Hydrology of catchments, rivers and deltas (CIE5450)

Dr.ir. M. Hrachowitz

Lecture ‘Flow paths’

Where does water go when it rains?

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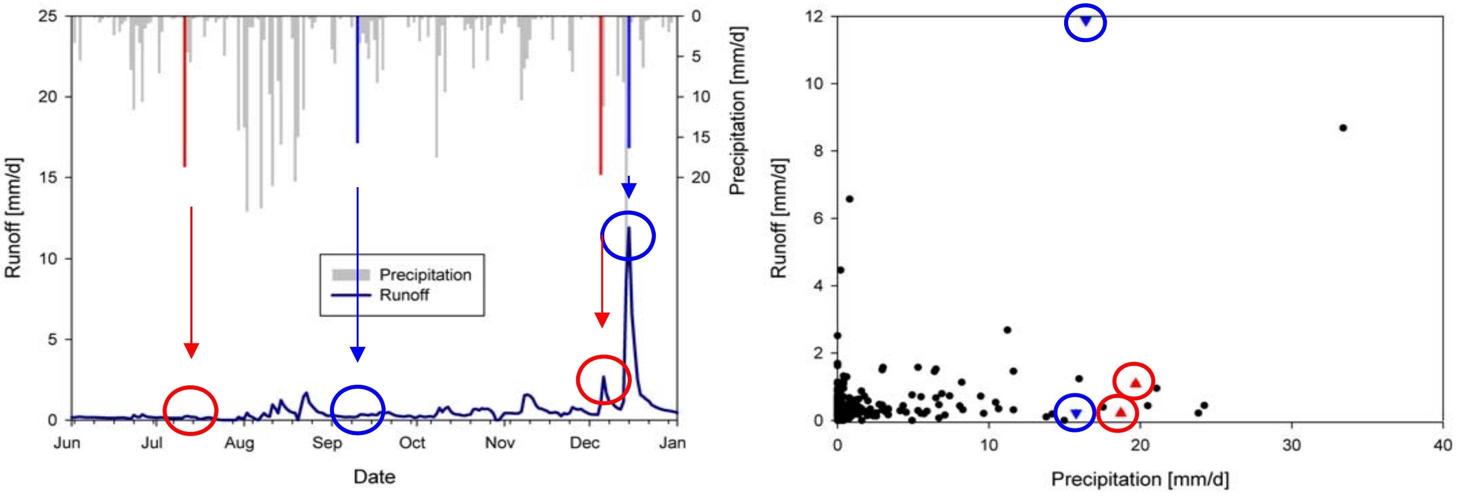
After this lecture you will

- know **what** flow paths are
- know **why** distinction of flow paths is important
- be able to **identify and classify** different flow paths
- be able to **describe** different flow paths
- know **how** flow paths can be distinguished

What is the problem?



For the same amounts of precipitation we can get significantly different stream flow responses.

Thus, there is no unique P – Q relationship → **<u>“Nonlinearity”</u>**

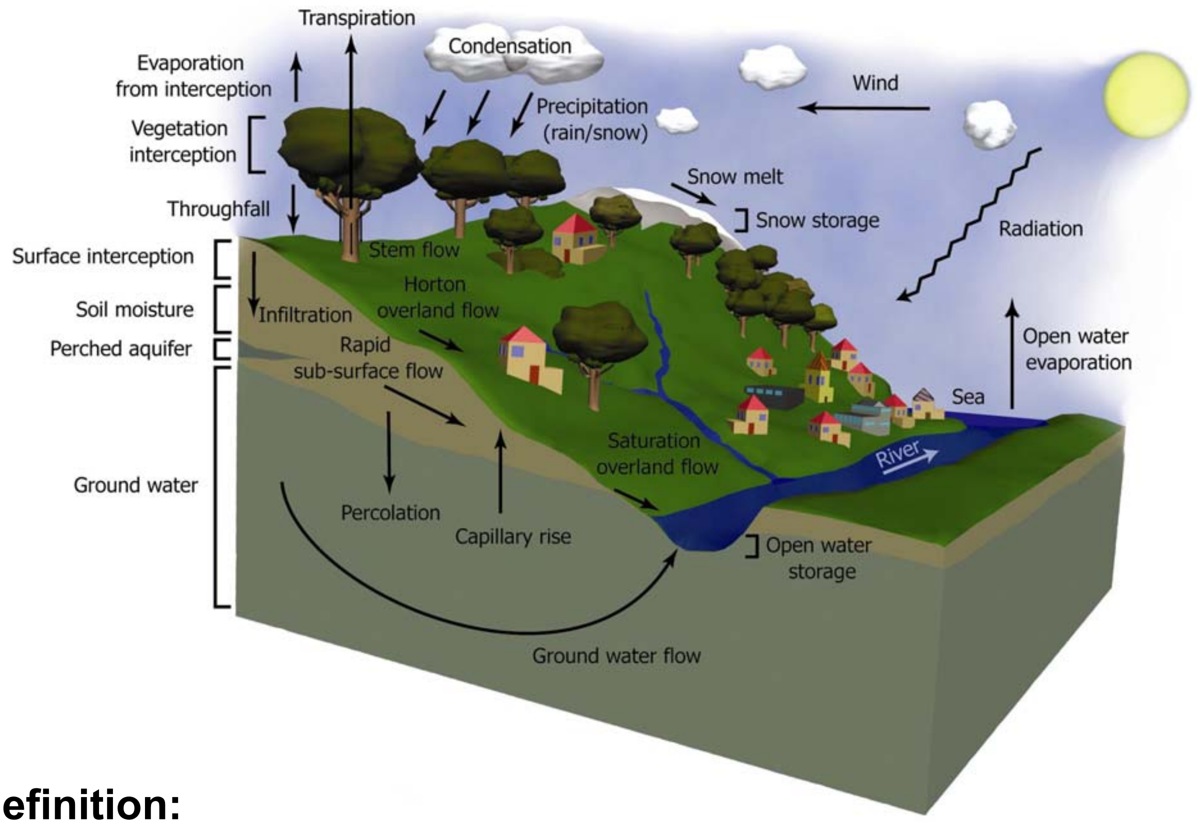
Main Issues

- Non-linearity
  - Non-linear differential equations
  - Hysteresis
    - flood wave
    - soil wetting and drying (pF-curve)
  - Threshold behaviour

- Heterogeneity

- The issue of scale
  - the problem of the ant

Flow paths

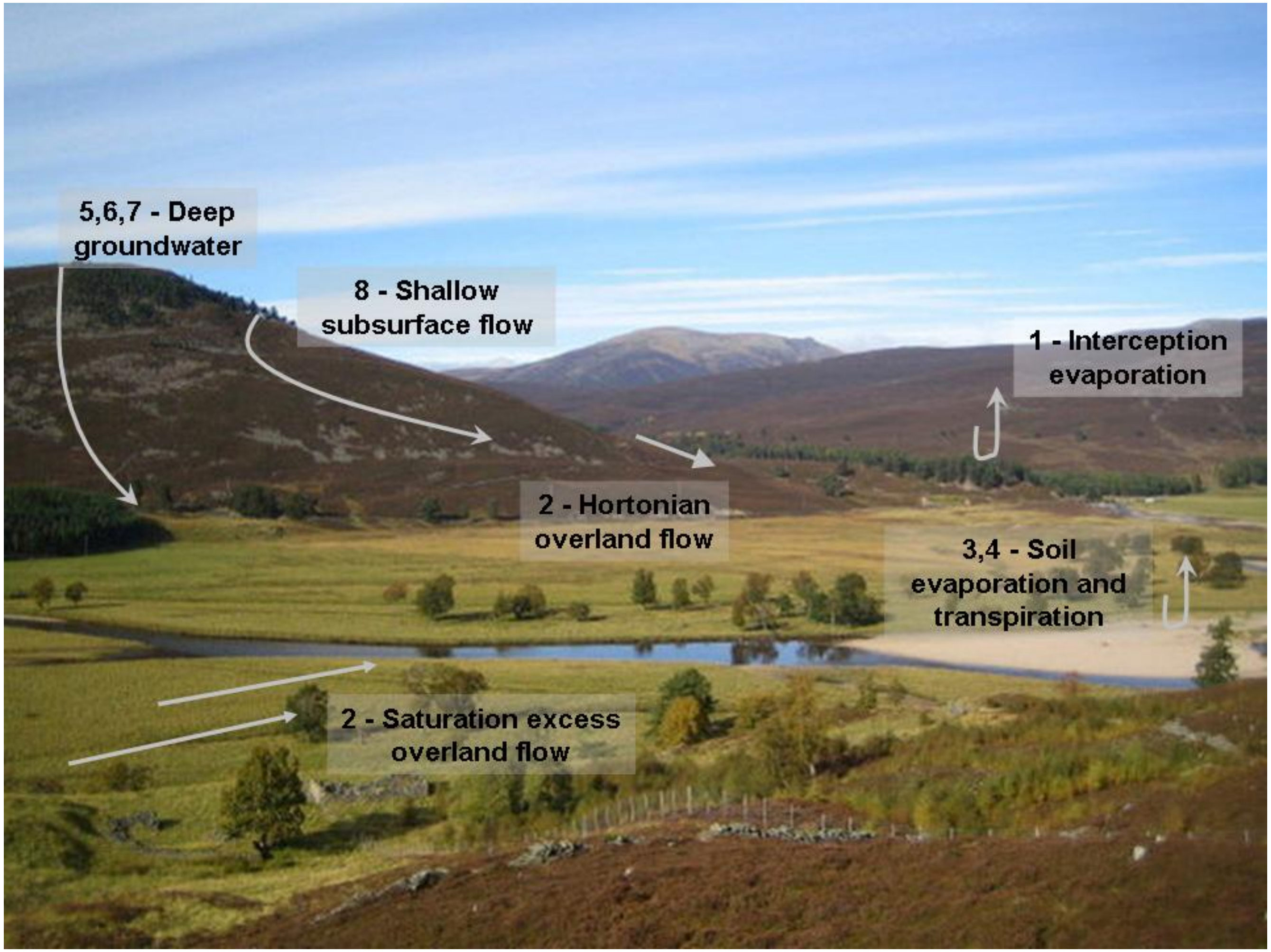


Definition:

Flow Paths, sometimes also called “Flow Processes”, are pathways the water follows once it entered the catchment as precipitation.

Flow paths that contribute to runoff generation are also referred to as “Runoff generation processes”

