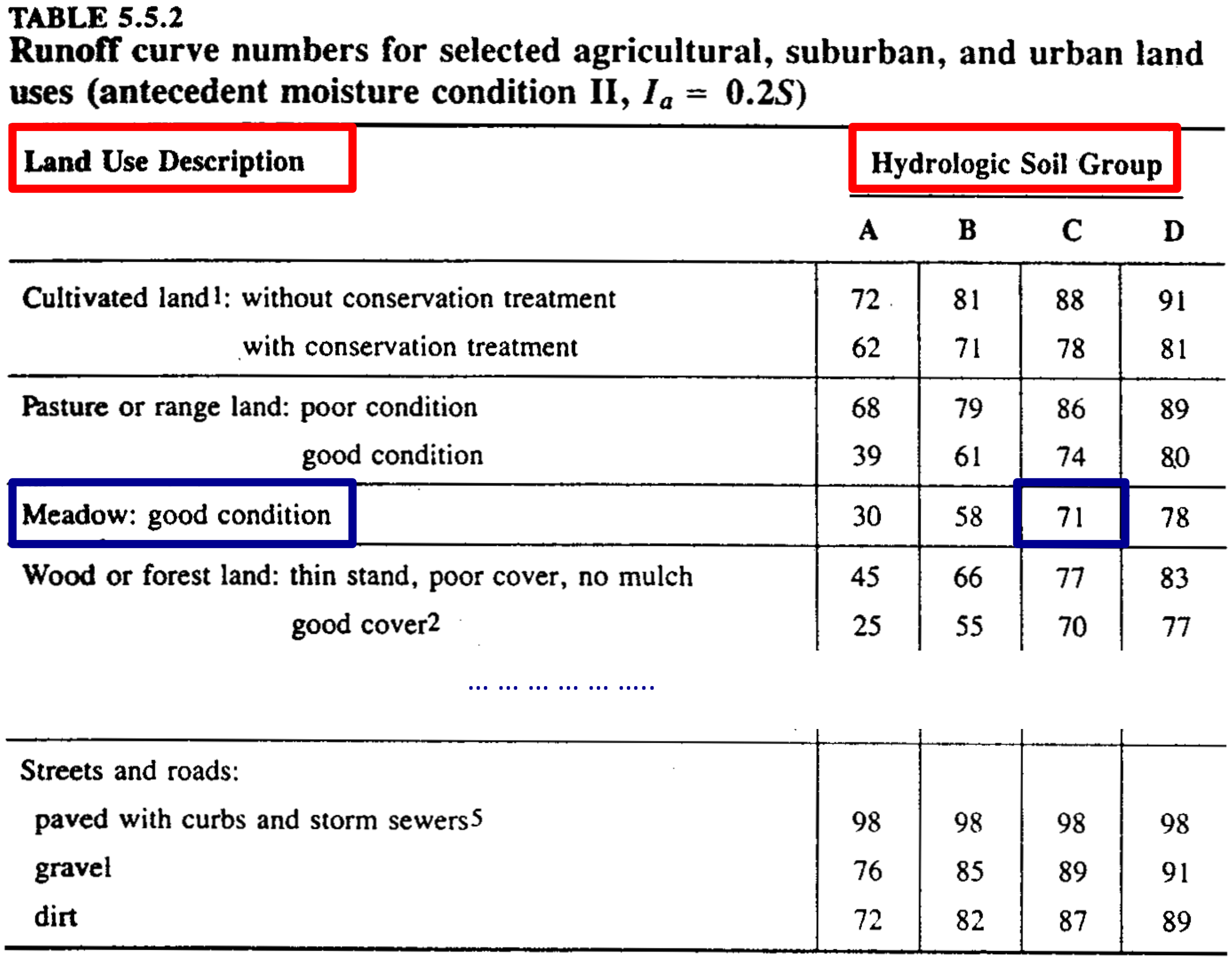


TABLE 5.5.2

Runoff curve numbers for selected agricultural, suburban, and urban land uses (antecedent moisture condition II, $I_a = 0.2S$)

Land Use Description	**Hydrologic Soil Group**			
	A	**B**	**C**	**D**
Cultivated land[1]: without conservation treatment	72	81	88	91
with conservation treatment	62	71	78	81
Pasture or range land: poor condition	68	79	86	89
good condition	39	61	74	80
Meadow: good condition	30	58	71	78
Wood or forest land: thin stand, poor cover, no mulch	45	66	77	83
good cover[2]	25	55	70	77

… … … … … …..

