Water management in urban areas

Processes 1

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12-2-2009

Content

- Urban climate
- Urban water balance
- Precipitation
- Evapotranspiration
- Groundwater
- Subsidence

Urban climate

The external driving force

- Precipitation
- Radiation
- Wind
- Temperature
- etc…

Urban climate

Deviation with the city's surrounding

- Higher concentrations of various aerosols
  - Clouds / fog
  - Dust particles
  - Air pollution / smog

⇨
- More heavy showers
- Less hours of sunshine

- Urban heat island
  - Low albedo
  - Limited evapotranspiration
  - Large heat capacity of buildings
  - Waste heat of energy usage

⇨
- Higher temperatures

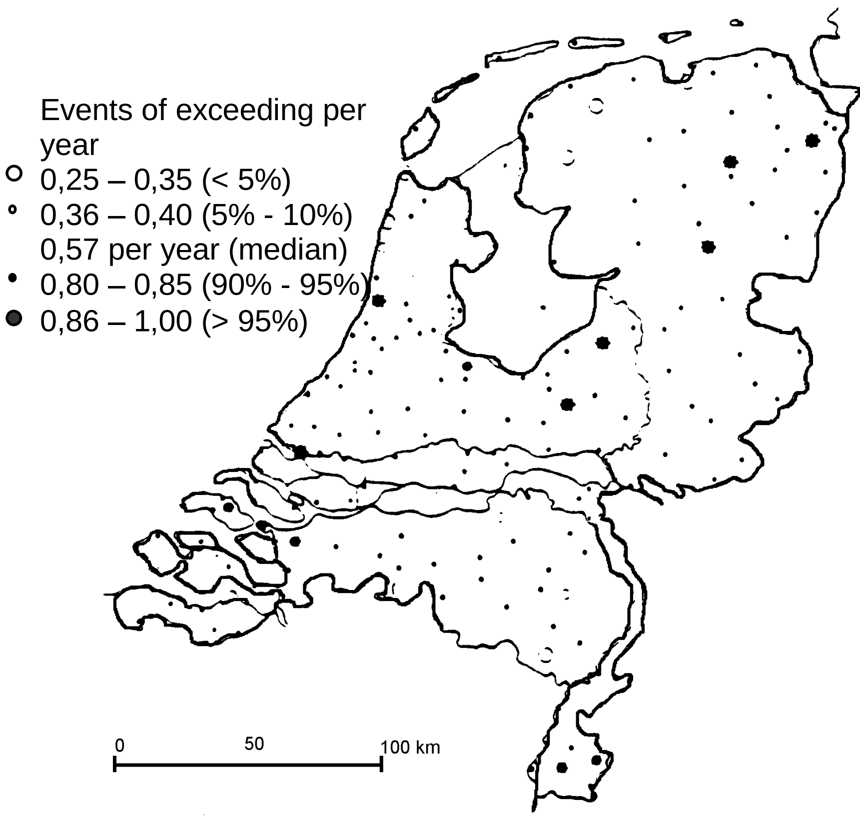
- Effects are relative to agglomeration size