Flow paths



5,6,7 - Deep groundwater

8 - Shallow subsurface flow

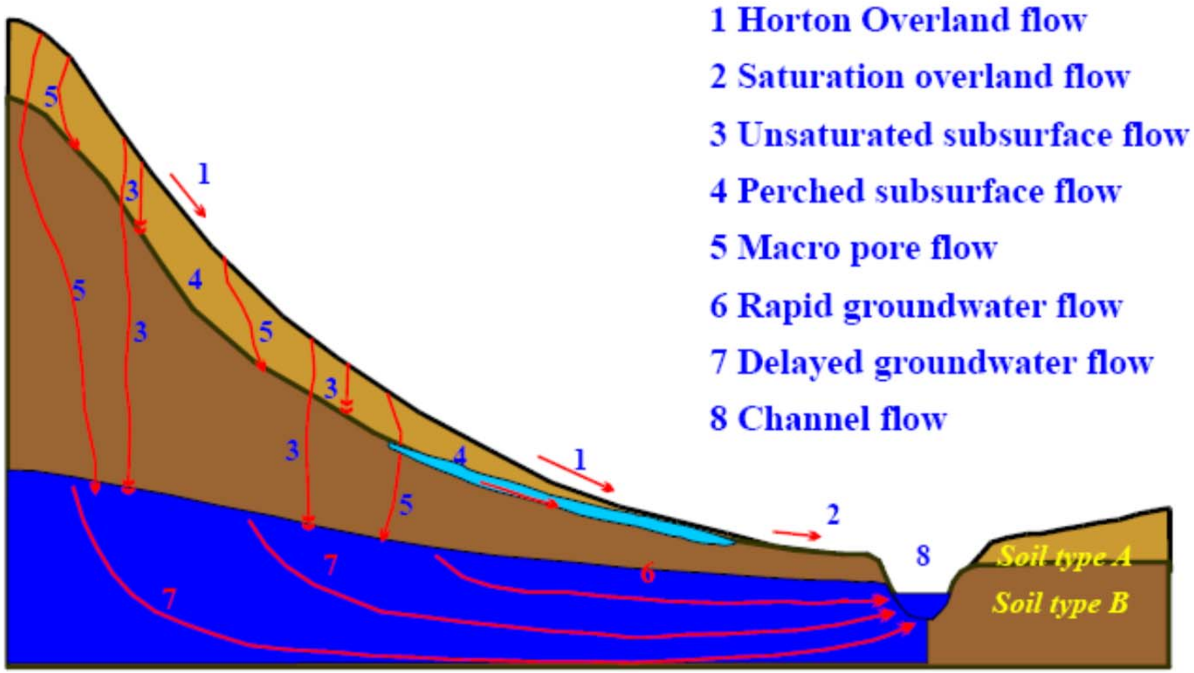
1 - Interception evaporation

2 - Hortonian overland flow

3,4 - Soil evaporation and transpiration

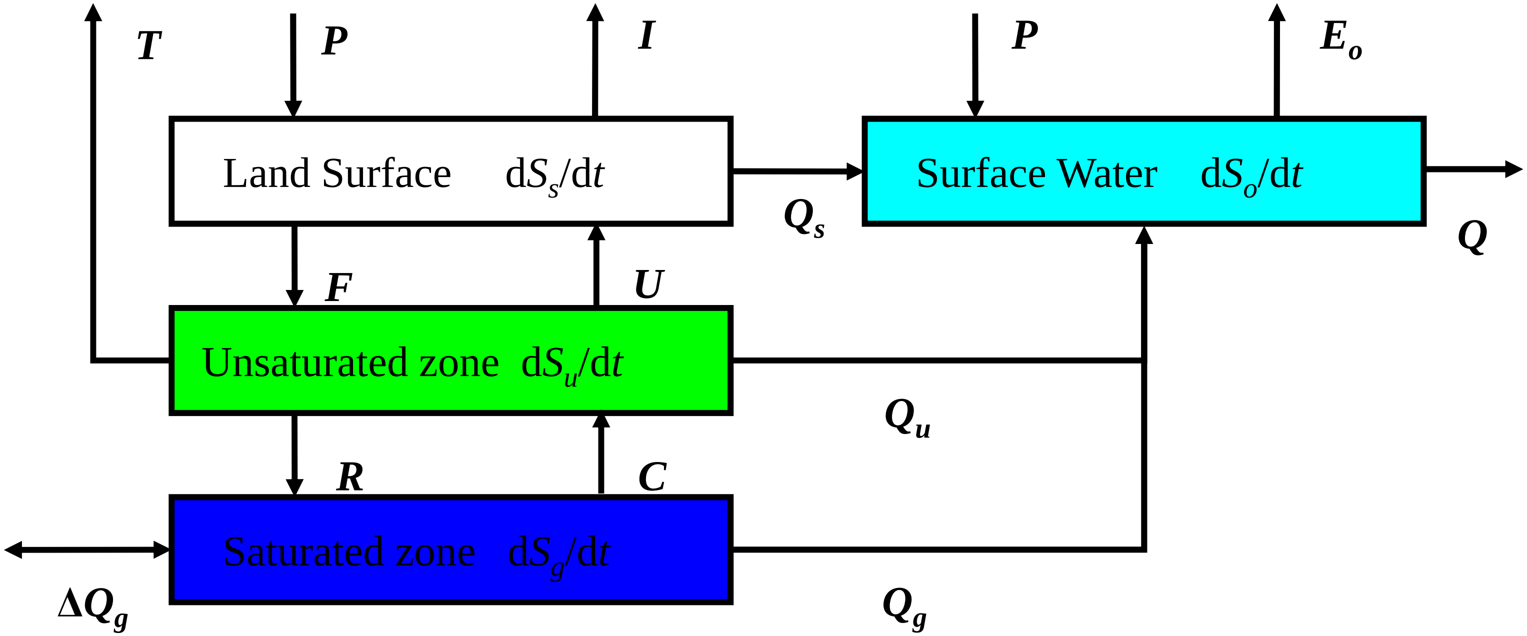
2 - Saturation excess overland flow

Flow paths

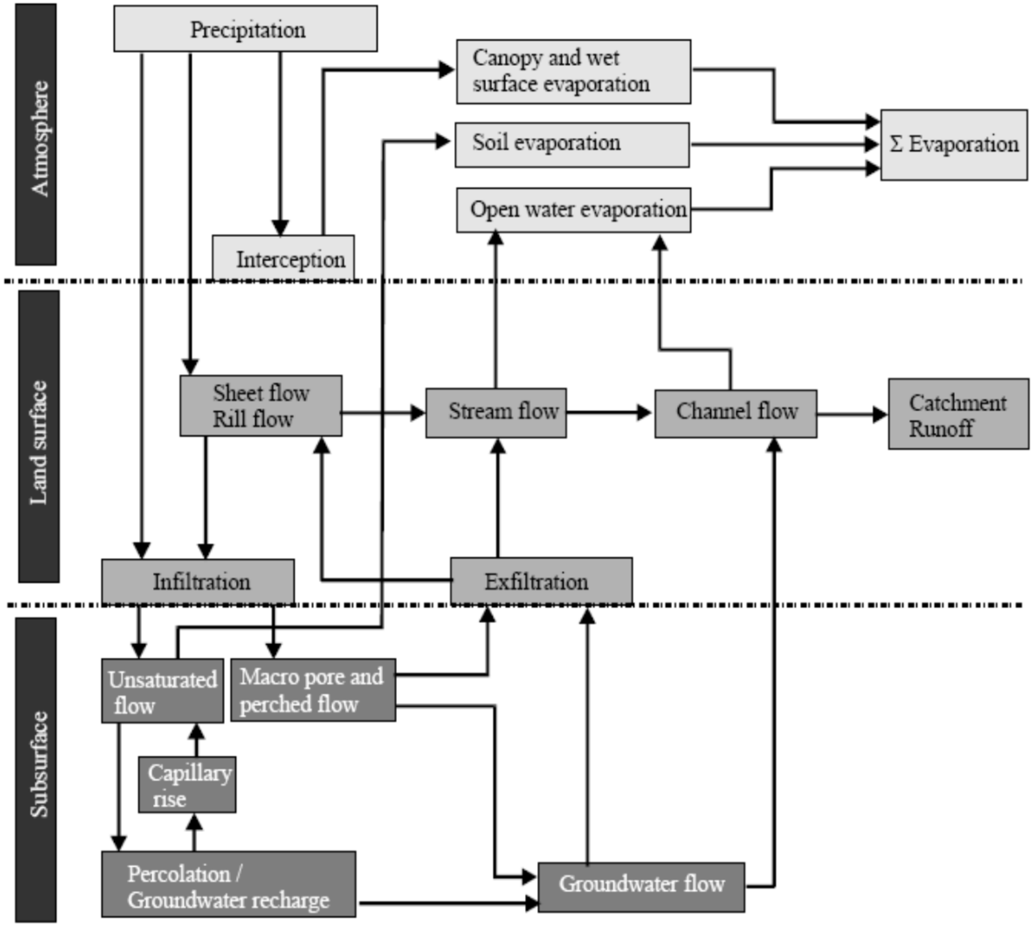


1 Horton Overland flow
2 Saturation overland flow
3 Unsaturated subsurface flow
4 Perched subsurface flow
5 Macro pore flow
6 Rapid groundwater flow
7 Delayed groundwater flow
8 Channel flow

Flow paths


T
P
I
P
E_o
Land Surface dS_s/dt
Q_s
Surface Water dS_o/dt
Q
F
U
Unsaturated zone dS_u/dt
Q_u
R
C
Saturated zone dS_g/dt
ΔQ_g
Q_g

Flow paths


Atmosphere
Land surface
Subsurface
Precipitation
Canopy and wet surface evaporation
Soil evaporation
Open water evaporation
Σ Evaporation
Interception
Sheet flow
Rill flow
Stream flow
Channel flow
Catchment Runoff
Infiltration
Exfiltration
Unsaturated flow
Macro pore and perched flow
Capillary rise
Percolation / Groundwater recharge
Groundwater flow

Scales

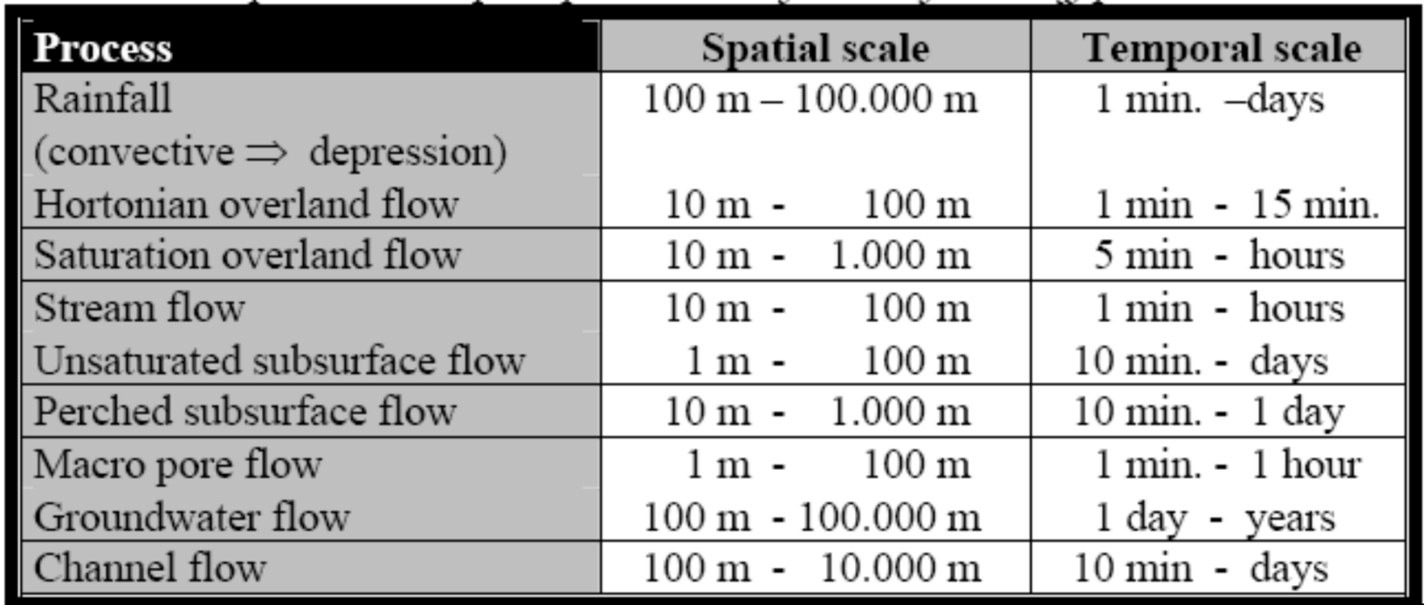


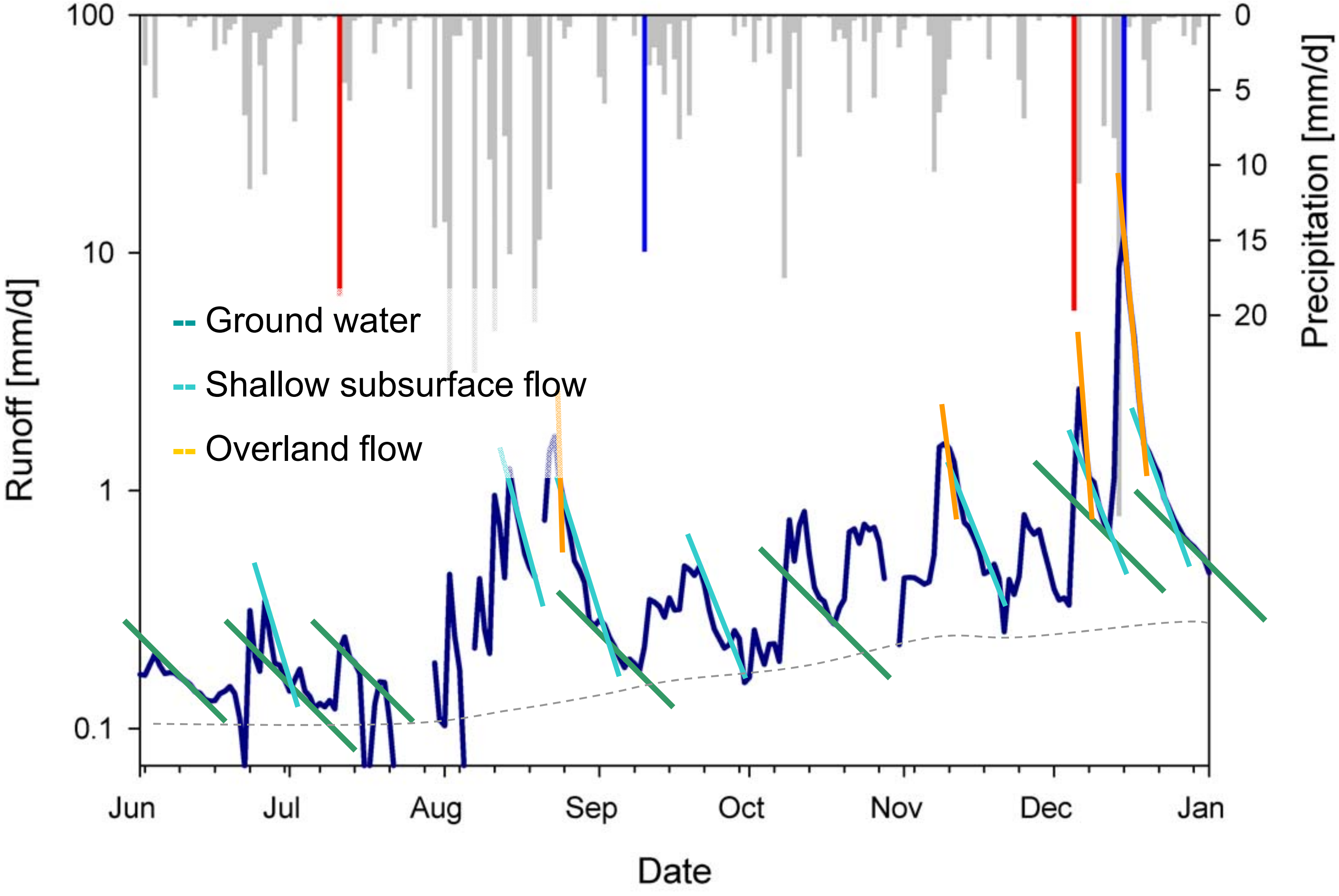
Table 12.1: *Spatial and temporal process scales of the rainfall-runoff processes*

Process	**Spatial scale**	**Temporal scale**
Rainfall (convective ⇒ depression)	100 m – 100.000 m	1 min. –days
Hortonian overland flow	10 m - 100 m	1 min - 15 min.
Saturation overland flow	10 m - 1.000 m	5 min - hours
Stream flow	10 m - 100 m	1 min - hours
Unsaturated subsurface flow	1 m - 100 m	10 min. - days
Perched subsurface flow	10 m - 1.000 m	10 min. - 1 day
Macro pore flow	1 m - 100 m	1 min. - 1 hour
Groundwater flow	100 m - 100.000 m	1 day - years
Channel flow	100 m - 10.000 m	10 min - days
Interception	same as rainfall	1 min - 1 day
Transpiration	same as catchment	weeks - months
Open water evaporation	same as water body	months - years

Flow processes are active at different timescales.