Streets and roads:				
paved with curbs and storm sewers[5]	98	98	98	98
gravel	76	85	89	91
dirt	72	82	87	89

① takes minimum value = 0
for **CN = 100**

takes max. theoretical value = ∞
for **CN = 0**

Example:

- Land use
  - ***meadow***
- Hydrologic Soil Type
  - ***moderatly permeable → C***

→ ***CN = 71***

Infiltration models – SCS-CN hydrologic soil types and AMC

Hydrologic Soil Type	Description	Permeability
A	Deep sand, deep loess, aggregated silts	very high
B	Shallow loess, sandy loam	high
C	Clay loams, shallow sandy loam, soils low in organic content, and soils usually high in clay	moderate
D	Soils that swell significantly when wet, heavy plastic clays, and certain saline soils	low

Infiltration models – SCS-CN and AMC

AMC = Antecedent Moisture Conditions

To account for the **temporal variability of the storage** *due to the temporal dynamics of the soil water content (effect of drainage and ET), the table values of CN can be* **converted** *to two* **ANTECEDENT MOISTURE CONDITIONS**

normal conditions (AMC II) → **tables**

dry conditions (AMC I) → $CN_I = \dfrac{4.2 CN_{II}}{10 - 0.058 CN_{II}}$

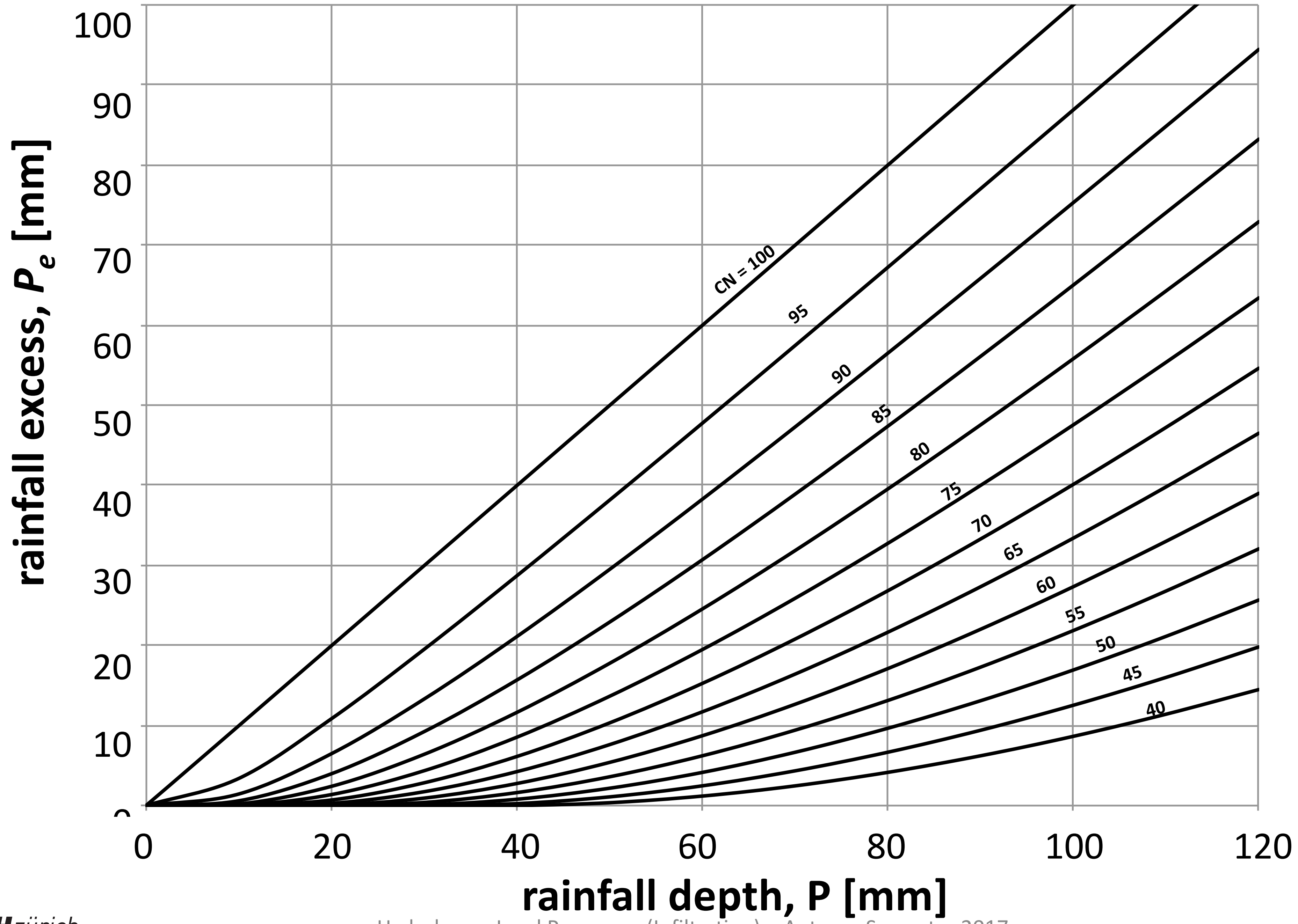
wet conditions (AMC III) → $CN_{III} = \dfrac{23 CN_{II}}{10 + 0.13 CN_{II}}$