Urban climate

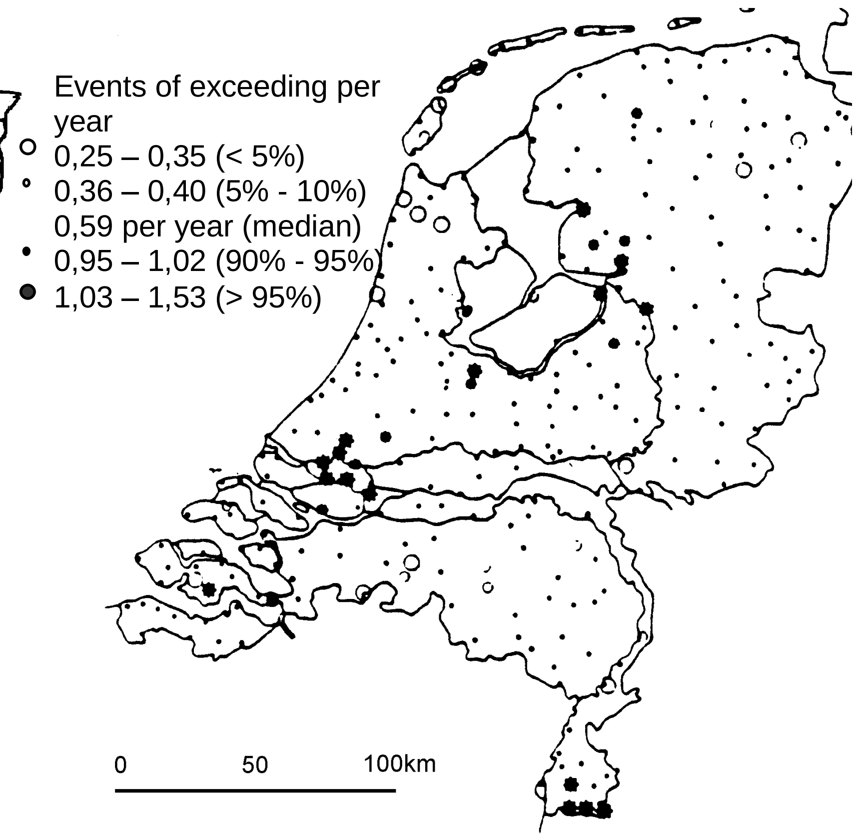
Urbanization effect on heavy showers

Source: Prak, Krayenhoff van de Leur, 1979

1933-1956

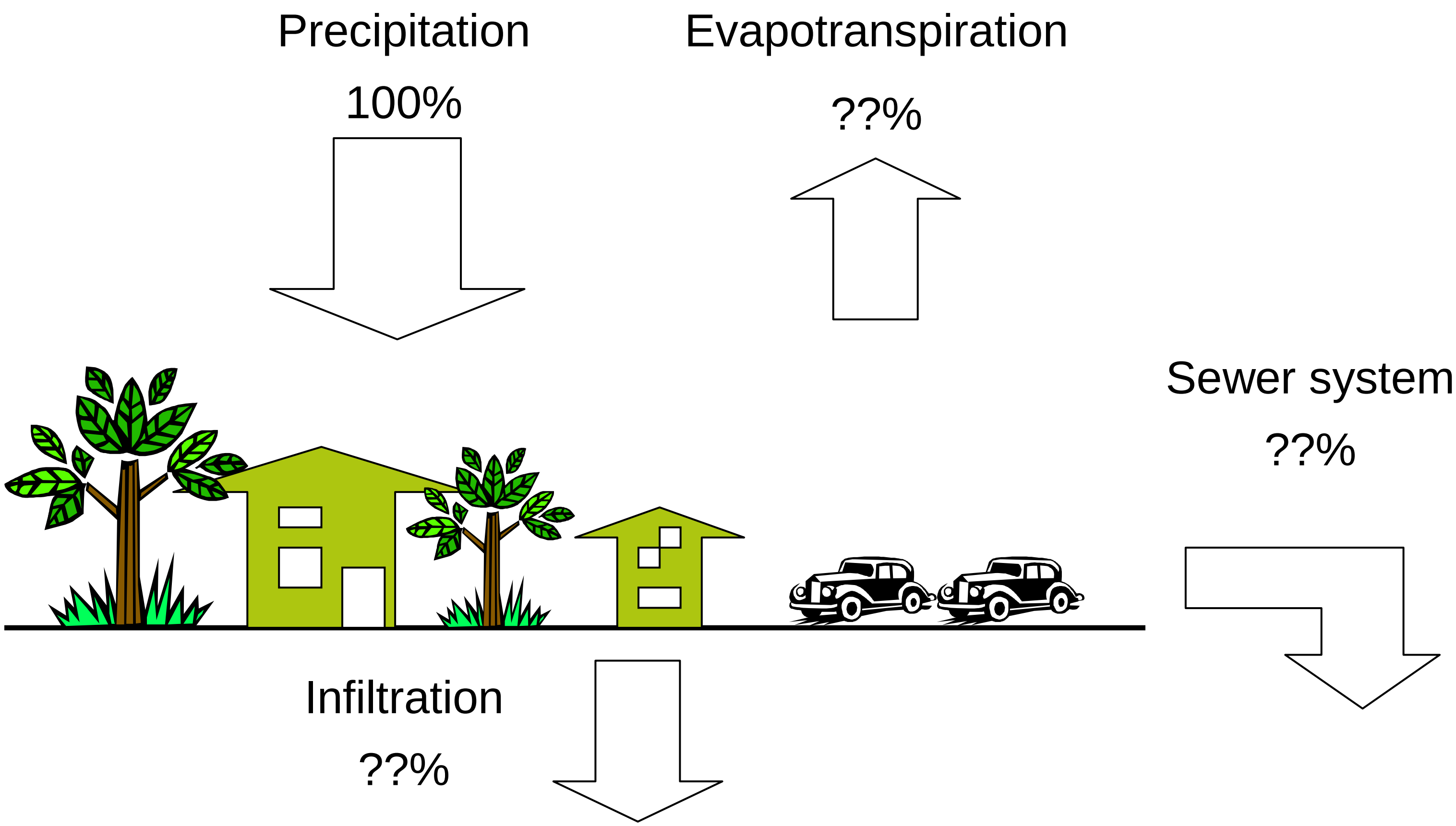


1957-1975



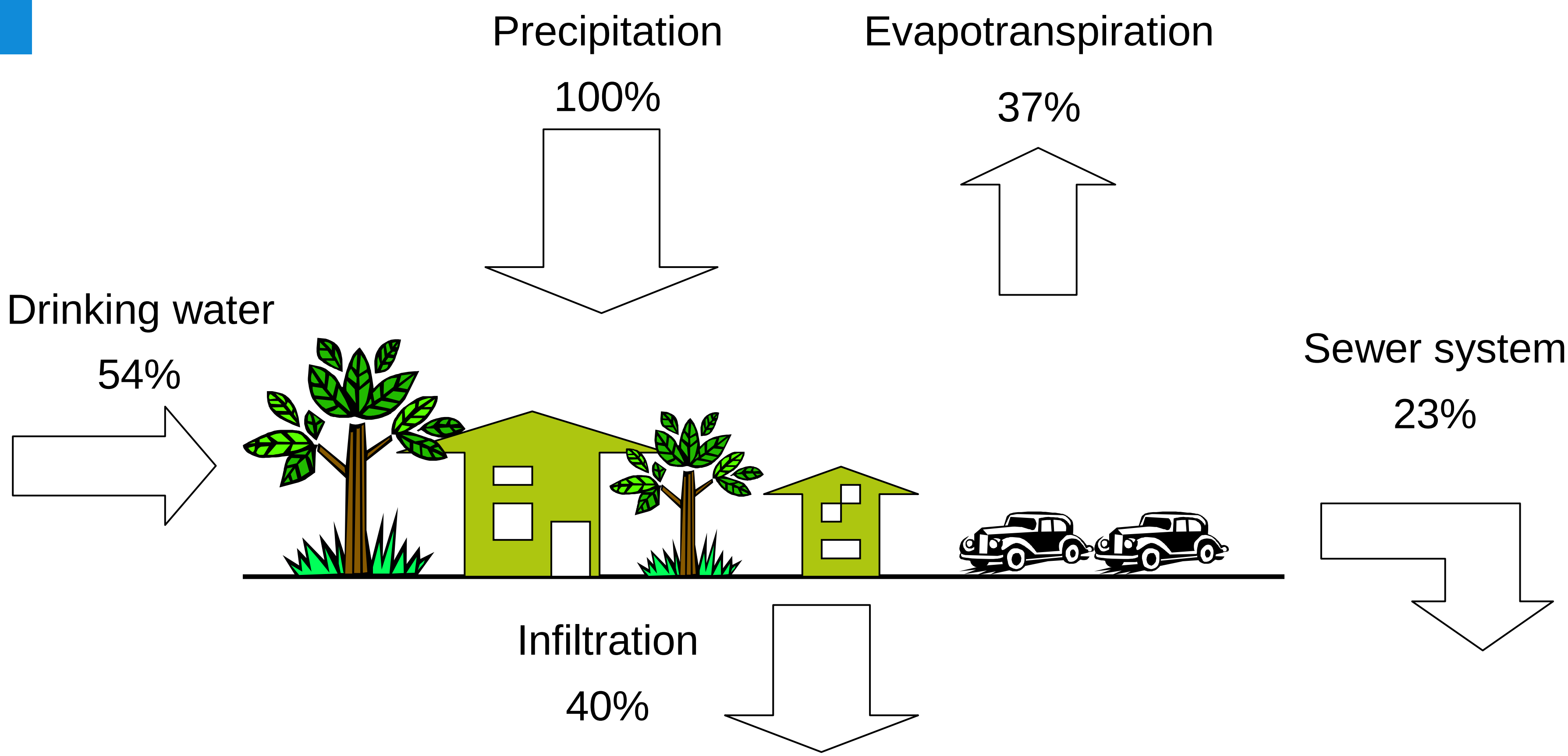
Water balance

A hydrological analysis



Water balance

A hydrological analysis



Water balance

Example: Lelystad

Source: Van de Ven, Voortman, 1985. Water balance of two experimental basins in Lelystad, 1968-1980

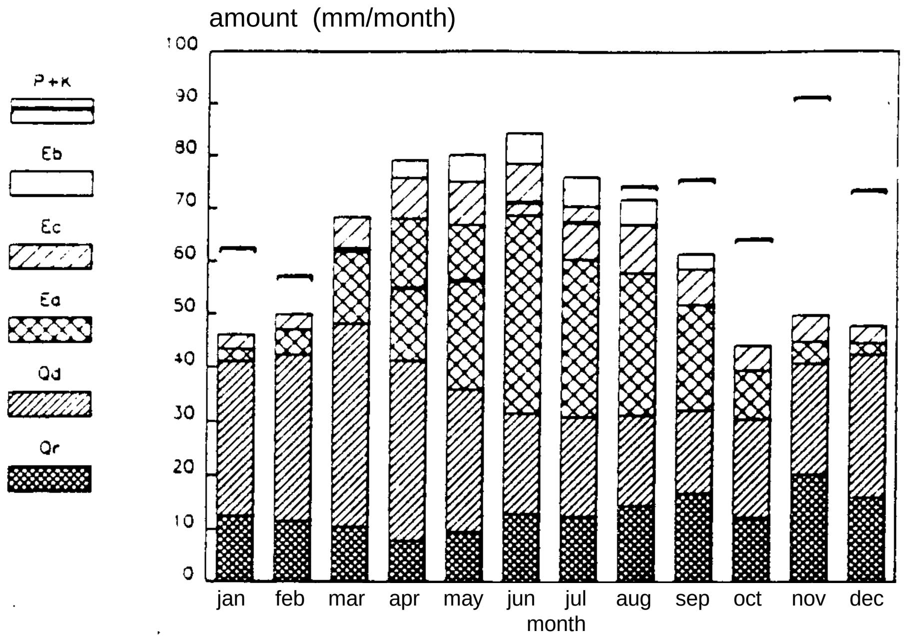
	residential area		**parking lot**	
	mm	%	mm	%
Precipitation (P)	698	87	739	88
Seepage (K)	108	13	101	12
Total inflow	806	100	838	100
Discharge stormwater sewerage (Q_r)	159	20	376	45
Subsurface drainage discharge (Q_d)	320	40	337	40
Evapo-transpiration unpaved area (E_a)	214	27		
Evaporation paved surface (E_c)	75	9	112	13
Evaporation solitary trees (E_b)	27	3	27	3
Change in storage (ΔS)	11	1	5	1

Water balance

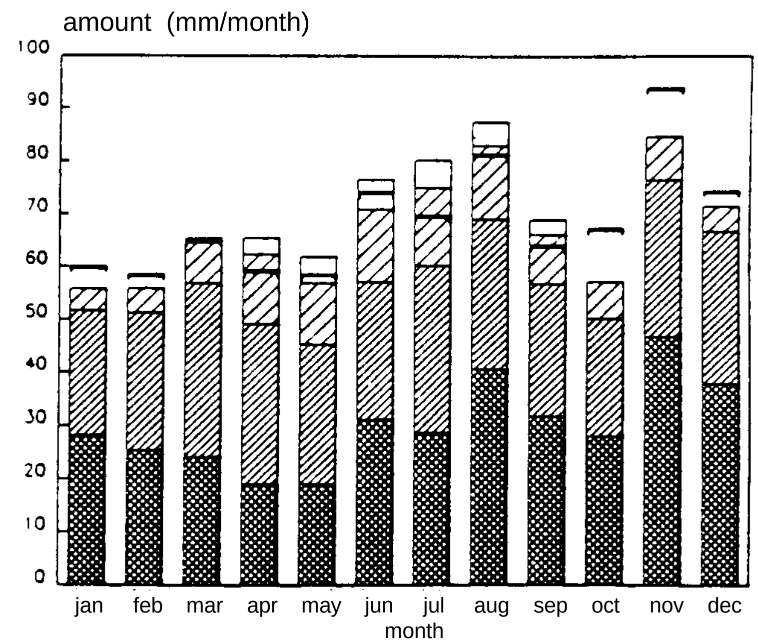
Example: Lelystad

Source: Van de Ven, Voortman, 1985. Monthly water balance of two experimental basins in Lelystad.

Residential area



Parking lot



Water balance

Summary

- Additional imports (drinking water, seepage)
- Limited discharge storm sewer
- Significant subsurface drainage
- Less evaporation from paved surfaces but not negligible
- Buffering behavior of unpaved soil

Precipitation

Source photo: www.flickr.com/creativecommons (mhaithaca)

Precipitation

Monitoring methods

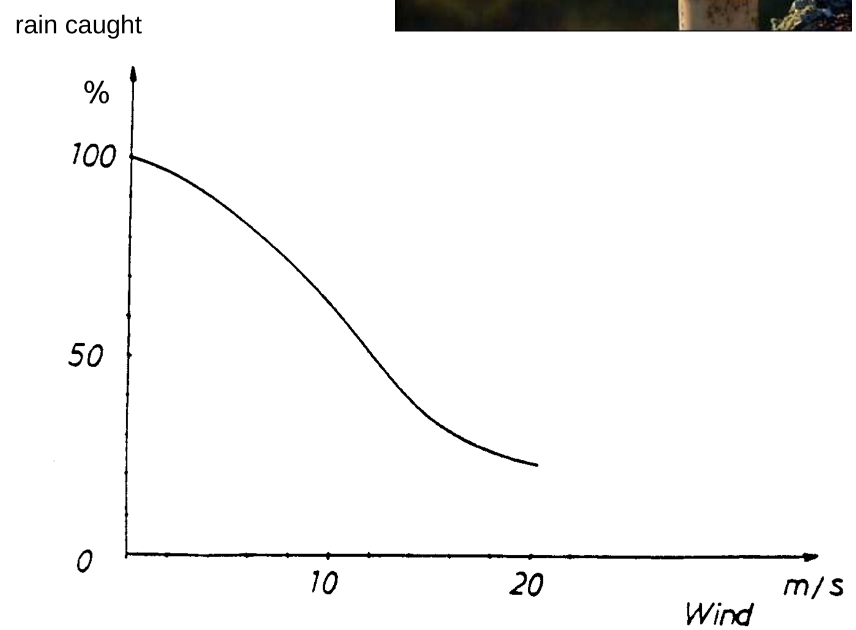
- Cumulative rain gauge measurements
- Continuous registering rain gauges
  - Pen recorder (fully continuous but analog!)
  - Data logger, fixed time interval
  - Data logger, event-sense
- Radar (wet vs. dry spots)