<u>To make things worse</u>:
All processes can and do occur at the same time!

Hydrograph


100
10
1
0.1
Runoff [mm/d]
0
5
10
15
20
Precipitation [mm/d]
-- Ground water
-- Shallow subsurface flow
-- Overland flow
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Date

Fundamentals

All flow pathways have to obey the principle of **Conservation of mass**:

$$\frac{dS}{dt} = I(t) - O(t)$$

Where t is the time step, S is the water storage, I is the input and O is the output

Conservation of mass for the entire catchment is the **Catchment Water Balance**:

$$\frac{dS}{dt} = P(t) - E(t) - T(t) - Q(t)$$

Where P is precipitation, E is evaporation, T is transpiration and Q is runoff.

Groundwater

Bernoulli equation

Velocity head

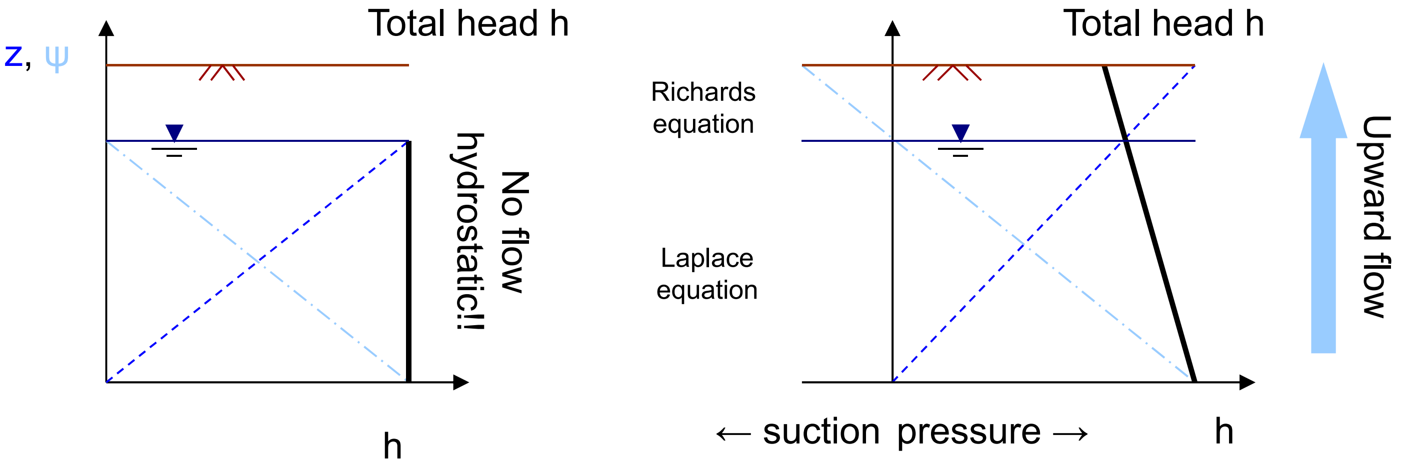
~ 0 in GW

Elevation head z

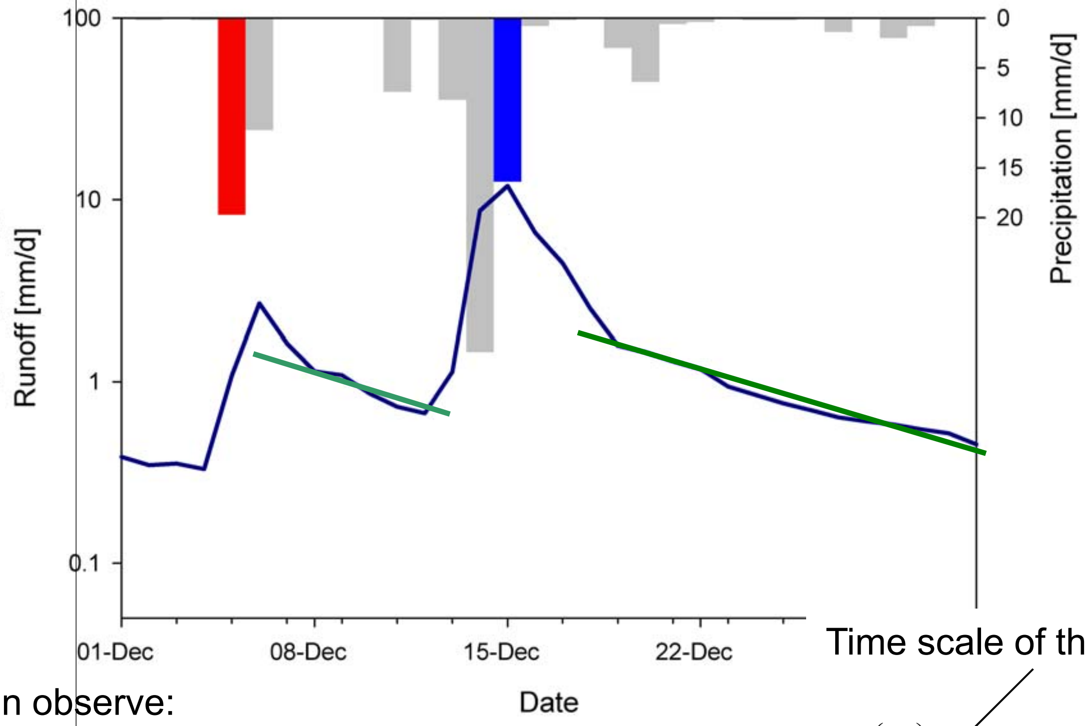
Pressure head ψ

$$h = \cancel{\frac{v^2}{2g}} + z + \frac{p}{\rho g} = const.$$

Where h is the total head, v is the velocity, z is the elevation above datum, p is the hydrostatic pressure and ρ is the density



Groundwater – Linear Reservoir



Time scale of the process!

We often observe:

$$Q(t) = Q_0 e^{\left(-\frac{t}{k}\right)}$$

and we know:

For deep groundwater in a dry period ~ 0

$$\frac{dS}{dt} = \cancel{P(t)} - \cancel{I(t)} - \cancel{T(t)} - Q(t)$$

$$\frac{dS}{dt} = -Q_0 e^{\left(-\frac{t}{\enclose{circle}{k}}\right)}$$

$$S(t) = kQ_0 e^{\left(-\frac{t}{k}\right)}$$

$$\boxed{Q(t) = \frac{S(t)}{k}}$$

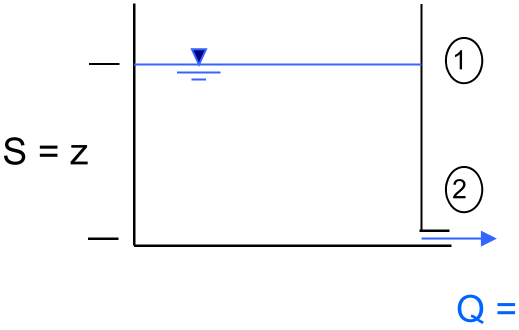
Linear Reservoir

Groundwater – Linear Reservoir

Linear Reservoir is an empirical concept. Does it relate to hydraulic laws?

Remember Bernoulli's Law: $h = \frac{v^2}{2g} + z + \frac{p}{\rho g} = const.$

And imagine groundwater as a simple large bucket with an outlet ($A_1 >> A_2$):



$$\frac{v_1^{\,2}}{2g} + S_1 + \frac{p_1}{\rho g} = \frac{v_2^{\,2}}{2g} + S_2 + \frac{p_2}{\rho g}$$

Atmospheric pressure!

$$\frac{0^2}{2g} + S_1 + \frac{0}{\rho g} = \frac{v_2^{\,2}}{2g} + 0 + \frac{0}{\rho g}$$

$$v_2 = \sqrt{2gS_1}$$

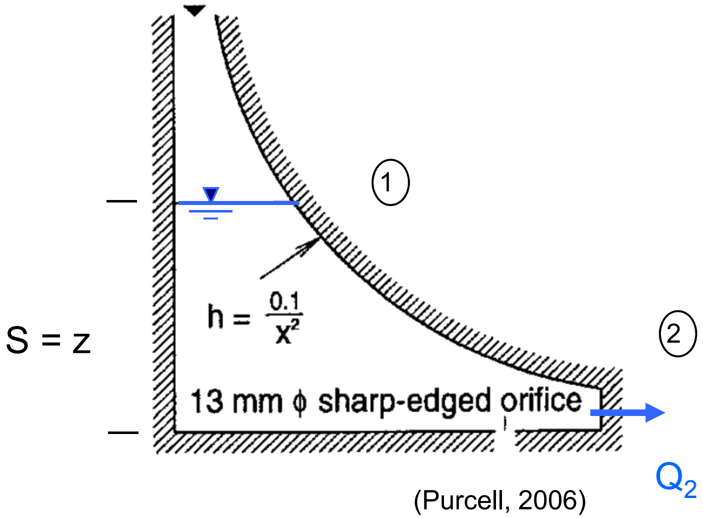
$$Q_2 = A_2\sqrt{2gS_1} = A_2\sqrt{2g}\sqrt{S_1} \qquad A_2\sqrt{2g} = \frac{1}{k}$$

But: $Q_{lin} = \frac{1}{k} S_1 \quad \neq \quad Q_2 = \frac{1}{k}\sqrt{S_1}$

→ ????

Groundwater – Linear Reservoir

It was shown that the shape of the reservoir influences the outflow.

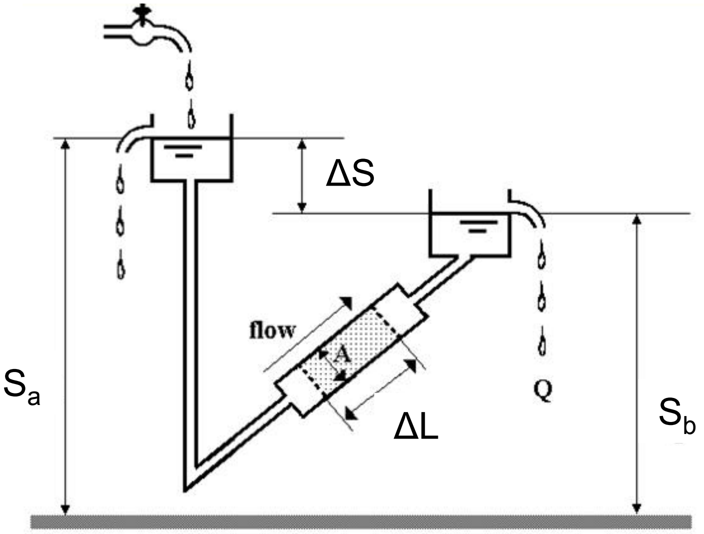


(Purcell, 2006)

$$Q_{lin} = \frac{1}{k} S_1 \quad = \quad Q_2 = \frac{1}{k} S_1$$

Reservoir shape which reminds of concave, convergent hillslopes reproduces the behaviour of the linear reservoir

Groundwater – Linear Reservoir



Different way to derive the Linear Reservoir is by turning to Mr.**Darcy** and his law of water flowing from high to low potential:

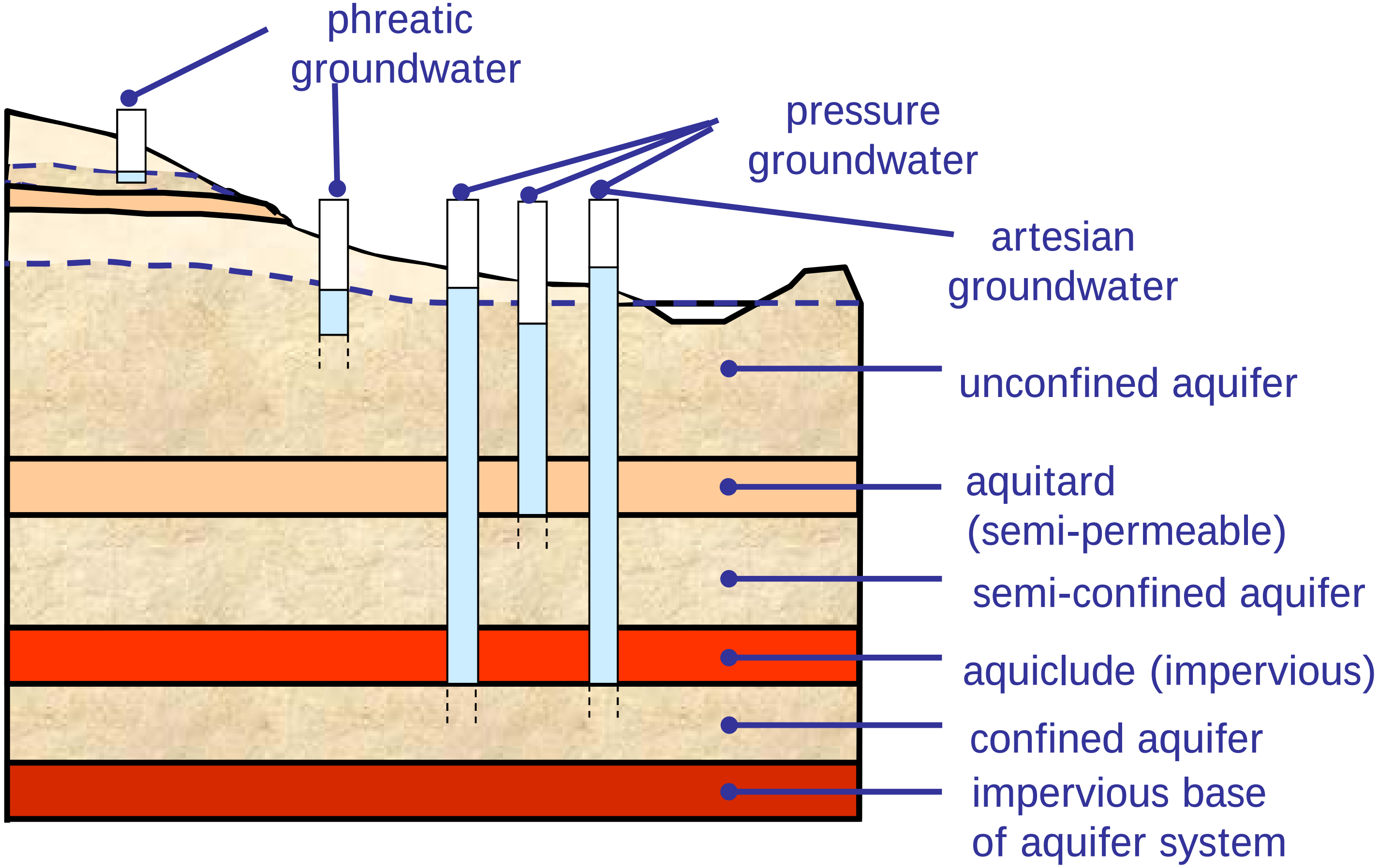
$$v = k_S \frac{dS}{dL}$$

$$Q_{Darcy} = A \cdot v = Ak_S \frac{dS}{dL} \qquad Ak_S \frac{1}{dL} = \frac{1}{k}$$