AMC conditions *are* **classified** *on the basis of the vegetation activity*

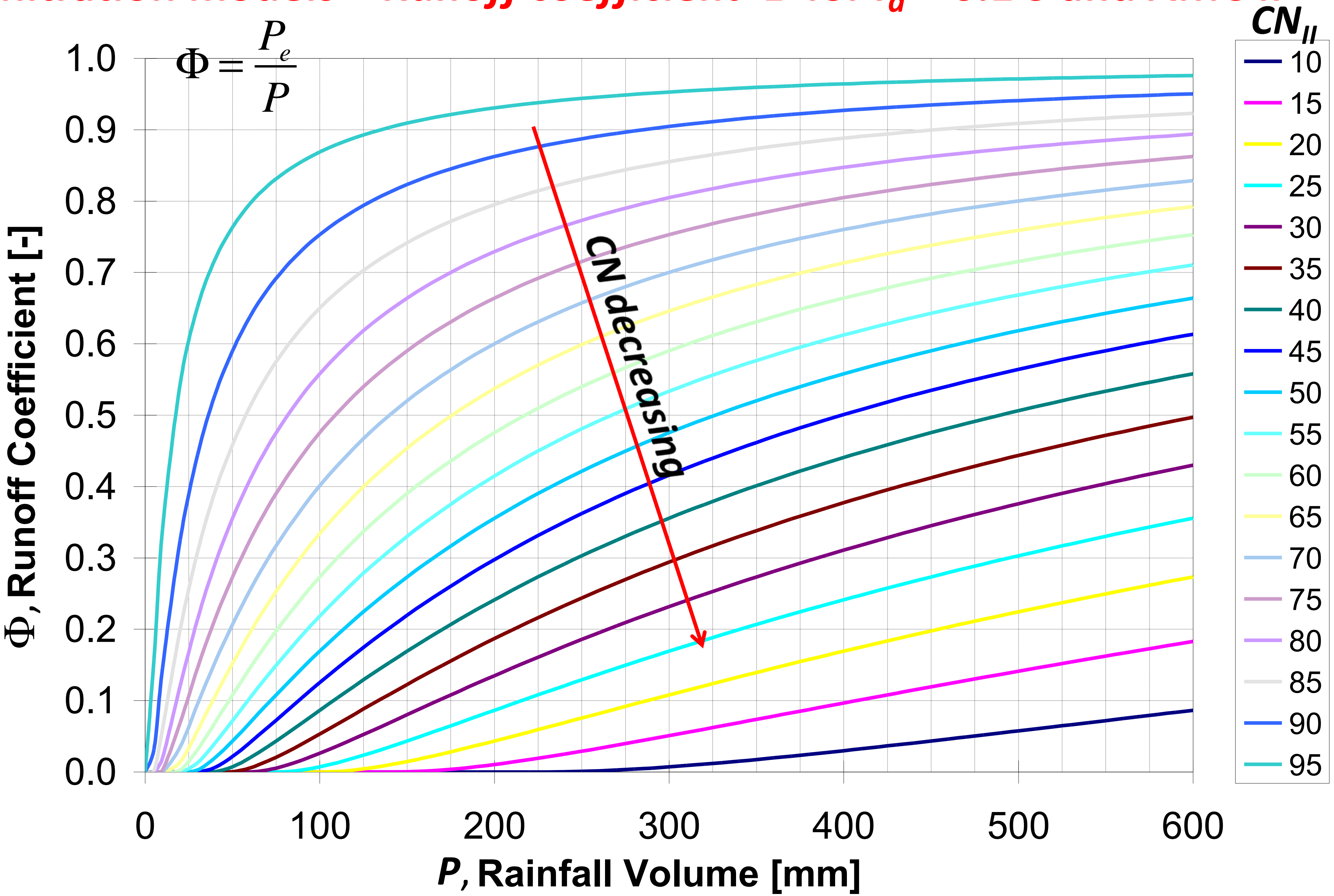
☞

	TOTAL 5-DAY ANTECEDENT RAINFALL, P [mm]	
AMC GROUP	*dormant season*	*growing season*