Source photo: www.buienradar.nl

Precipitation

Monitoring factors

- Internal errors
  - Evaporation, splashing…
- Installation errors
  - Wind influence: Elevation, obstacles
  - Vandalism precautions
- Network density
  - Spatial variability, purpose
- Frequency
  - Studied phenomenon

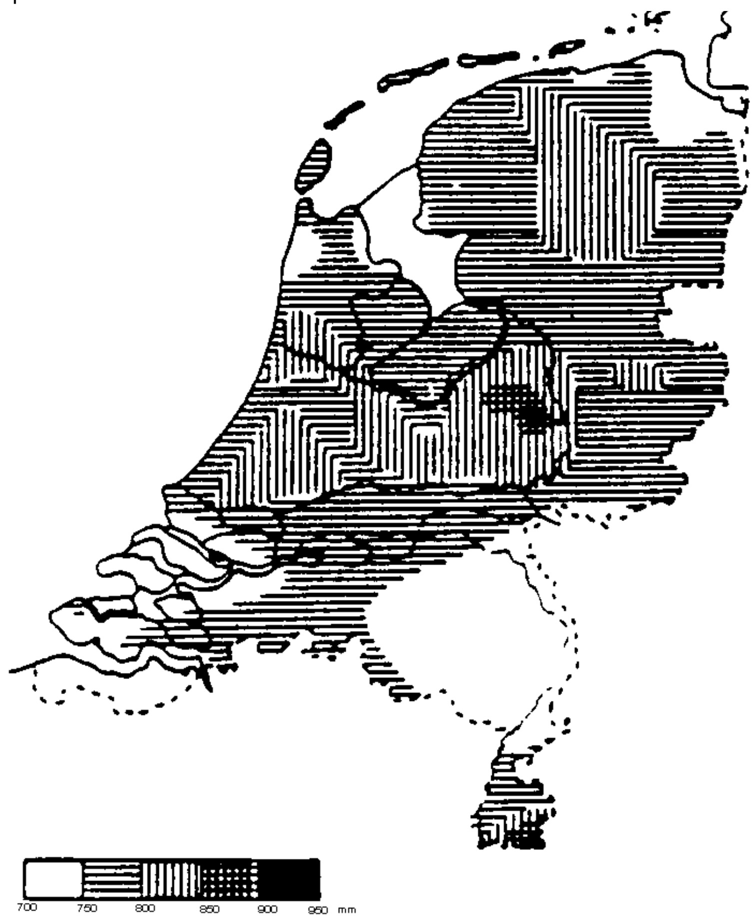


Source graph: Pfeiff, 1971. Relation between amount of precipitation caught and wind velocity for a rain gauge

Precipitation

Annual distribution

Source: Buishand, Velds,1980. Precipitation distribution of the Netherlands

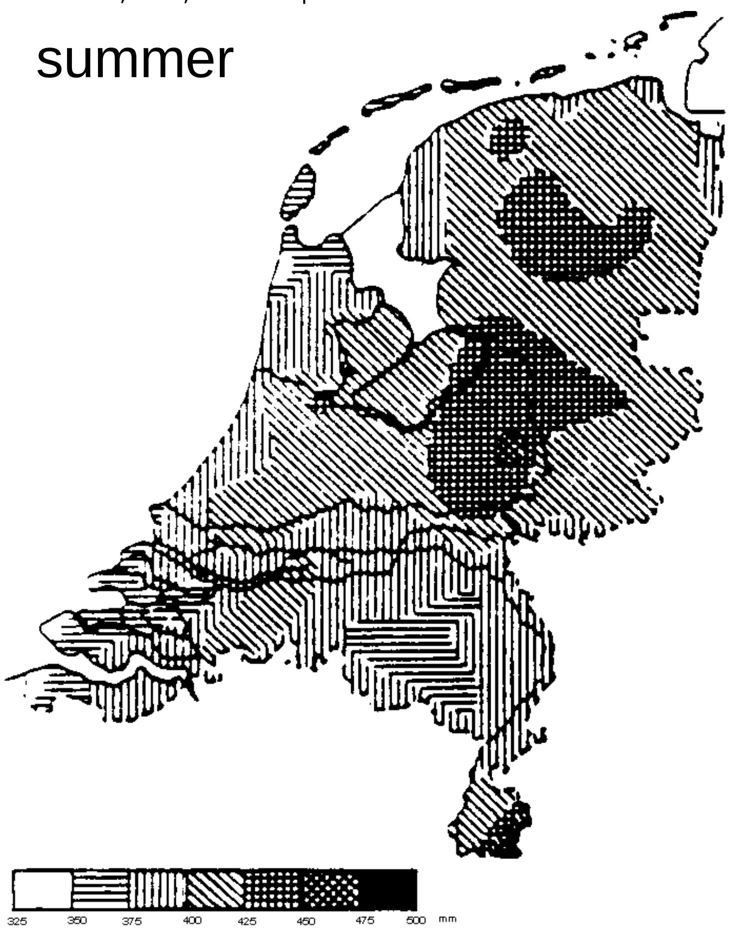


Precipitation

Seasonal distribution

Source: Buishand, Velds, 1980. Precipitation distribution of the Netherlands

summer



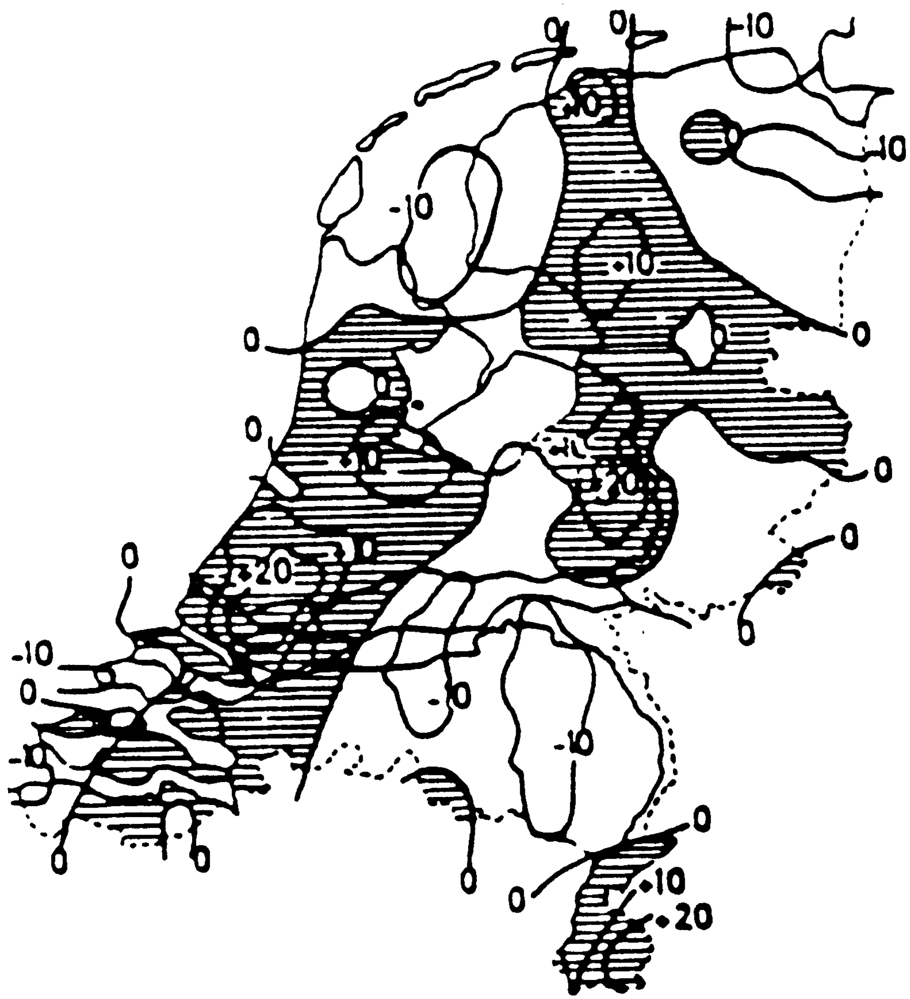
winter

Precipitation

Heavy rainstorms

Source: Witter, 1984

Deviation (%) from average number of days per year with > 20 mm precipitation



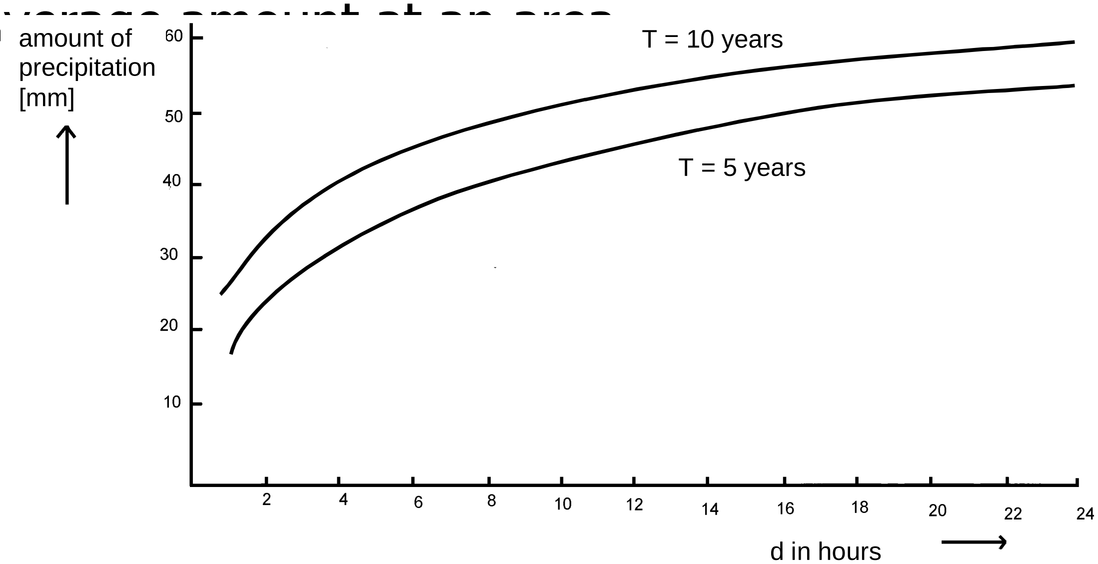
Precipitation

Extreme precipitation intensities

- Extremes often determine the design situation
- Amount at a single location

  Rainfall *depth-duration-frequency* curves (DDF)