With $dS = S_1$ →

$$\boxed{Q_{lin} = \frac{1}{k} S_1 \;=\; Q_{Darcy} = \frac{1}{k} S_1}$$

Groundwater



phreatic groundwater

pressure groundwater

artesian groundwater

unconfined aquifer

aquitard (semi-permeable)

semi-confined aquifer

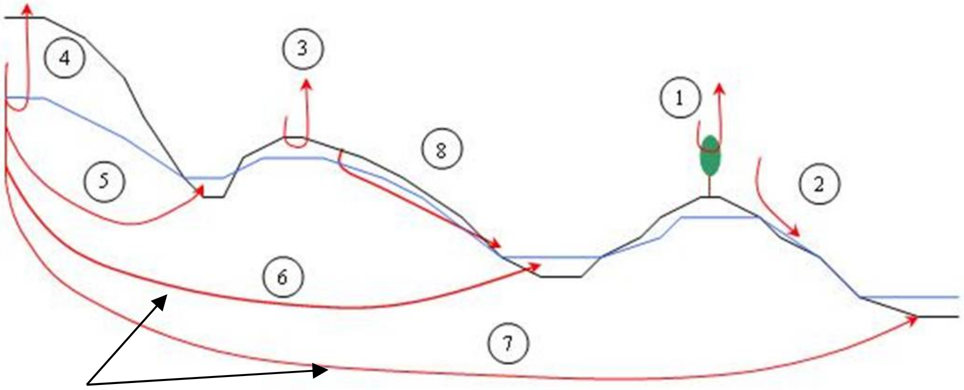
aquiclude (impervious)

confined aquifer

impervious base of aquifer system

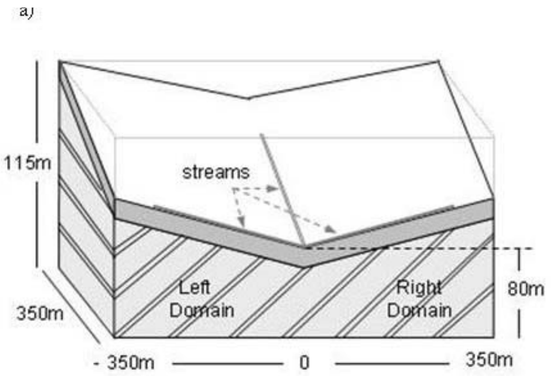
Water storage and movement in pores, fractures, solution channels and caverns (e.g. Karst)

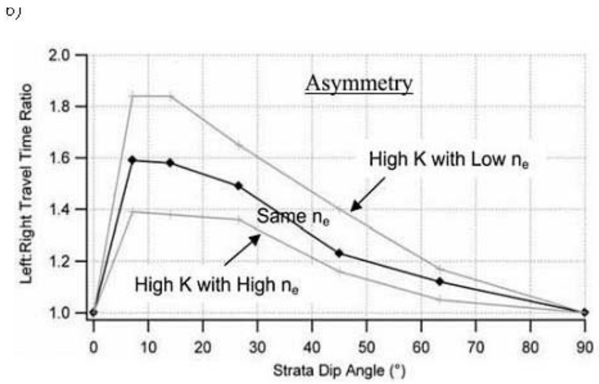
Groundwater import and export



Regional Groundwater flow (5,6)

→ catchments can gain or loose water, depending on geology and topography !!!





Groundwater resources

Advantages of groundwater resources

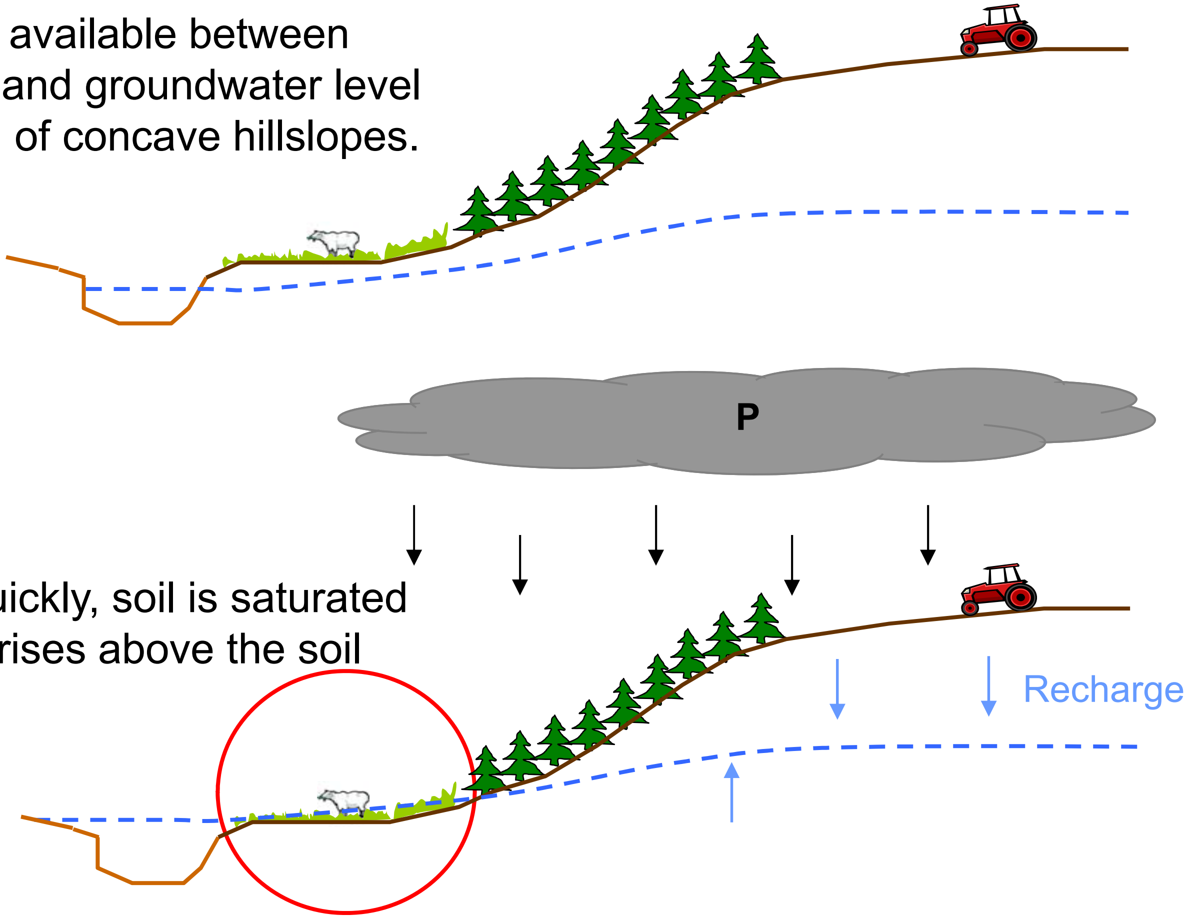
- reliable resource
- bacteriologically safe
- frequently available in-situ
- water supply at times that surface water resources are limited
- not affected by evaporation loss, if deep enough
- large storage capacity
- easily managed

Disadvantages of groundwater resources

- Strongly limited resource
- Recovery is expensive due to pumping costs
- Vulnerable and sensitive to pollution
- Impact on land subsidence and/or salinization

Saturation Overland Flow

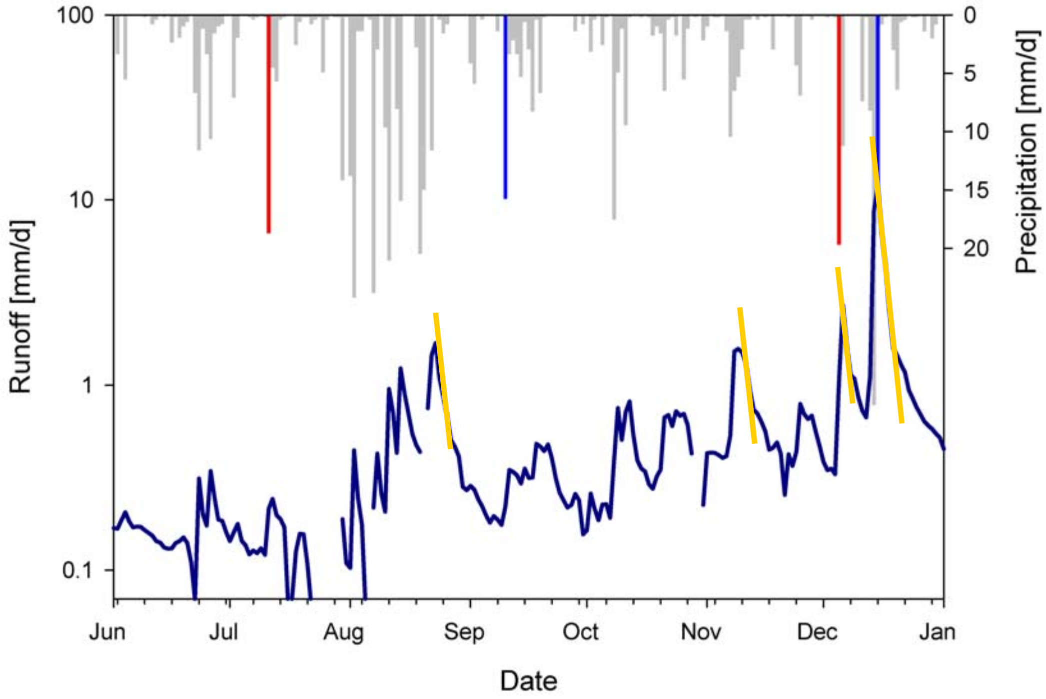
Little storage available between soils surface and groundwater level at the bottom of concave hillslopes.



Storage fills quickly, soil is saturated → water level rises above the soil surface

Saturation overland flow (SOF)

Saturation Overland Flow



Saturation overland flow (SOF) is a very fast flowpath with timescales between minutes and hours.

Occurrence not only dependent on wetness and hillslope shape, but also on permeability of the soil.

Saturation Overland Flow

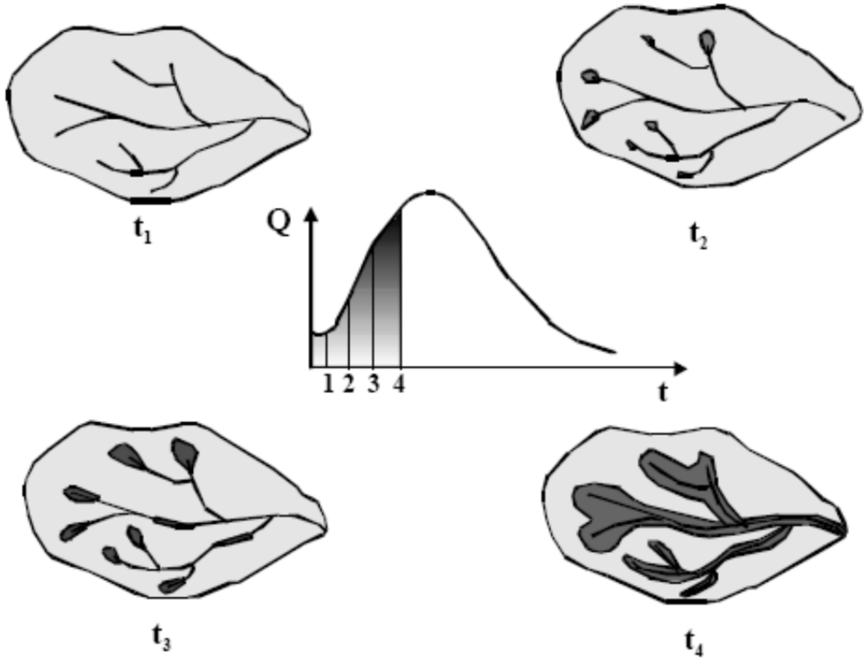
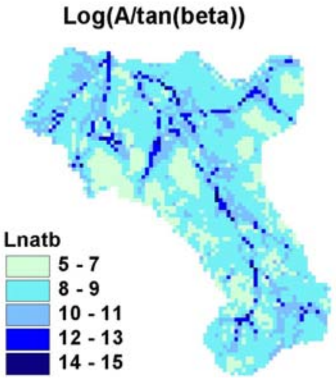


Figure 12.5: *Expansion of the saturation overland flow source area during a storm event [modified after Dunne, 1978]*