I	< 12.7	< 35.6
II	12.7 ≤ P ≤ 27.9	35.6 ≤ P ≤ 53.3
III	> 27.9	> 53.3

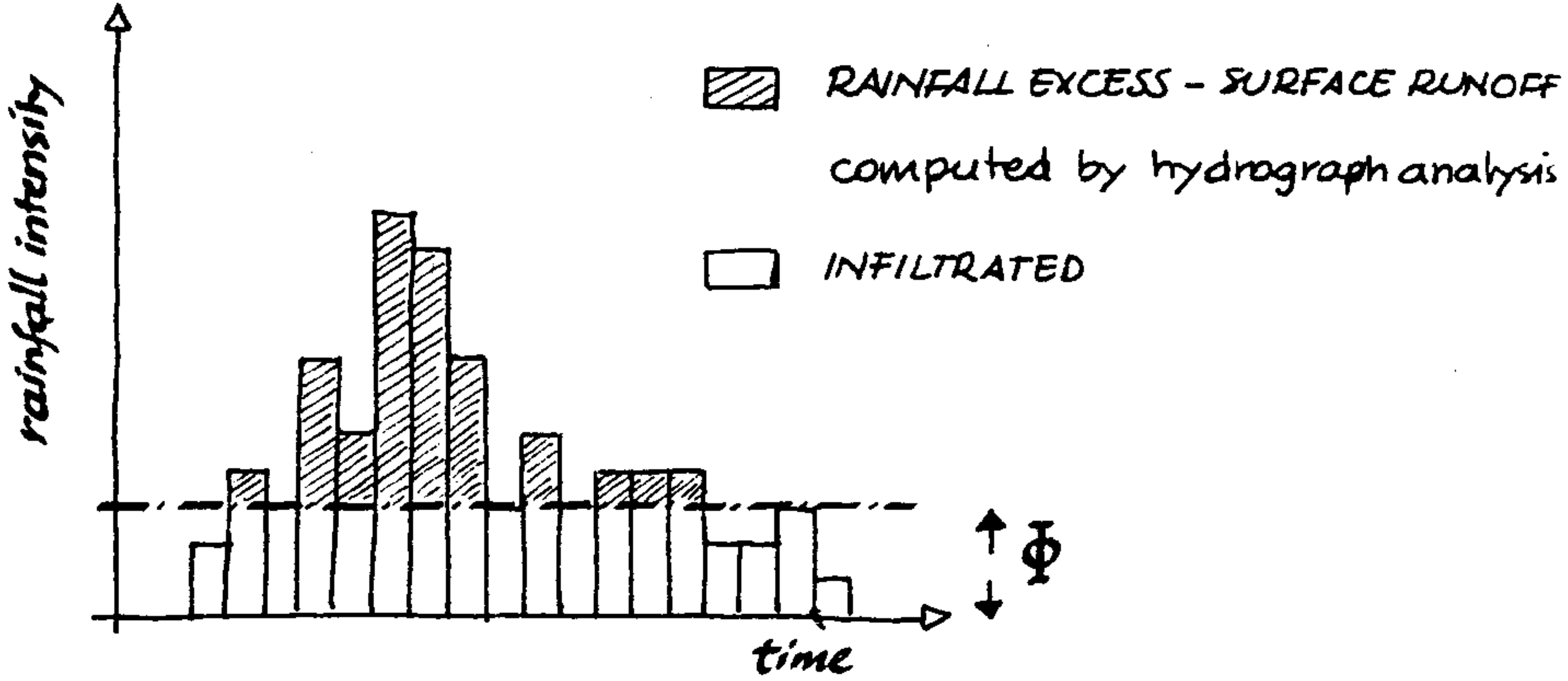
Infiltration models – P_e vs P template for I_a = 0.1 S and AMC II