  Rainfall *intensity-duration-frequency* curves (IDF)
- Average amount at an area



Precipitation

Extreme precipitation intensities

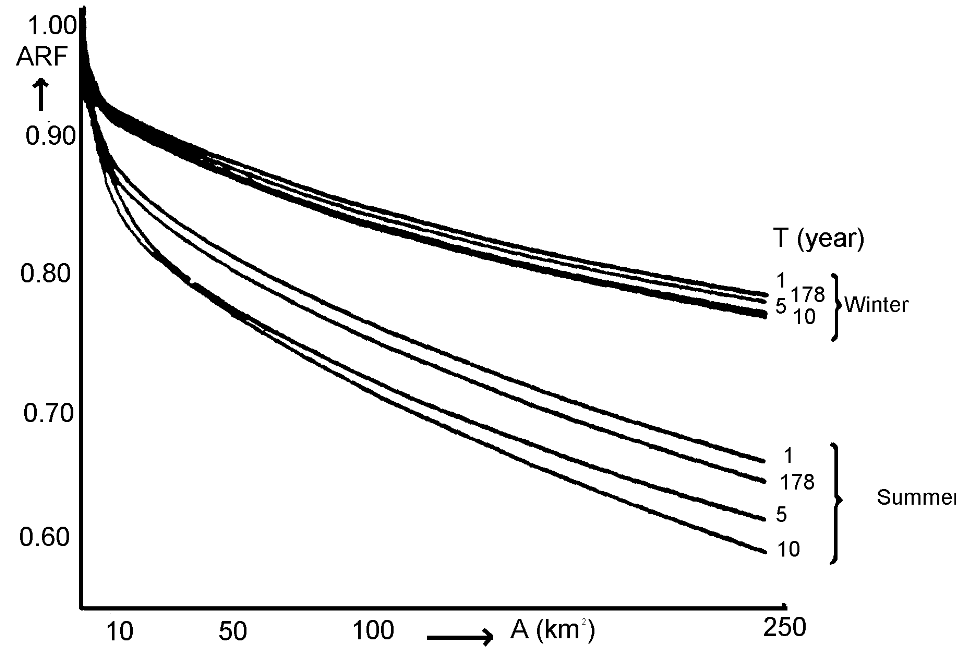
Area size effects

- x_g = maximum precipitation in a certain time interval within a year for the area
- x_{pj} = maximum precipitation in a certain time interval within a year for point j

$$ARF = \frac{\overline{x}_g}{\overline{x}_p}$$

$$\overline{x}_g = \frac{\sum_{i=1}^{n} x_g(i)}{n}$$

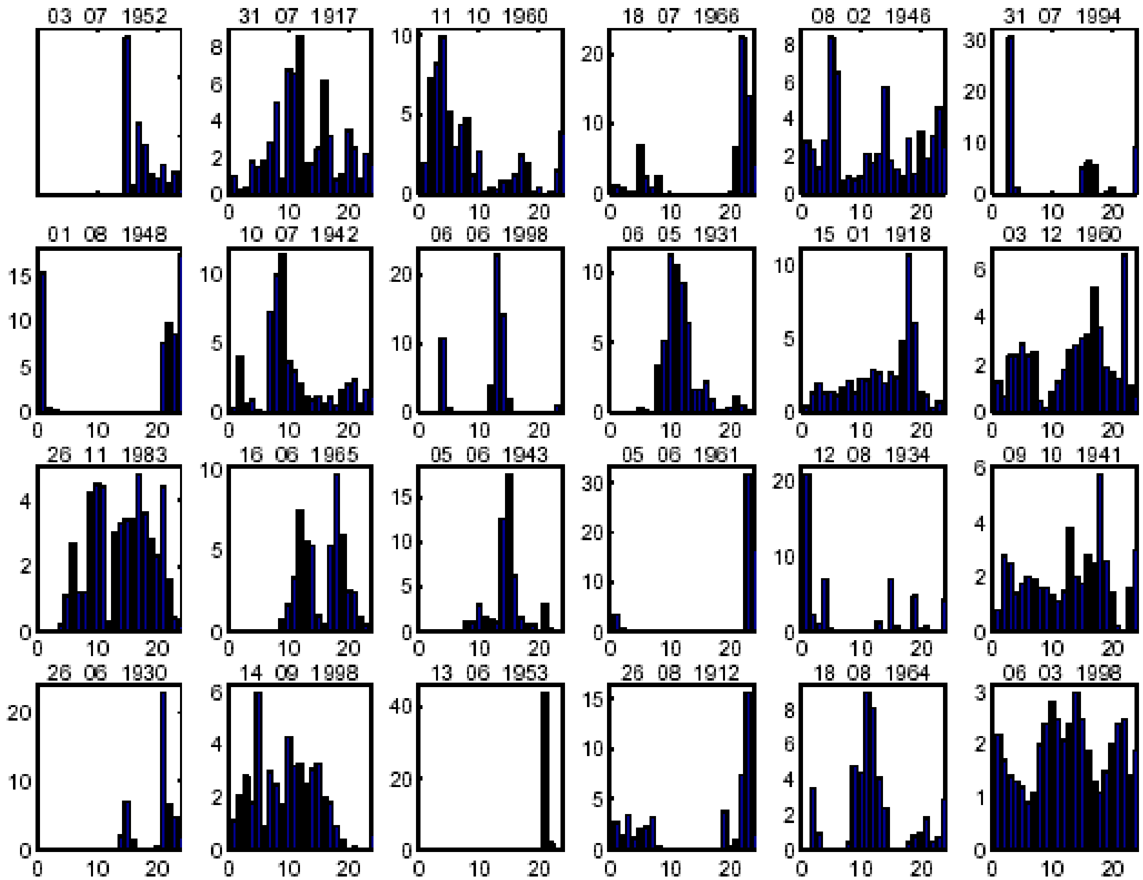
$$\overline{x}_p = \frac{\sum_{j=1}^{n} \overline{x}_{pj}}{N} \qquad \overline{x}_{p1} = \frac{\sum_{i=1}^{n} x_{p1}(i)}{n}$$



Precipitation

Intention duration patterns

Source: STOWA, 2004. Various observed patterns of precipitation for a 24 hour period.



Precipitation

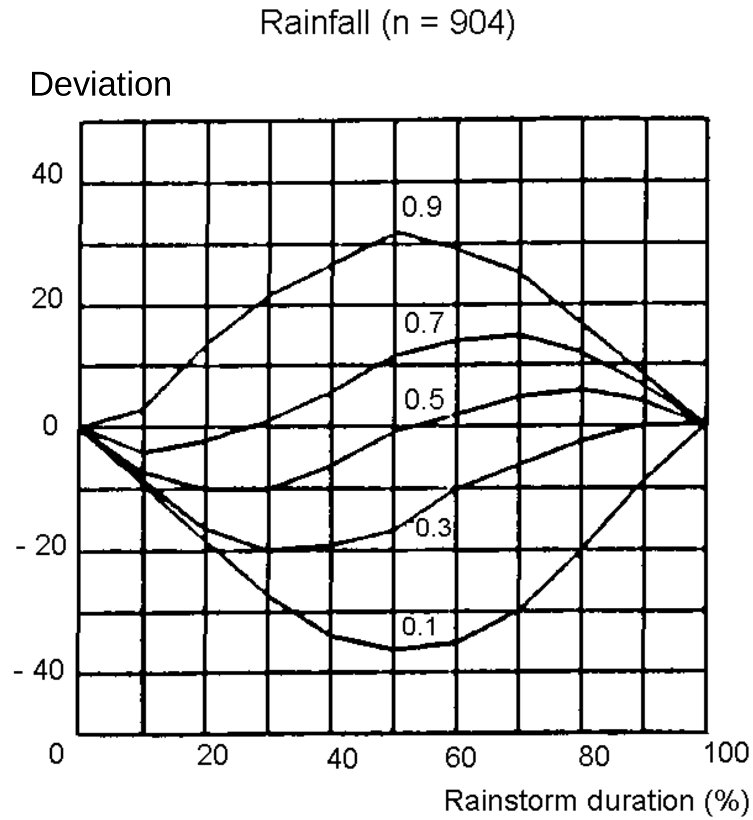
Intention duration patterns

Source: Van de Ven, 1983

Rainstorms with

- a peak at the start
- a peak at the end
- a less pronounced peak
- two peaks at 5% and 50% of their duration

Probability distribution of the deviations from a constant precipitation intensity



Evapotranspiration

Source photo: www.flickr.com/creativecommons

Evapotranspiration

Radiation

- $Q^* = K + \Lambda = K\downarrow - K\uparrow + \Lambda\downarrow - \Lambda\uparrow$

  Q* = net radiation [$W \cdot m^{-2}$]

  K = short wave component consisting of an incoming and outgoing component [$W \cdot m^{-2}$]