Saturation Overland Flow - TWI

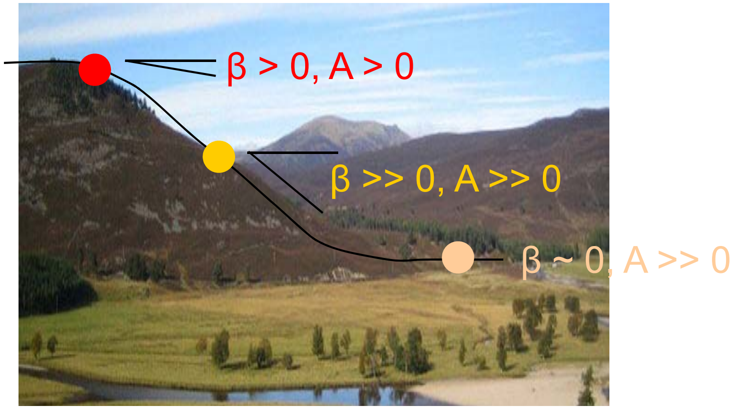
Topographic Wetness Index (TWI; Beven and Kirkby, 1979)

$$TWI = \ln\left(\frac{A}{\tan\beta}\right)$$



Where A is the contributing area per unit contour length and β is the angle of the local slope

TWI indicates the **likelihood of saturation** in a certain point of the catchment



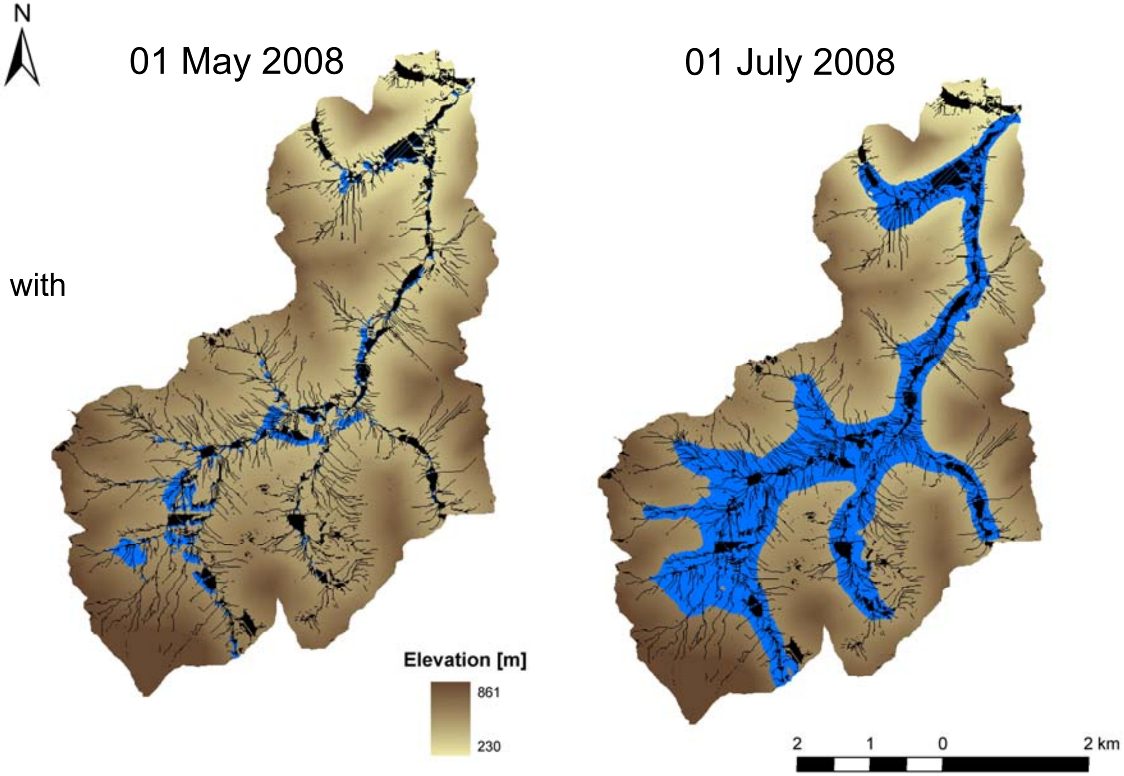
→ TWI: low

→ TWI: medium - low

→ TWI: high

Saturation Overland Flow - TWI

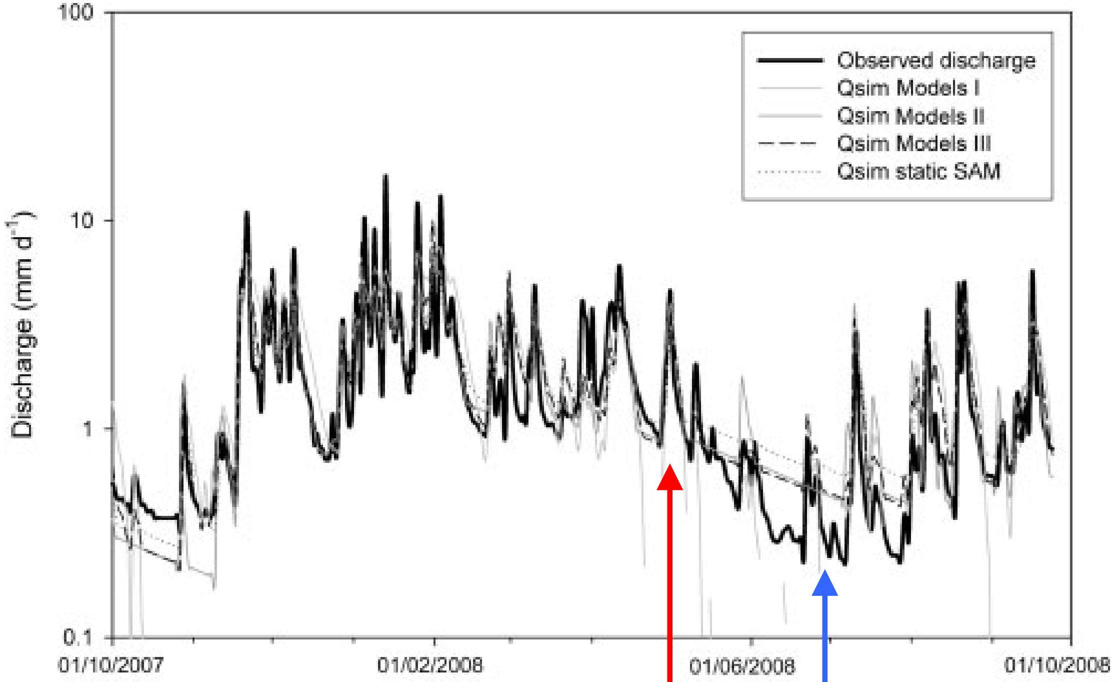
█ - Areas with high TWI

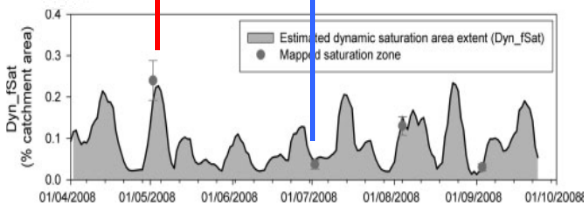

01 May 2008

01 July 2008


(Birkel et al., 2009)

Saturation Overland Flow





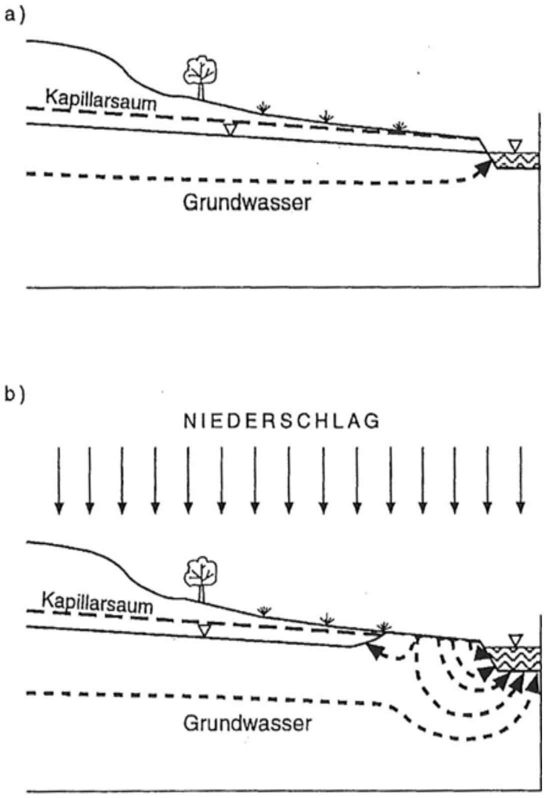
High proportions of saturated area when groundwater level is high, low proportion when groundwater level is low

(Birkel et al., 2009)

Saturation Overland Flow

Groundwater Ridging:

- Closely related to SOF
- Capillary fringe of near-surface groundwater is quickly saturated as result of the reduced available empty pore volume.



Uhlenbrook, S. (1999)

Saturation Overland Flow

Where does SOF occur?

Frequently in wide
valley bottoms.
Rare in steep terrain.

Indicator plants include:

- Poplar (*Populus*)
- Willow (*Salix*)
- Alder (*Alnus*)

and the most other species in and around the Dutch Polder landscape

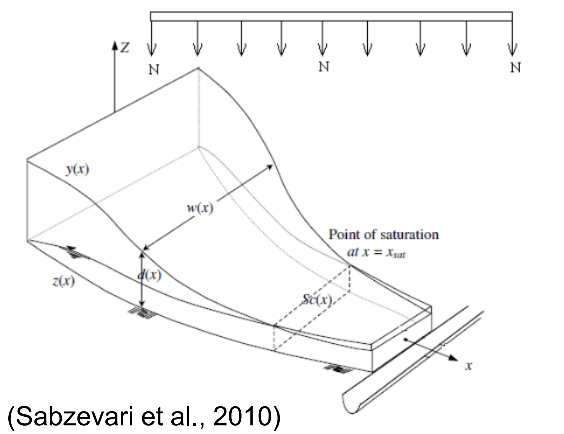
Saturation Overland Flow

Saturation Overland Flow

Saturation Overland Flow

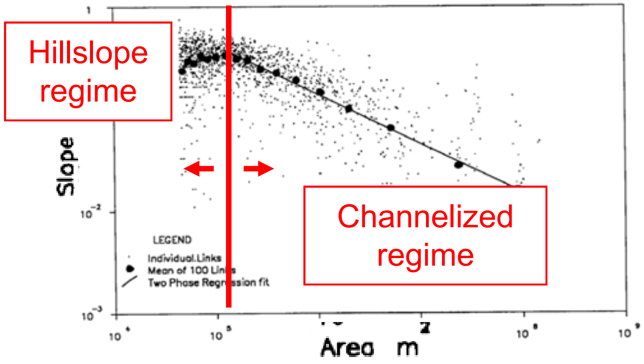
SOF can also be found in the headwaters !

Saturation Overland Flow

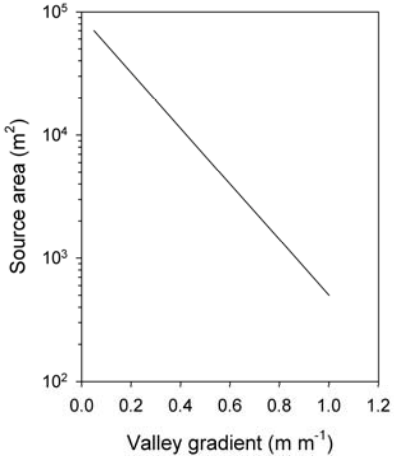


(Sabzevari et al., 2010)

On mostly (convergent) hillslopes, constant saturation can lead to the formation of channels: **springs**



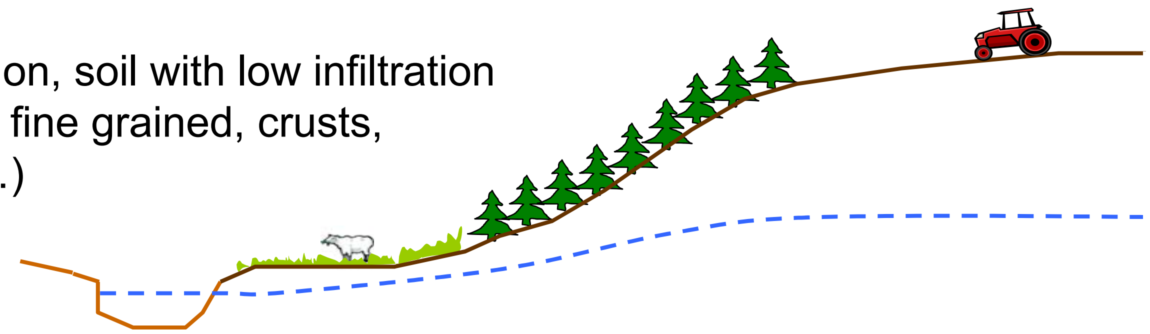
(Tarboton et al., 1992)