Infiltration models – *Runoff coefficient* Φ for I_a = 0.1 S and AMC II

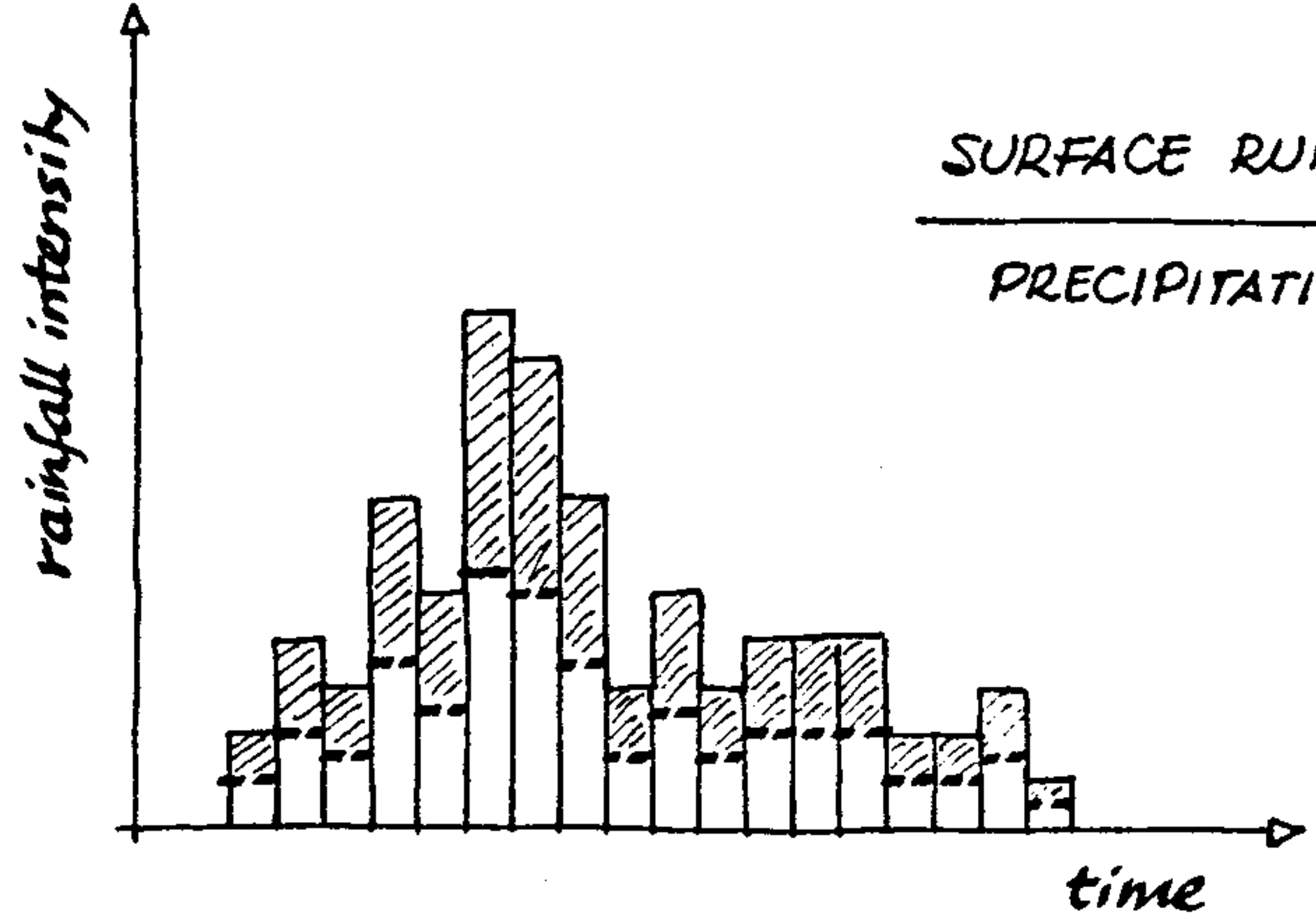


Infiltration models – Φ-index method



Φ INDEX = AVERAGE RAINFALL INTENSITY FOR WHICH RAINFALL EXCESS EQUALS SURFACE RUNOFF

Infiltration models – Percentage method



$$\frac{\text{SURFACE RUNOFF}}{\text{PRECIPITATION}} = \alpha$$

RAINFALL EXCESS $i_N = \alpha i$ ▨

INFILTRATION RATE $f = (1-\alpha) i$ ☐

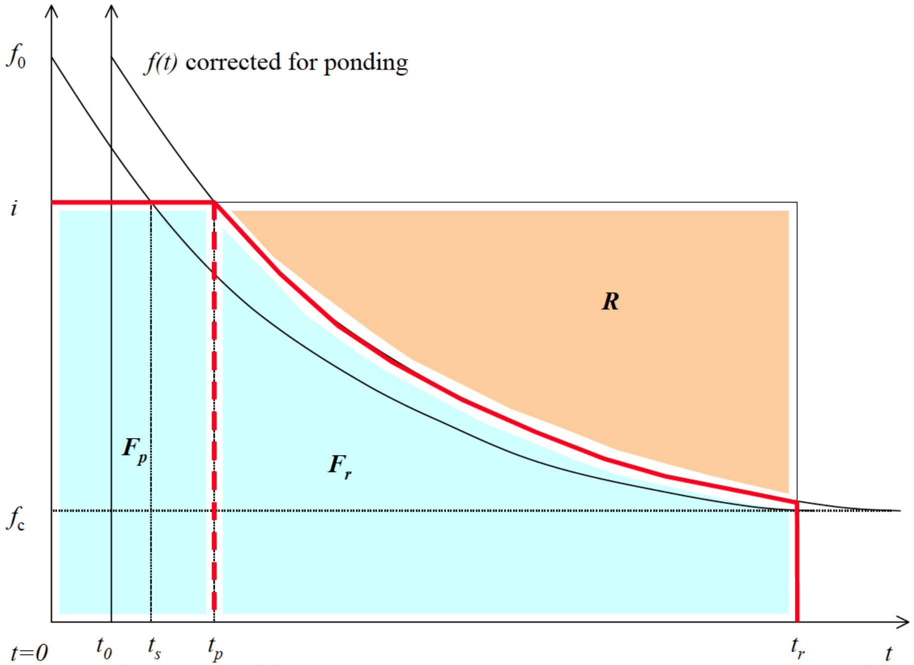
Ponding time (1)

The infiltration rate provided by Horton's equation (and by some other equations derived from Richards' eq.) is a ***potential infiltration rate*** → i.e. considering that water is continuously available at the surface → all water available for infiltration infiltrates.

We have to account for this condition when applying the model to determine rainfall excess (net rainfall) → ***ponding time, t_p = elapsed time between the beginning of rainfall and the instant that water begins to pond on the soil surface***, i.e. ponding begins

↳ $t < t_p$ → $i < f(t)$ → no rainfall excess; $t = t_p$ → $i = f(t)$ → ponding; $t > t_p$ → $i > f(t)$ → rainfall excess

→ *Horton's infiltration curve needs to be corrected for ponding*



The correction is obtained by shifting the (potential) infiltration curve by a time t_0 which is computed such that

$$P = \int_0^{t_p} i(t)\,dt = \int_{t_0}^{t_p} f(t - t_0)\,dt = F$$

P = cum. rainfall, F_p = cum. infiltration

Ponding time (2)

To shift the curve by t_0 :

1) **compute ponding under potential infiltration conditions**

↳ $i = f(t_s)$ ○ → compute t_s

↳ compute $F(t_s)$ = *cumulated amount of infiltrated water that would lead to ponding under potential infiltration conditions*