  Λ = long wave component consisting of an incoming and outgoing component [$W \cdot m^{-2}$]

- $K = (1 - r)\, K\downarrow$

  r = reflection coefficient (albedo) [%]

- $\Lambda\uparrow = \sigma\, T_0^4$

  σ = Stephan-Boltzman constant $5.67 \cdot 10^{-8}$ [$W \cdot m^{-2} \cdot K^{-4}$]

  T_0 = surface temperature [K]

- $\Lambda\downarrow$ empirical function of vapour pressure and clouds

Evapotranspiration

Energy balance

$$Q^* = G + LE + H$$

Q^* = net radiation [$W \cdot m^{-2}$]

G = heat absorbed by the earth's surface [$W \cdot m^{-2}$]

LE = heat used for evaporation *(latent heat)* [$W \cdot m^{-2}$]

L is evaporation heat $\approx 2.5 \cdot 10^6$ [$J \cdot kg^{-1}$]

E is vapour transport [$kg \cdot m^{-2} \cdot s^{-1}$]

H = *tangible heat* transferred to the atmosphere [$W \cdot m^{-2}$]

Evapotranspiration

Methods

- Penman: E_0 (international standard)
  - Open water evaporation
  - Heat storage in the water ignored
  - Input: Radiation / Hours of sunshine
    Air temperature
    Wind (function)
    Relative humidity

- Makking: E_r (KNMI)
  - Reference crop evaporation (well watered grass)
  - Input: Global radiation flow density
    Air temperature

Evapotranspiration

Unpaved surfaces

- Wet conditions
  - Similar as for open water
  - Albedo 10 - 25 %

- Dry, well watered vegetated conditions
  - Potential evaporation ($E_{pot} = g\ E_0 = fE_r$)
  - Crop factors depending on type and state of the vegetation (<1)
  - Actual evaporation ≤ potential evaporation ($E_{act} \leq E_{pot}$)

Evapotranspiration

Unpaved surfaces

- Actual evaporation (Thornthwaite & Mather)

$$S = S_0 e^{-APWL/S_0}$$

S	= actual moisture content in root zone [mm]
S_0	= moisture content in root zone at start of the dry season [mm]
APWL	= Accumulated Potential Water Loss ($\Sigma E_{pot} \cdot t$) [mm]

$E_{act} = P - \Delta S$ if $P < E_{pot}$

$E_{act} = E_{pot}$ if $P > E_{pot}$

E_{act}	= actual evaporation
P	= precipitation
ΔS	= $S - S_0$

Evapotranspiration

Unpaved surfaces

Source: Van der Molen, 1972

Example: water balance for a meadow in the Netherlands

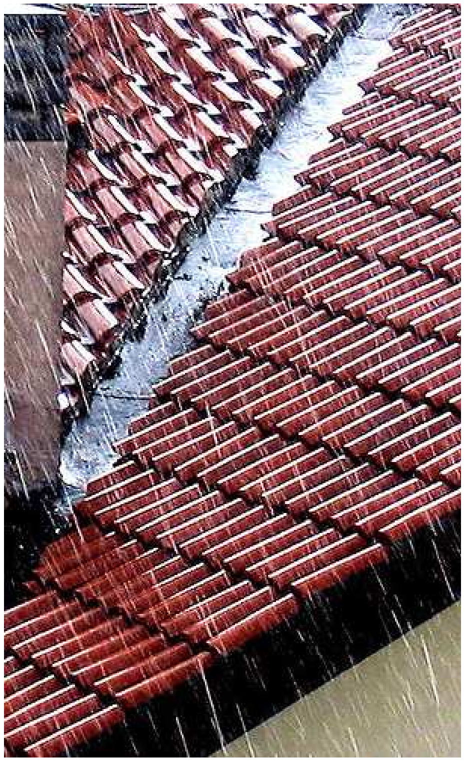
- $Q = P - E_{act} - \Delta S$
- $PE = E_{pot} = 08 \cdot E_0$
- all parameters in mm

		J	F	M	A	M	J	J	A	S	O	N	D	Year
Precipitation	P	69	52	44	49	52	57	78	89	71	72	70	64	767
Pot. Evap.	PE	5	14	33	63	88	101	98	82'	52	25	9	3	573
	P-PE	64	38	11	-14	-36	-44	-20	+7	19	47	61	61	194
	APWL				14	50	94	114					-	
	S	100	100	100	87	61	39	32	39	58	100	100	100	-
	(S_0 = 100)													
	ΔS	0	0	0	-13	-26	-22	-7	+7	+19	+42	0	0	-
Act. Evap.	AE	5	14	33	62	78	79	85	82	52	25	9	3	527
Runoff	Q	64	38	11	0	0	0	0	0	0	5	61	61	240

Evapotranspiration

Paved surfaces

- Limited knowledge
- No transpiration
- Extra heat capacity of the pavement / roof tiles
  - Example: asphalt of 55°C on surface of 40°C



Time	H_s	Evaporation flux		Total evaporation
(h)	(W/m^2)	(x 10^{-5} mm/s)	(mm/d)	(mm)
5/60	1500	43	37	0.27
30/60	620	18	15	0.69
1	440	13	11	1.0
2	310	8.9	7.7	1.4

Source table: Van de Ven, 1985. Computed heat flow and evaporation with a rainstorm on a sunny summer day.

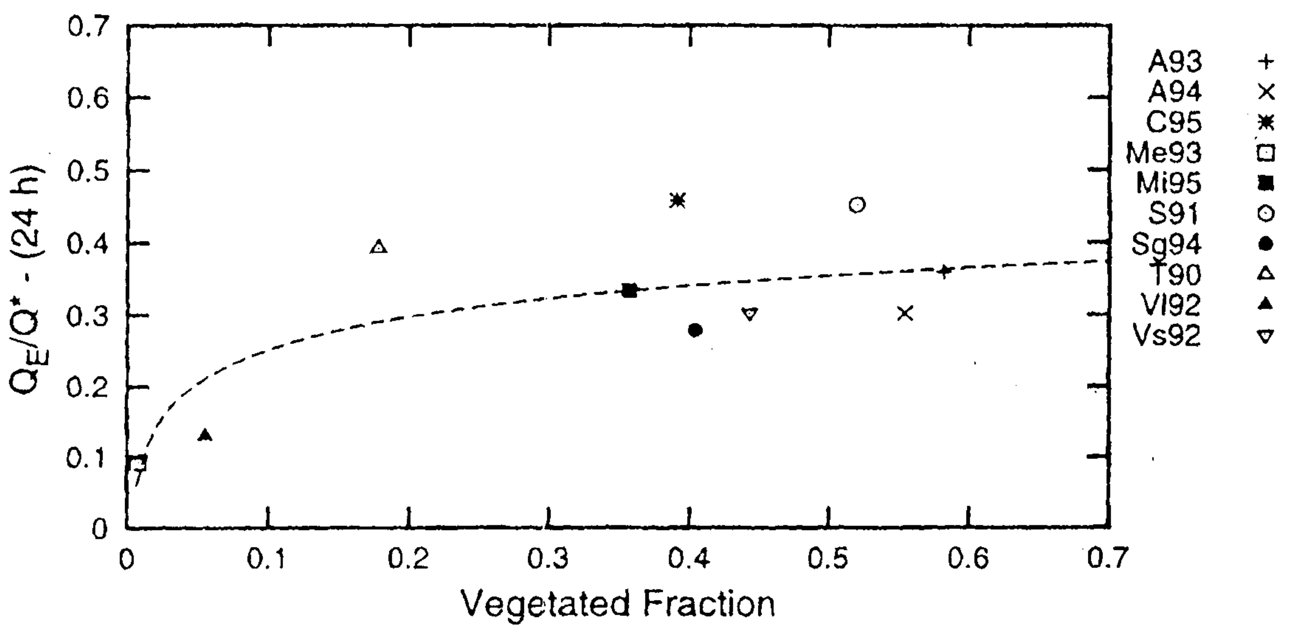
Evapotranspiration

Paved surfaces

Source: Grimmond and Oke, 1999. Relation between relative evaporation and vegetated fraction.

Considerable flux even with completely paved area

- Q_E = latent heat
- Q_E / Q^* = heat fraction used for evaporation



Groundwater

Photo: Groundwater level rise up to the crawlspace

Groundwater

Groundwater balance

- Infiltration
  - Unpaved surface
  - Semi-pervious pavement
  - Stormwater infiltration facilities
- Seepage
  - Deep semi-confined aquifers
- Leakage
  - Permeable sewer system
  - Broken drinking water mains
- Evapotranspiration
  - Surface evaporation
  - Plant uptake and transpiration
- Drainage
  - Natural discharge
  - Groundwater drainage system
- Extractions
  - Drinking water
  - Irrigation
  - Industrial purpose