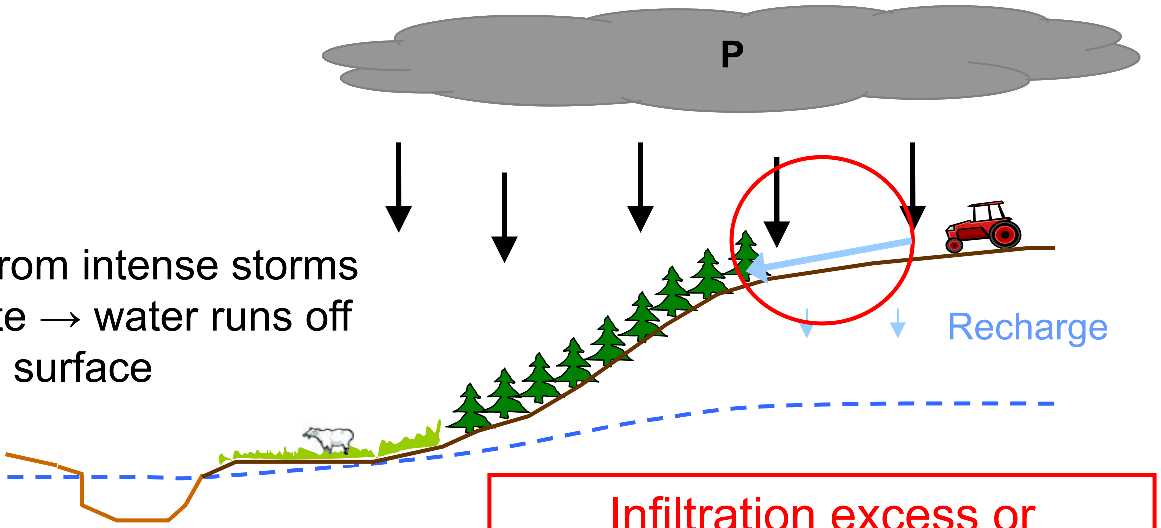
(after Montgomery and Dietrich, 1988)

Hortonian Overland Flow

Thin vegetation, soil with low infiltration capacity (i.e. fine grained, crusts, compacted…)



Precipitation from intense storms cannot infiltrate → water runs off on the ground surface

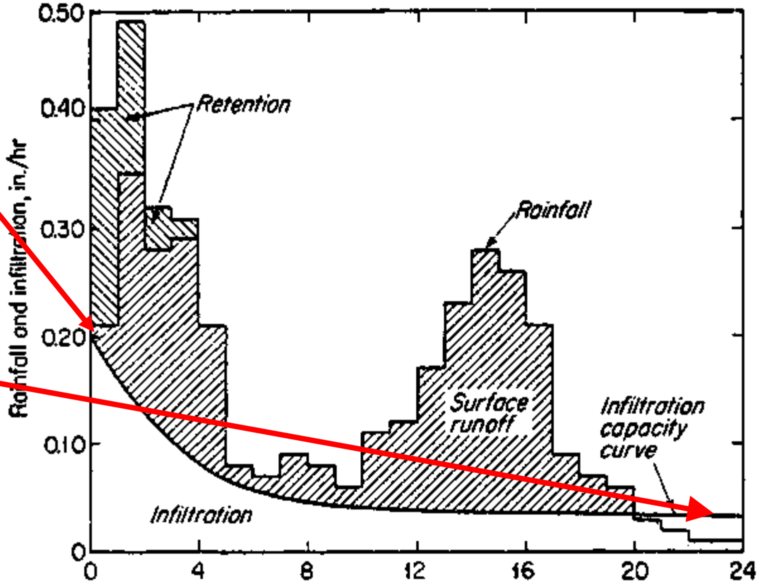


Infiltration excess or Hortonian overland flow (HOF)

Infiltration

Infiltration capacity $\mathbf{Q_i}$ reduces from an high initial infiltration capacity to the saturated infiltration capacity $\mathbf{Q_i^{sat}}$ or the saturated hydraulic conductivity $\mathbf{K^{sat}}$

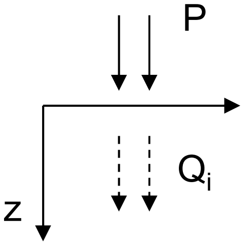
But why is $\mathbf{Q_i}$ declining when soil moisture increases ?????



Darcy's Law:

$$q = K \frac{\partial h}{\partial L}$$

Here: vertical infiltration → ∂L = ∂z



$$q_i = K \frac{\partial h}{\partial z} = K \frac{\partial(\psi + z)}{\partial z} = K \frac{\partial \psi}{\partial z} + K \frac{\partial z}{\partial z} = K\left(\frac{\partial \psi}{\partial z} + 1\right)$$

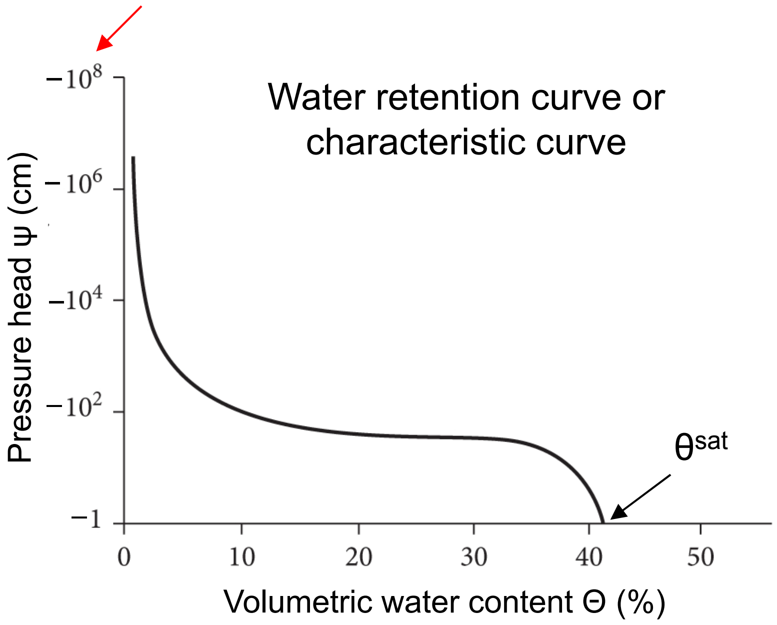
Pressure head ψ

Elevation head z

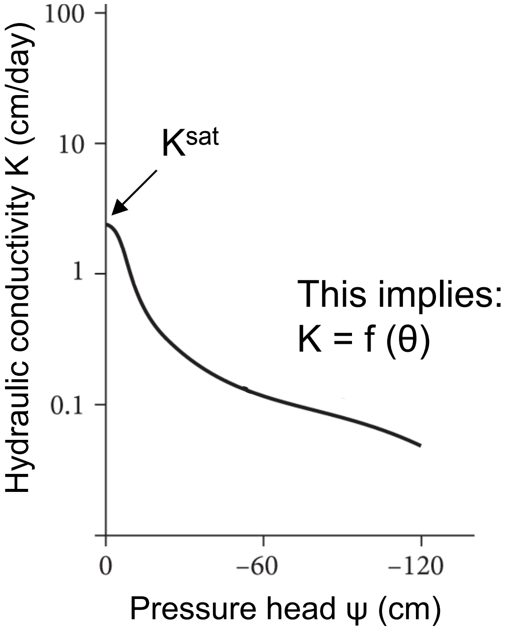
Pressure gradient ∂ψ/∂z

Infiltration

Negative in unsaturated zone → suction !!



Water retention curve or characteristic curve



This implies:
$K = f(\theta)$

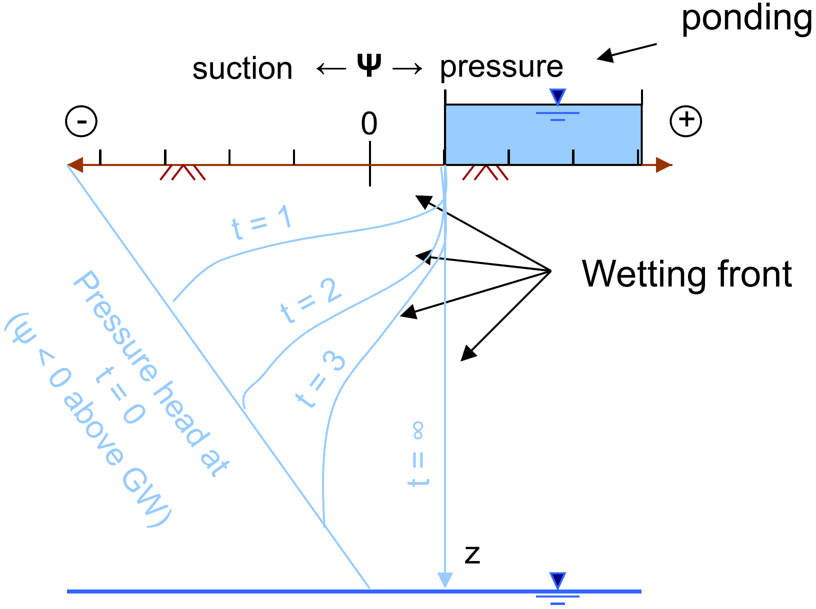
Volumetric water content $\theta = V_w/V_{total}$

As volumetric water content θ increases (i.e. suction or water tension decreases), pressure head ψ increases as well.

Hydraulic conductivity K increases with increasing pressure head ψ
→ the wetter the soil the more conductive !

If K increases with water content, why does infiltration decrease then???????

Infiltration



Pressure gradient:

$$\frac{\psi(0)-\psi(Z)}{z(0)-z(Z)}=\frac{\partial\psi}{dz}$$

at t = 0: pressure gradient dψ/dz high → $q_i = K(\theta)\left(\frac{\partial\psi}{\partial z}+1\right)$ → q_i is high

at t > 0: pressure gradient dψ/dz decreasing (wetting)

at t = ∞: no more pressure gradient dψ/dz = 0 → $q_i = K(\theta)\left(\frac{\partial\psi}{\partial z}+1\right)$

→ $q_i = K^{sat}$ = low

Infiltration capacity q_i decreases, in spite of high hydraulic conductivity $K = K^{sat}$, because with increasing water content at depth, the vertical hydraulic gradient decreases as well !!

Hortonian Overland Flow

Hortonian overland flow important in **arid to sub-humid** climate in areas with tendency for **intensive rainstorms** and **thin vegetation layer** or disturbed soil

Surface type	Infiltration capacity K^{sat} (cm/hr)	Dominant flow path
Clay rangeland	0.2	HOF
Sandy rangeland	2	
	~ limit of rainfall intensity	
Sandy soils, humid	8	SSF
Rainforest	135	
Oregon coast range	> 500	SOF

<u>However:</u>

if rainfall rate > infiltration capacity not immediately HOF
→ water has to overcome depression (surface) storage
→ more time for infiltration !

Hortonian Overland Flow

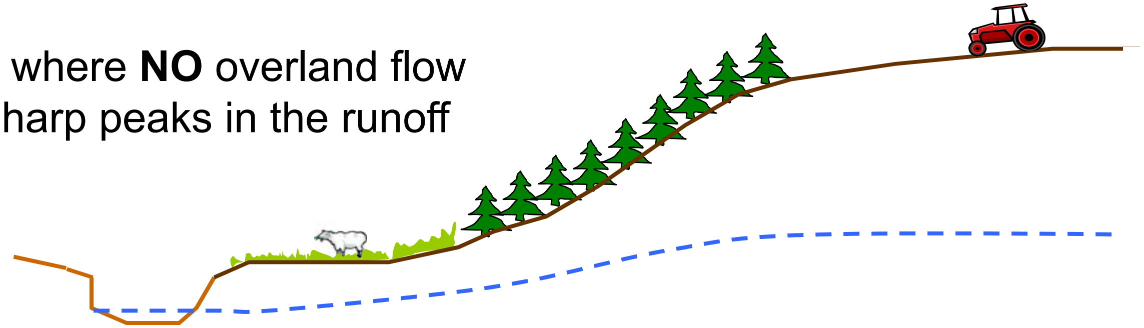
Hortonian Overland Flow

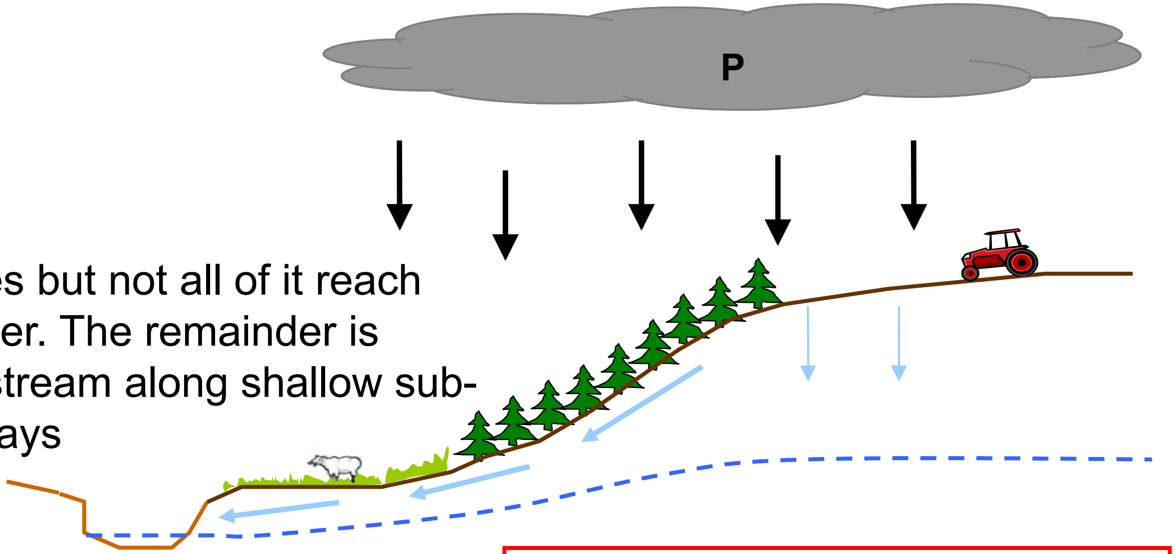
fredhoogervorst.com ©

(c) Cranfield University, 2000

Shallow subsurface flow

Even in areas where **NO** overland flow is observed, sharp peaks in the runoff occur.