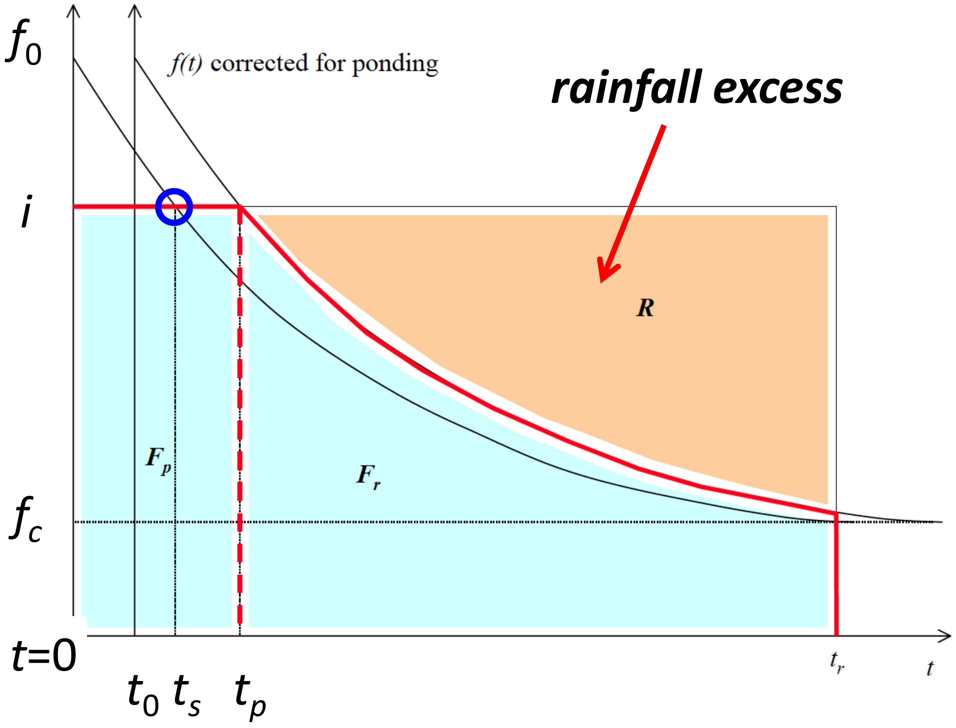
2) **compute the actual ponding time** by imposing $i \cdot t_p = F_p$

↳ $F(t_s) = F_p = i \cdot t_p \rightarrow t_p = \ldots$

↳ $t_p > t_s$ if $i < f_0$

3) **shift the curve** to account for $t_p > t_s$ using the condition

↳ $t_p - t_0 = t_s - 0 \rightarrow t_0 = t_p - t_s$ with t_s computed from step 1)



rainfall excess

For constant rainfall rate:

$$t_s = \frac{1}{k}\ln\left(\frac{f_0 - f_c}{i - f_c}\right)$$

$$t_p = \boxed{\frac{1}{i\,k}[f_0 - i + f_c \ln(\frac{f_0 - f_c}{i - f_c})]}$$

↳ $F_p = F(t_s)$

$$t_0 = t_p - \frac{1}{k}\ln\left(\frac{f_0 - f_c}{i - f_c}\right)$$

Horton‘s equation (summary + ponding)