Groundwater

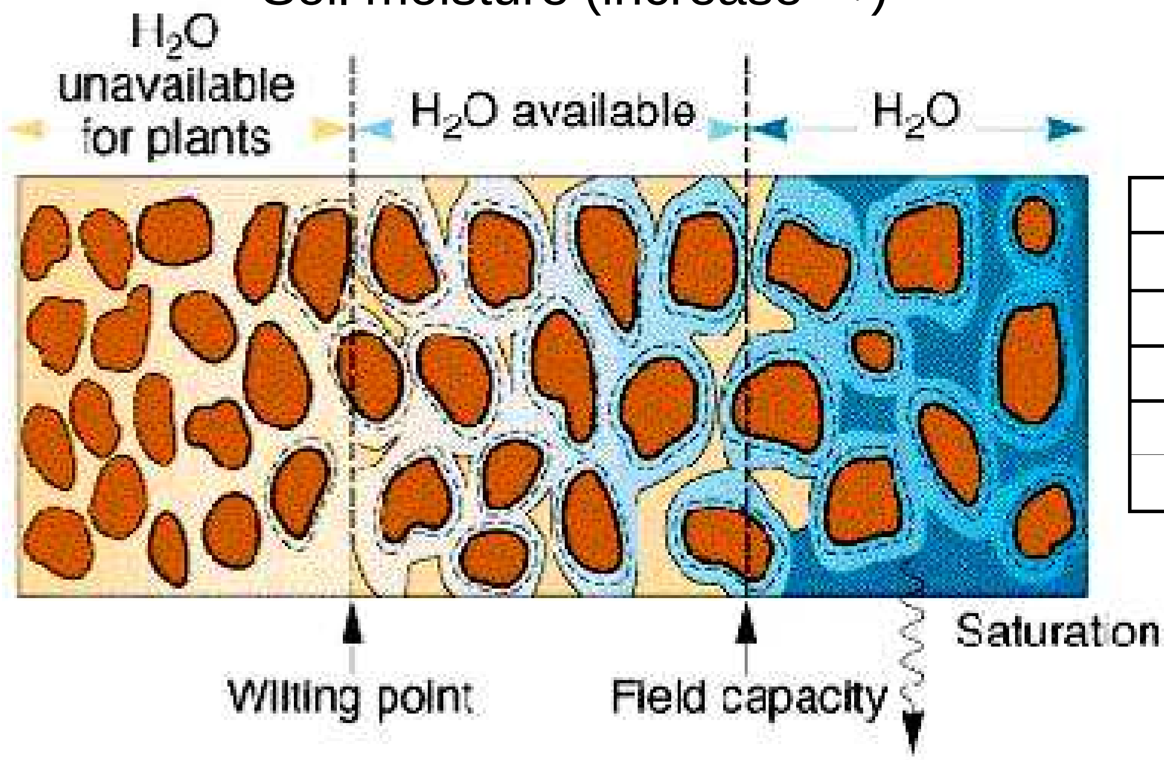
Unsaturated zone

- Air, water and soil particles
- Root zone
- $P = z + \varphi_s$
  - P = potential [m]
  - z = elevation [m]
  - φ_s = suction pressure [m]
- $pF = {}^{10}\log(\varphi_s \cdot 100)$

Groundwater

Unsaturated zone moisture

Soil moisture (increase →)



pF	Situation
> 4,2	Evaporation
4,2	Wilting point
2< <4,2	Transpiration
2	Saturation point
< 2	Percolation

Groundwater

Unsaturated zone flow

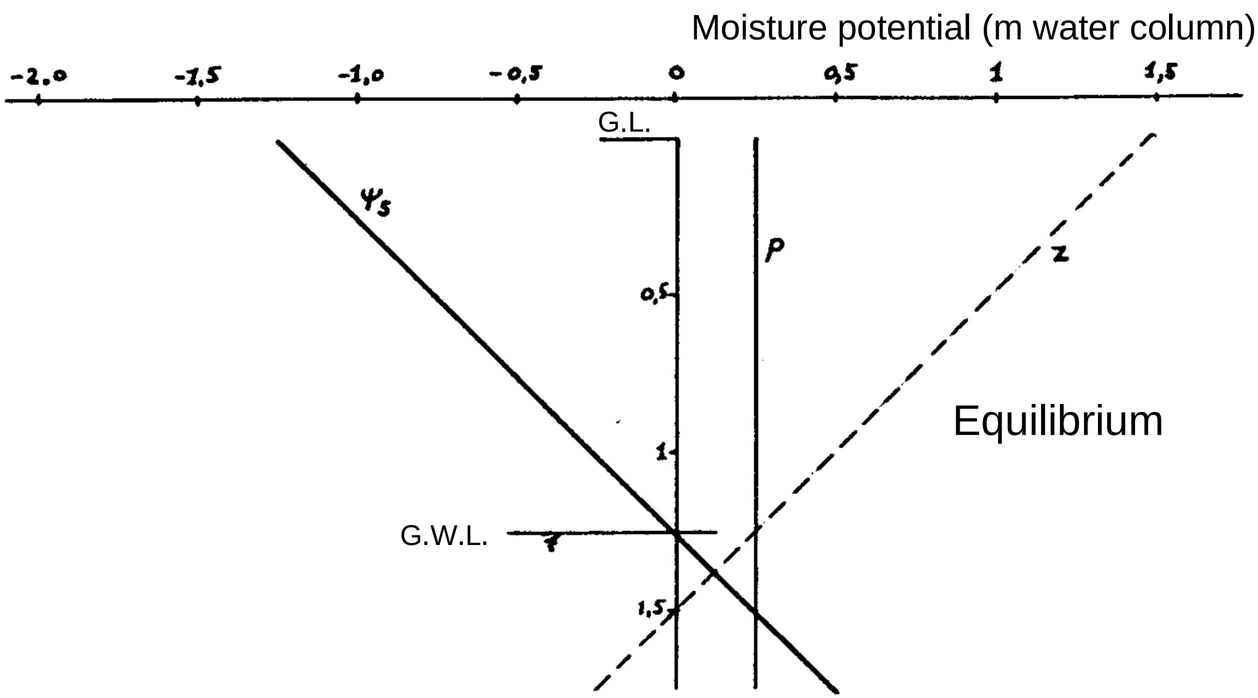
- Flow from high to low potential:

$$v = -K(\varphi_s)\frac{dp}{dz} = K(\varphi_s)\frac{dp}{dh}$$

  - v = flow velocity [$m \cdot s^{-1}$]
  - $K(\varphi_s)$ = permeability of the unsaturated soil [$m \cdot s^{-1}$]
  - z = elevation compared to reference level [m]
  - h = elevation compared to ground level [m]