Water infiltrates but not all of it reach the groundwater. The remainder is routed to the stream along shallow sub-surface pathways

Shallow or Rapid Subsurface Infiltration Excess flow (SSF)

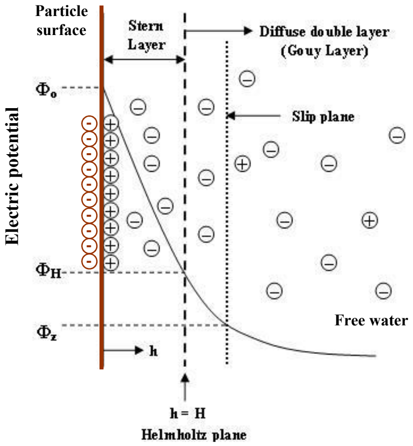
Unsaturated zone

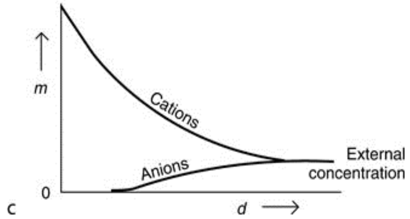
The unsaturated zone (also: vadose zone or soil moisture zone) is the zone above the phreatic groundwater table.

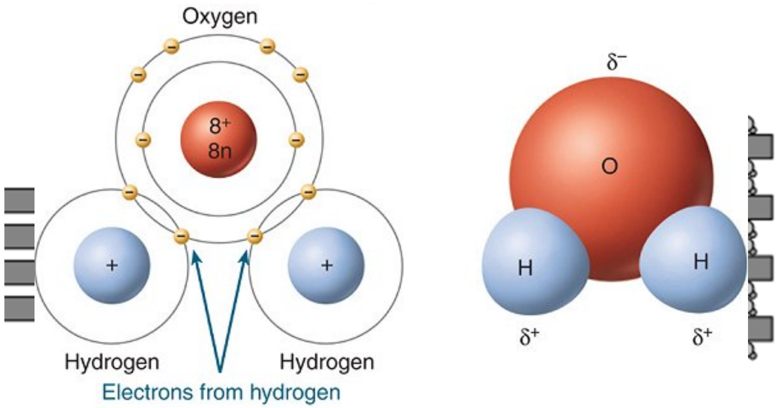
Pressure head $\psi < 0$ → suction (caused by evaporation, transpiration and water tension)

First source of nonlinearity in the rainfall-runoff process.

What does actually happen in the unsaturated zone?







(a) Electron shells in a water molecule

(b) Distribution of partial charges in a water molecule

Polar molecule!

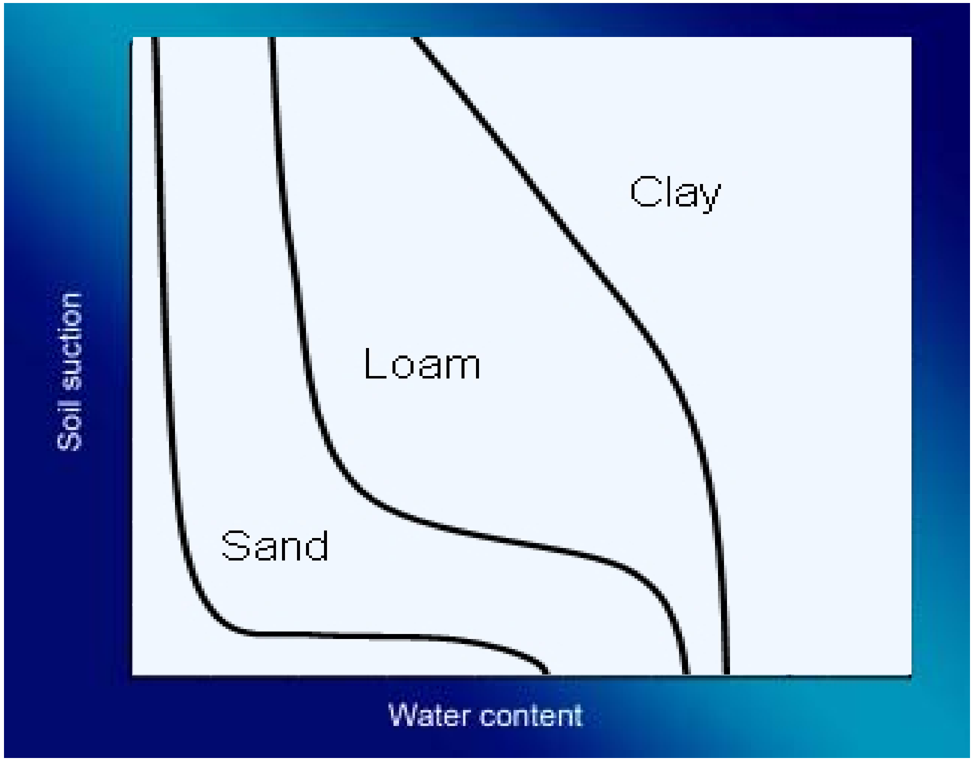
Unsaturated zone

Flow in soil with different water content:

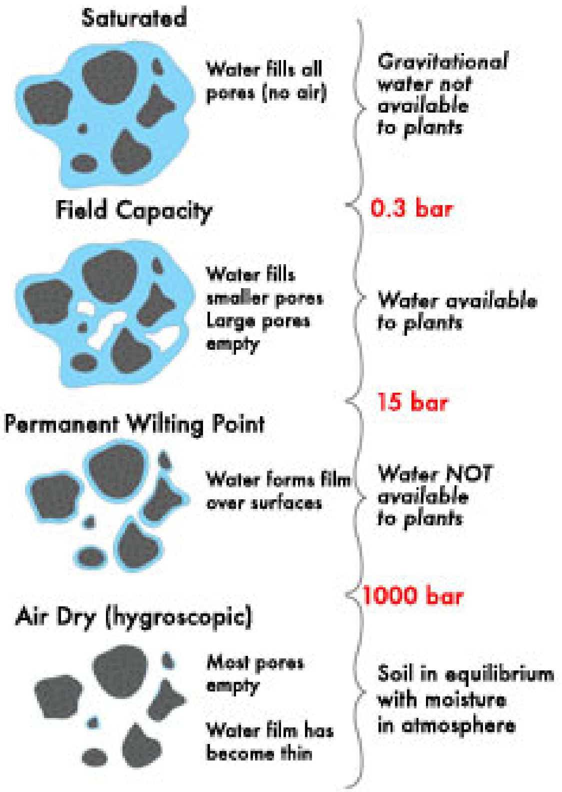
(a) at saturation building of hydrostatic pressure head → Darcy
(b) partial saturation → Richards equation
(c) No flow

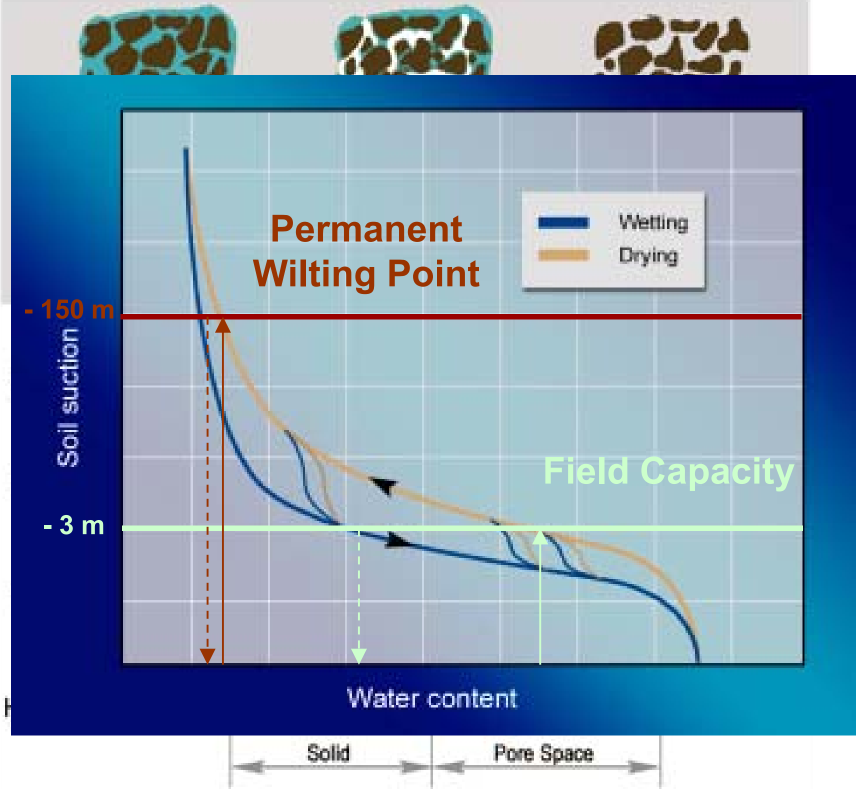
Water retention curve

- also "characteristic curve"
- gives us the pressure head at a given water content in the unsaturated zone.
- Pressure head ψ negative → **suction!!**
- As water content increases, pressure head increases (or suction decreases)
- Different for every soil



Unsaturated zone

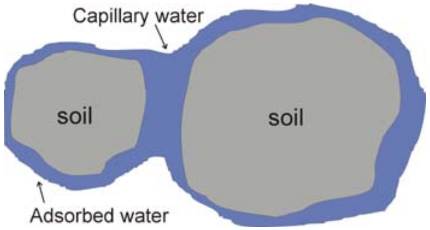


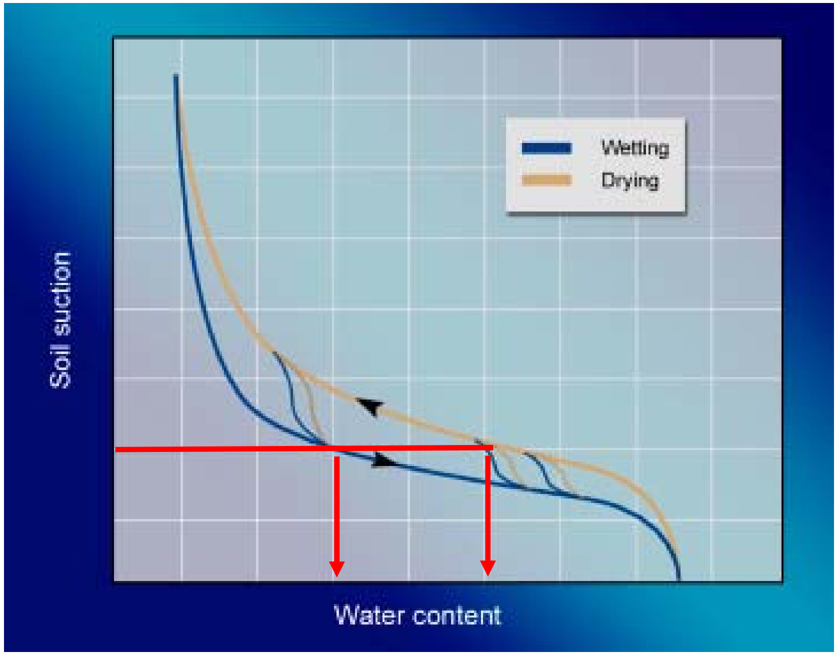


<u>Field capacity</u> is the amount of water that can be held **against gravity**. It is the water content held in the soil after excess water drained away. Reached ~ 2-3 days after precipitation.

<u>Permanent wilting point</u> is the minimal amount of water at which plants can extract water against the suction forces.

Hysteresis - Capillarity

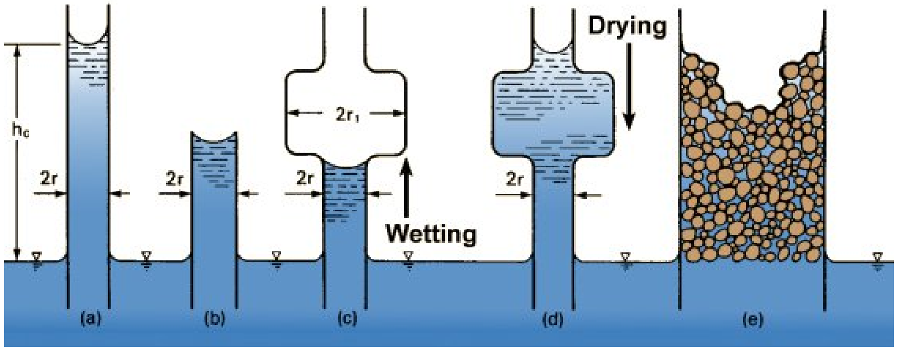




Pressure head different at equal water content for wetting and drying → Hysteresis

Why? Capillary action!

- Capillarity is the ability of a fluid to flow against gravity in thin tubes
- Caused by surface tension of fluid and adhesion
- dependent on fluid and tube radius



$$h_c = \frac{2\gamma \cos \beta}{\rho g r}$$

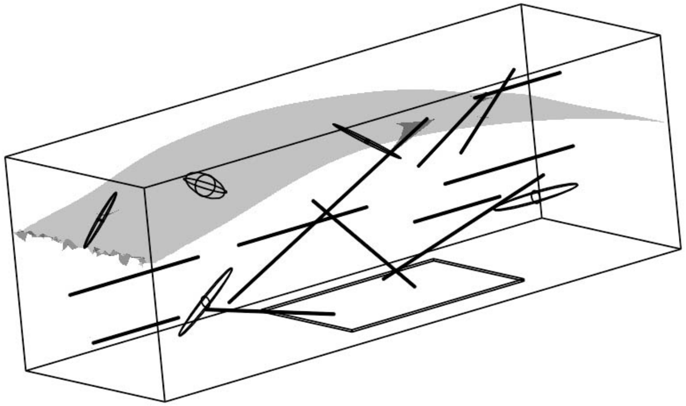
Where h_c is the capillary rise, γ is the liquid-air surface tension, β is the contact angle, ρ is the density of the liquid, g is gravity and r is the radius of the tube

Macropores

How can shallow subsurface flow be explained?