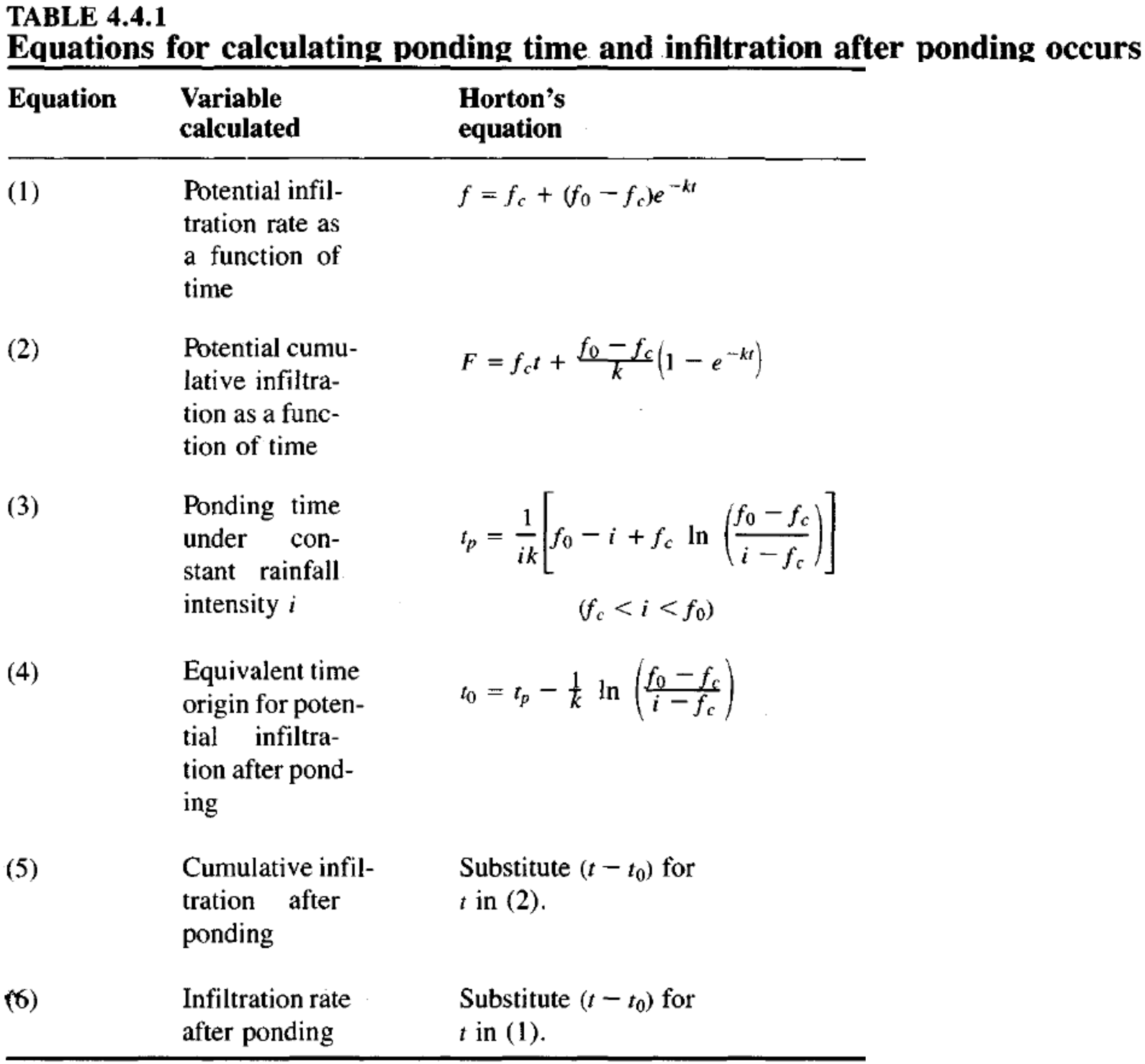


TABLE 4.4.1

Equations for calculating ponding time and infiltration after ponding occurs

Equation	Variable calculated	Horton's equation
(1)	Potential infiltration rate as a function of time	$f = f_c + (f_0 - f_c)e^{-kt}$
(2)	Potential cumulative infiltration as a function of time	$F = f_c t + \frac{f_0 - f_c}{k}\left(1 - e^{-kt}\right)$
(3)	Ponding time under constant rainfall intensity i	$t_p = \frac{1}{ik}\left[f_0 - i + f_c \ln\left(\frac{f_0 - f_c}{i - f_c}\right)\right]$ $(f_c < i < f_0)$
(4)	Equivalent time origin for potential infiltration after ponding	$t_0 = t_p - \frac{1}{k} \ln\left(\frac{f_0 - f_c}{i - f_c}\right)$
(5)	Cumulative infiltration after ponding	Substitute $(t - t_0)$ for t in (2).
(6)	Infiltration rate after ponding	Substitute $(t - t_0)$ for t in (1).

Infiltration

example of application of knowledge

Engineering Problem:

↳ *Design of flood protection structure → estimate the amount of surface runoff generated by a given area/catchment to determine the flood volume to be stored by an artificial polder*

Solution

↳ *Compute the rainfall excess volume for the design rainfall event (e.g. obtained from a DDF for the design return period and rainfall duration)*

Method

↳ *e.g. SCS-CN*