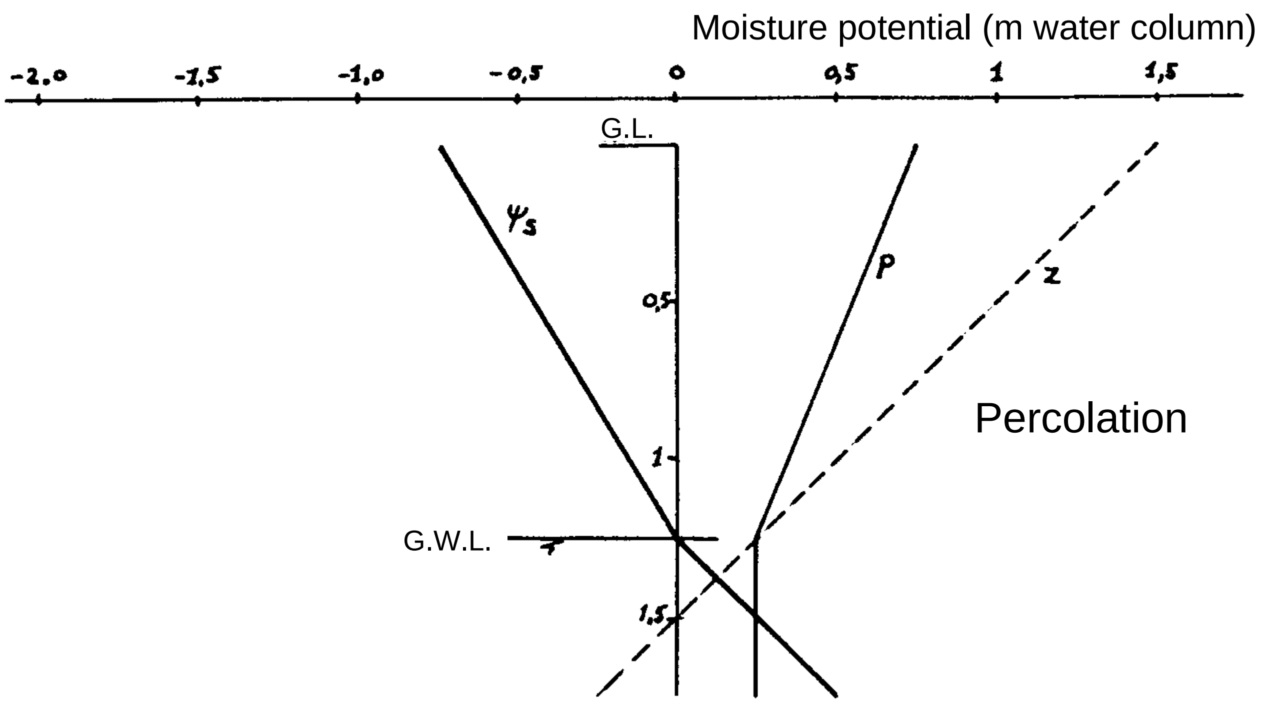
Groundwater

Unsaturated zone potential



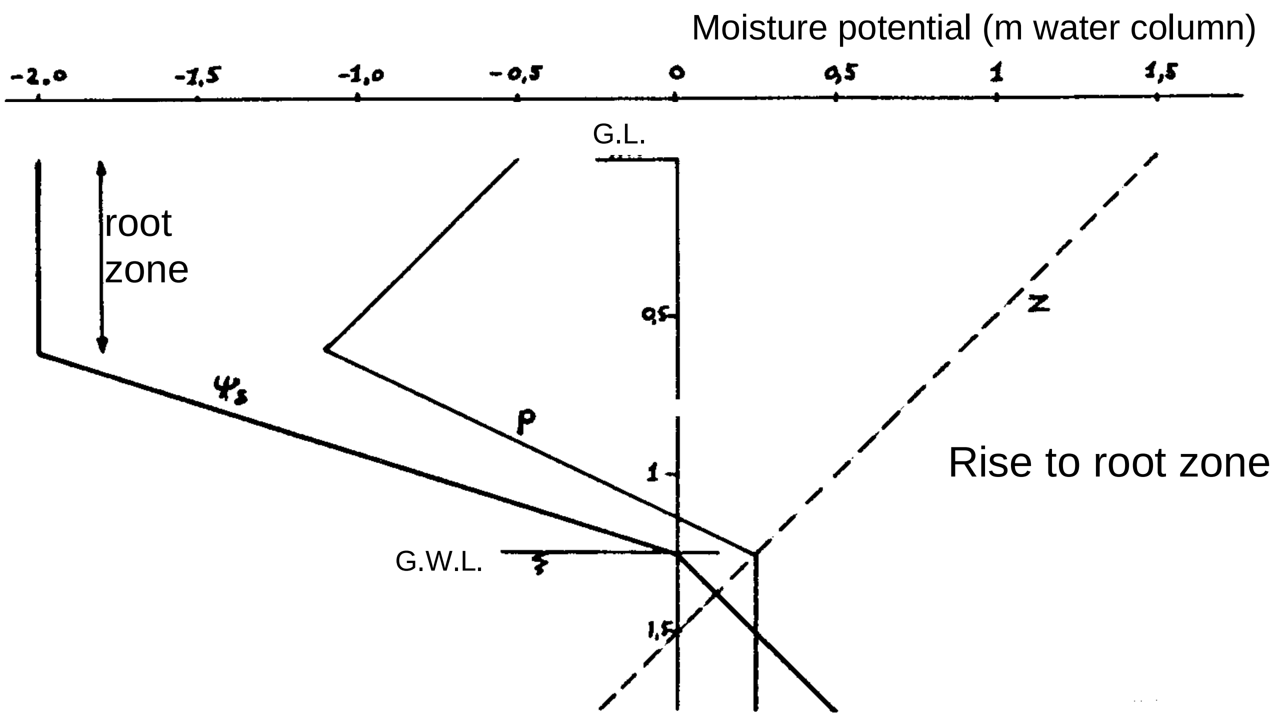
Groundwater

Unsaturated zone potential



Groundwater

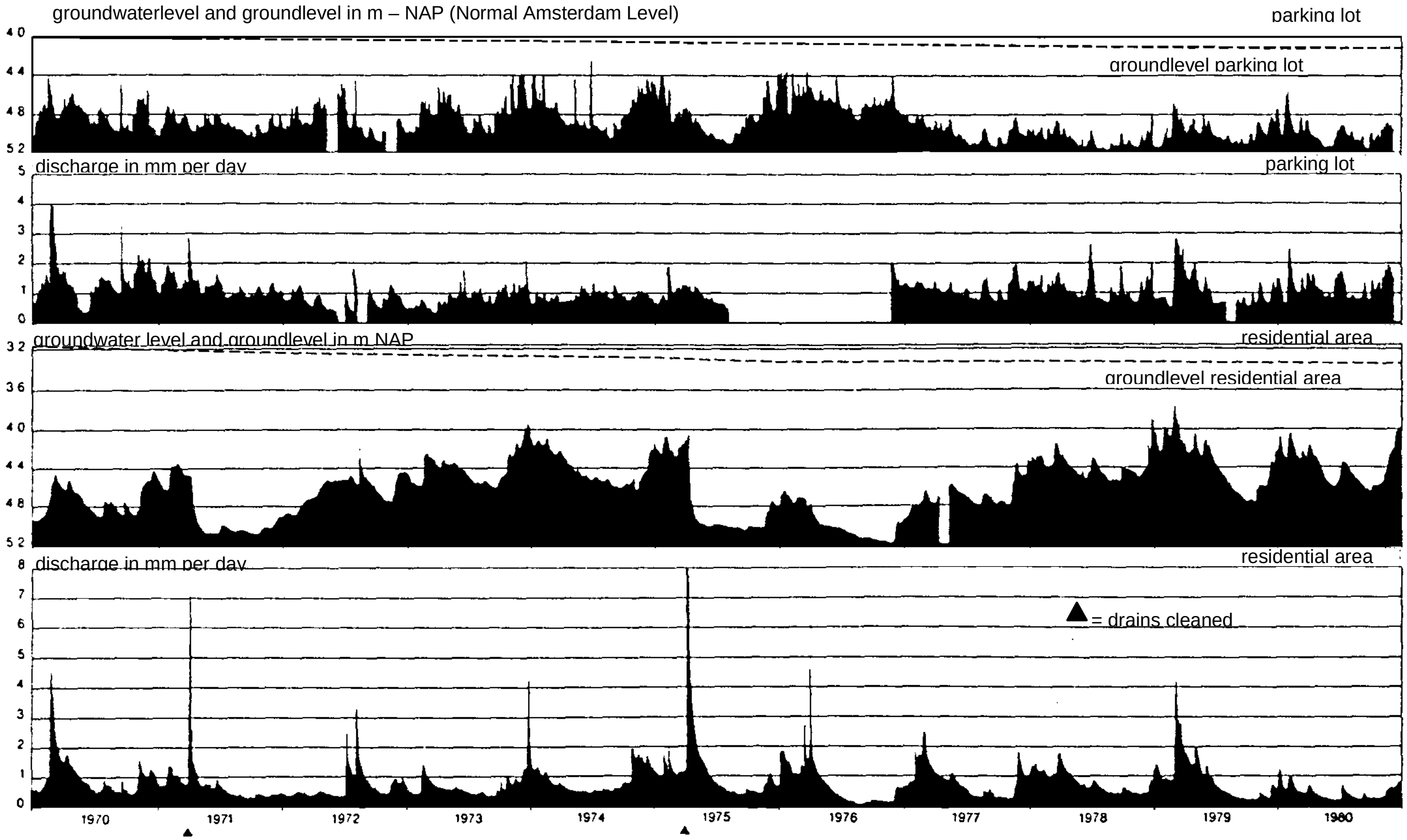
Unsaturated zone potential



Groundwater

Groundwater level and discharge

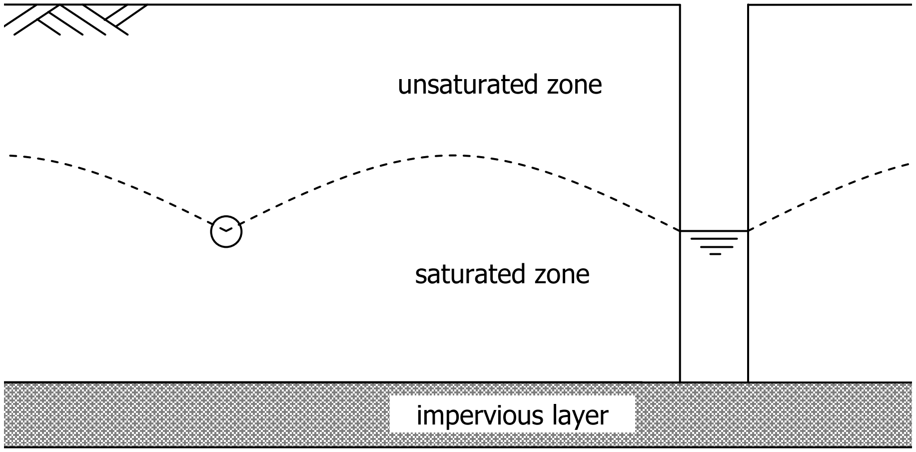
Source: Unknown. Progress of groundwater levels and drain discharges of two areas in Lelystad (1970-1980).



Groundwater

Saturated zone flow

- Based on Darcy: $v = -K \cdot i$
- q-h relations:
  - Donnan
  - Hooghoudt
  - Ernst
  - Glover-Dumm

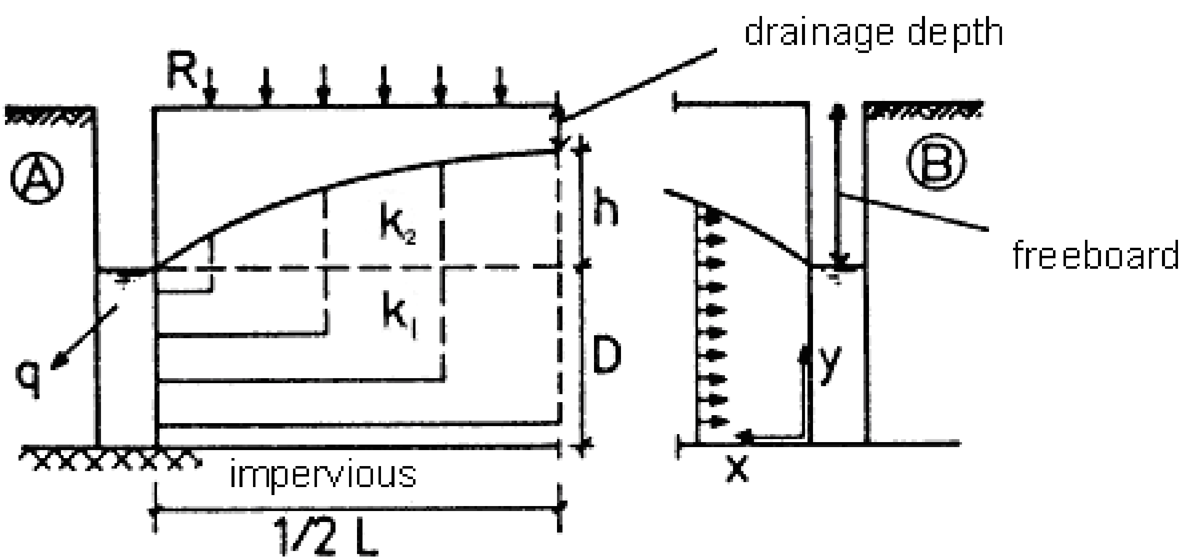


Groundwater

Donnan

- Horizontal flow with small bulge (D>>h)
- Constant precipitation (R)

$$q = (= R) = \frac{8.K_1.D.h + 4.K_2.h^2}{L^2}$$

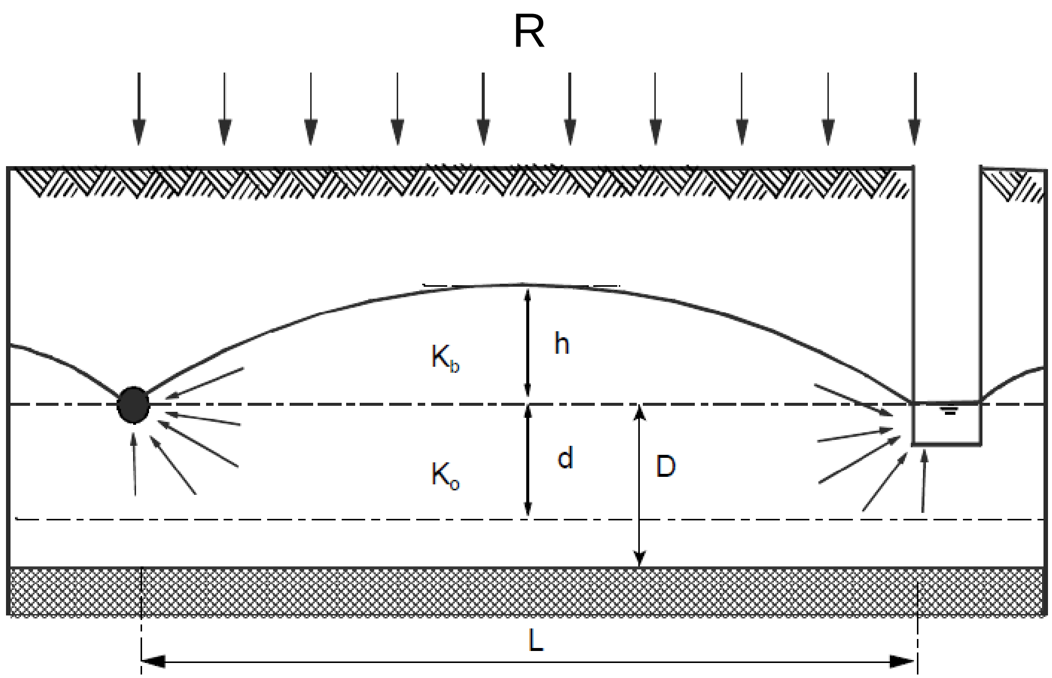


Groundwater

Hooghoudt

- Radial flow
- Equivalent depth d
  - Radius of the drain r_0

$$q = \frac{8 \cdot K_o \cdot d \cdot h + 4K_b \cdot h^2}{L^2}$$



Groundwater

Ernst

- Pressure losses
  - Vertical
  - Horizontal
  - Radial
  - Entry
- Geometry-factor *a*

$$h = q\frac{D_v}{K_v} + q\frac{L^2}{8\sum_i (KD)_i} + q\frac{L}{\pi K_r} ln\frac{aD_0}{u} + qLW_i$$

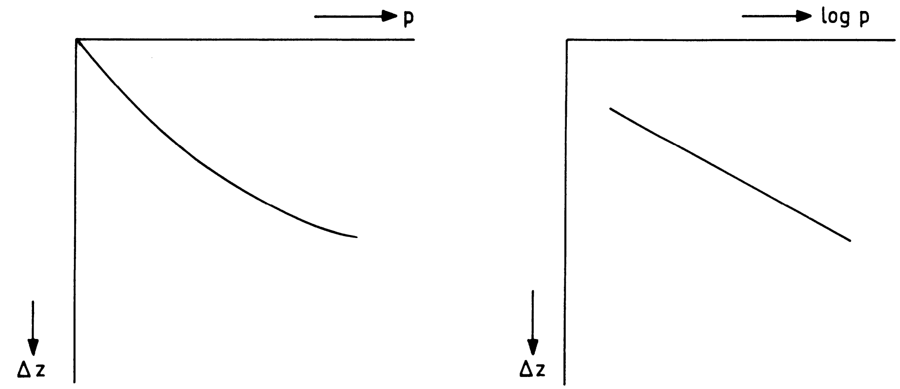
Subsidence

Photo: Subsidence of more than a meter around dwellings in Schiedam, 2001.

Subsidence

Load-subsidence

$$\frac{\Delta z}{z} = \frac{1}{C} \ln \frac{p'_2}{p'_1} \qquad \text{(Terzaghi)}$$



- z = thickness [m]
- Δz = compression [m]
- p'_1 = original effective stress [kN·m^{-2}]
- p'_2 = effective stress after loading [kN·m^{-2}]
- C = compression constant [-]

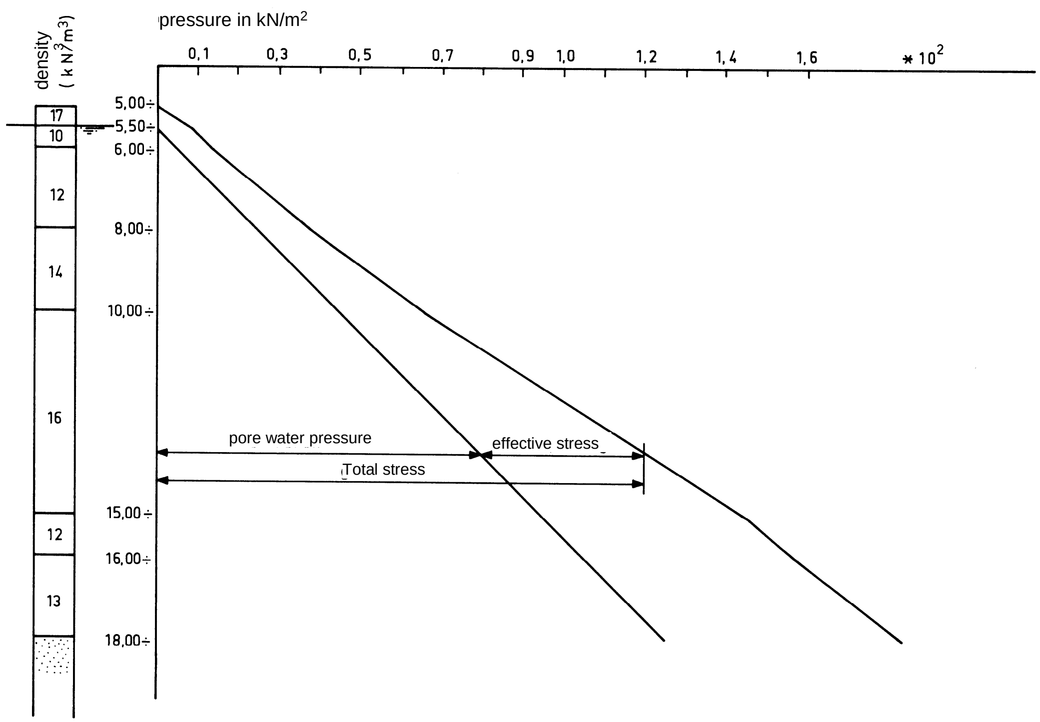
C-values:

- sand 20 – 200
- loam and clay 10 – 20
- peat 2 – 7

Subsidence

Hydro-dynamic period

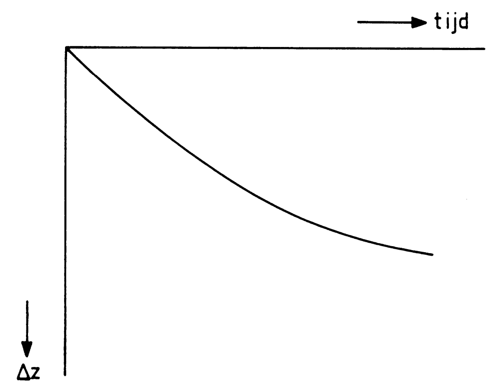
- Consolidation theory (volume change by outflow)
- $\sigma_{total} = \sigma_{effective} + \sigma_{water}$



Subsidence

Hydro-dynamic period

- Terzaghi: $t_e = \dfrac{m_v . \gamma_w . z^2}{2K}$
  - m_v = compression coefficient [m^2/kN]
  - γ_w = density of water [$kN \cdot m^{-3}$]
  - K = permeability of the soil [$m \cdot s^{-1}$]



Subsidence

Hydro-dynamic period

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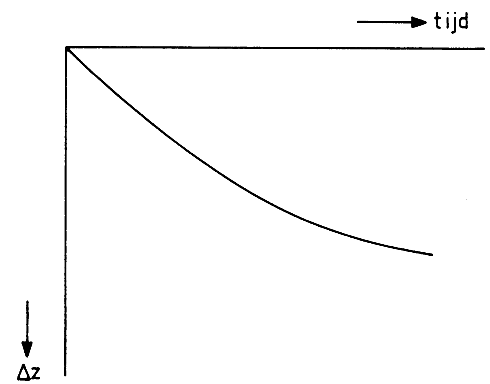

- Terzaghi + Keverling-Buisman secondary effect = Koppejan:

$$\Delta z = z\left(\frac{1}{C_p} + \frac{1}{C_s} \log \frac{t}{t_0}\right) \ln \frac{p'_2}{p'_1}$$

  - C_p = primary compression constant
  - C_s = secondary compression constant
  - t = loading time (t_0= unit of time)

Subsidence

Acceleration

- Decrease discharge distance with vertical drains
- Kjellmann: $t_e = \frac{m_v . \gamma_w . D^2}{8.K_h} \cdot \left[ln\left(\frac{D}{d}\right) - \frac{3}{4} \right] \cdot 5$
  - D = centre to centre distance of drains [m]
  - d = diameter of drains [m]
  - K_h = horizontal permeability [$m \cdot s^{-1}$]