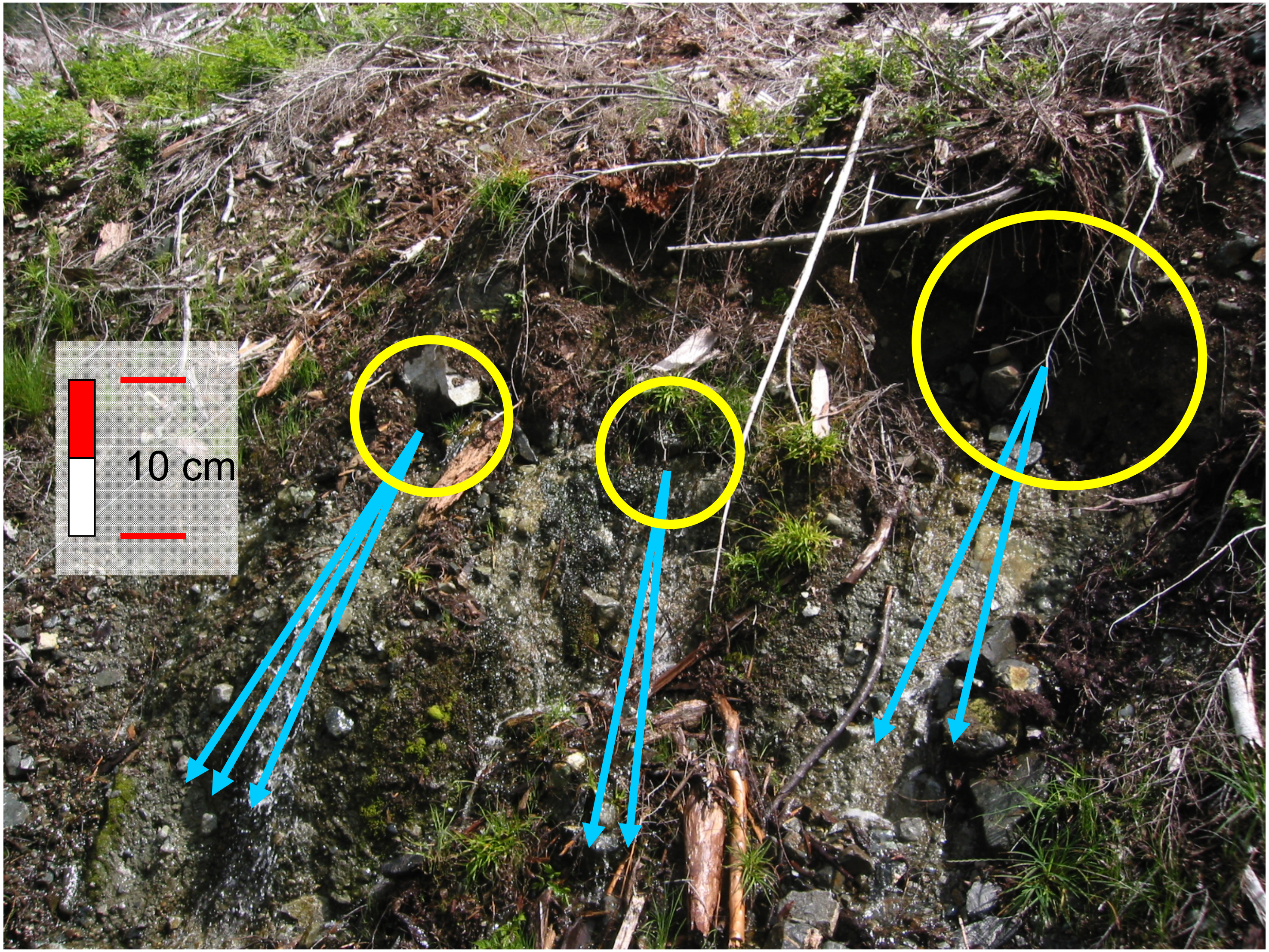
<u>For example:</u>
(1) by macropores or
(2) by the Fill-and-Spill Theory

- Macropores are defined as cavities in the soil that have a diameter **> 75 µm**
- they are created by **root canals**, **animal burrows**, **subsurface erosion**, **cracks** and **fissures**
- depending on their degree of connectivity with the stream they can **rapidly route water** laterally through the soil before it reaches the groundwater
- yield depends also on **size**, **shape**, **direction** and **distribution** of macropores
- active macropore network expands as degree of saturation increases

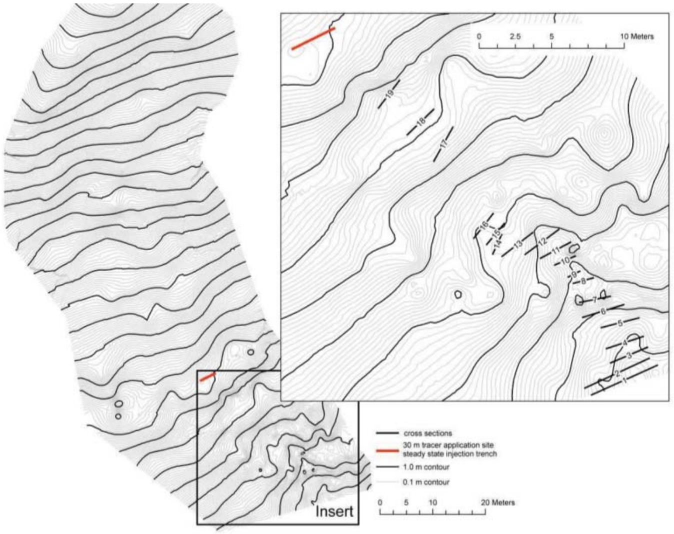


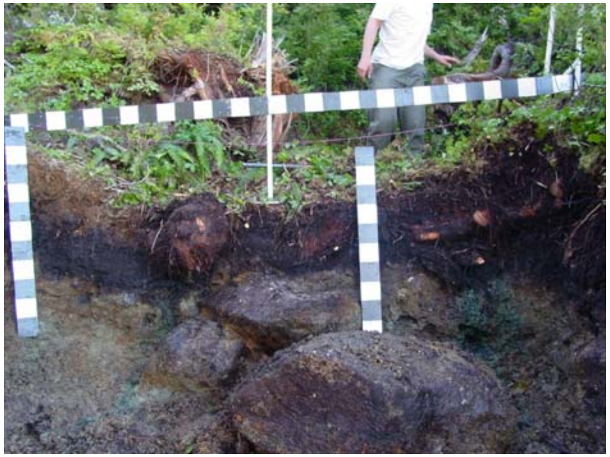
Nieber, J.L., Sidle, R.C., Steenhuis, T.C. (2006)

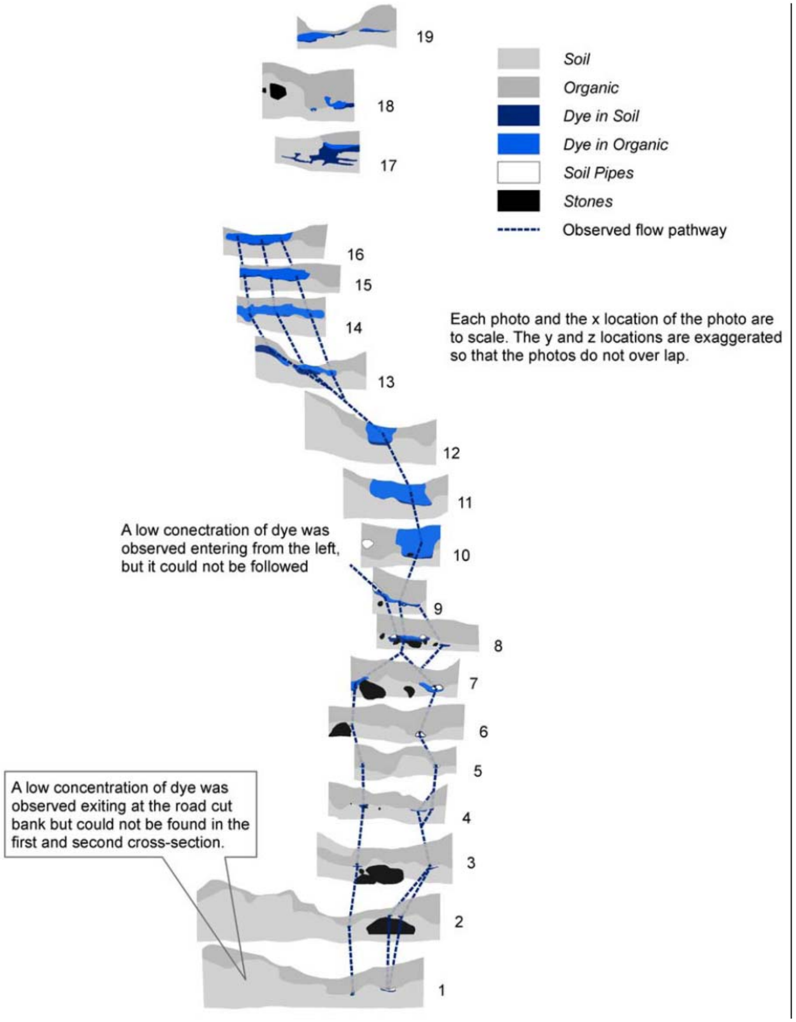
Macropores



Macropores







Each photo and the x location of the photo are to scale. The y and z locations are exaggerated so that the photos do not over lap.

A low conectration of dye was observed entering from the left, but it could not be followed

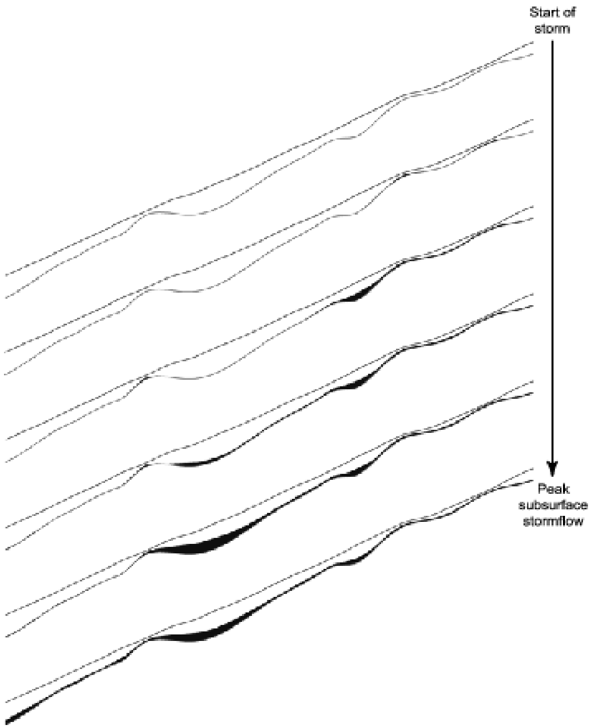
A low concentration of dye was observed exiting at the road cut bank but could not be found in the first and second cross-section.

Anderson et al., 2009

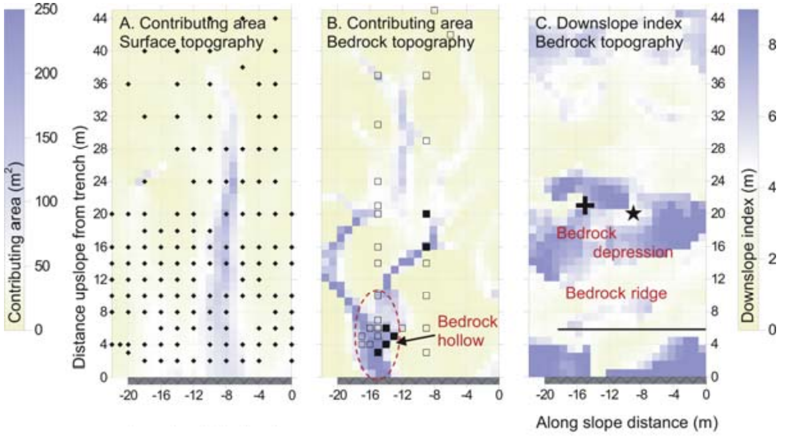
Fill-and-Spill hypotheses

The Fill-and-Spill hypotheses rejects the assumption of bedrock topography reflecting surface topography

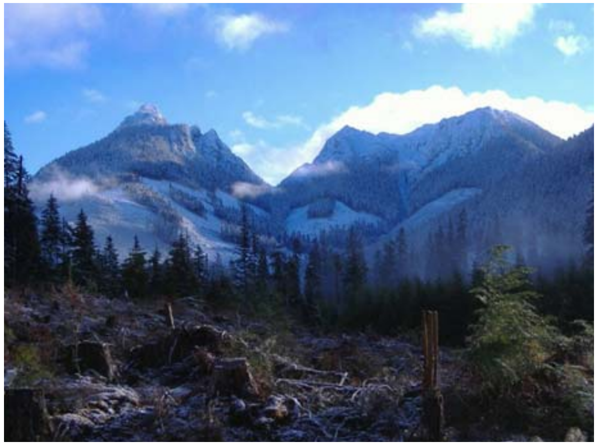
Ponding storage above a flow impeding layer must be exceeded (i.e. threshold precipitation)
→ water is then rapidly routed to the stream on top of the flow impeding layer

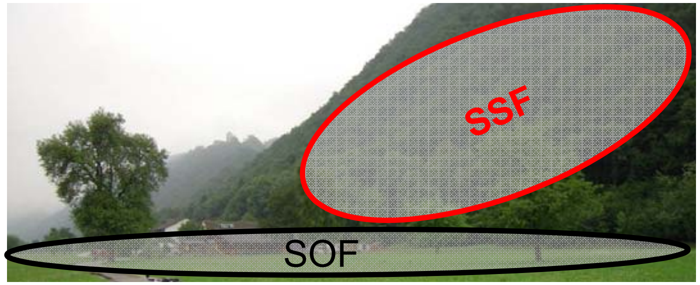


Fill and spill, Tromp-van Meerveld, H.J., McDonnell,J.J. (2006)

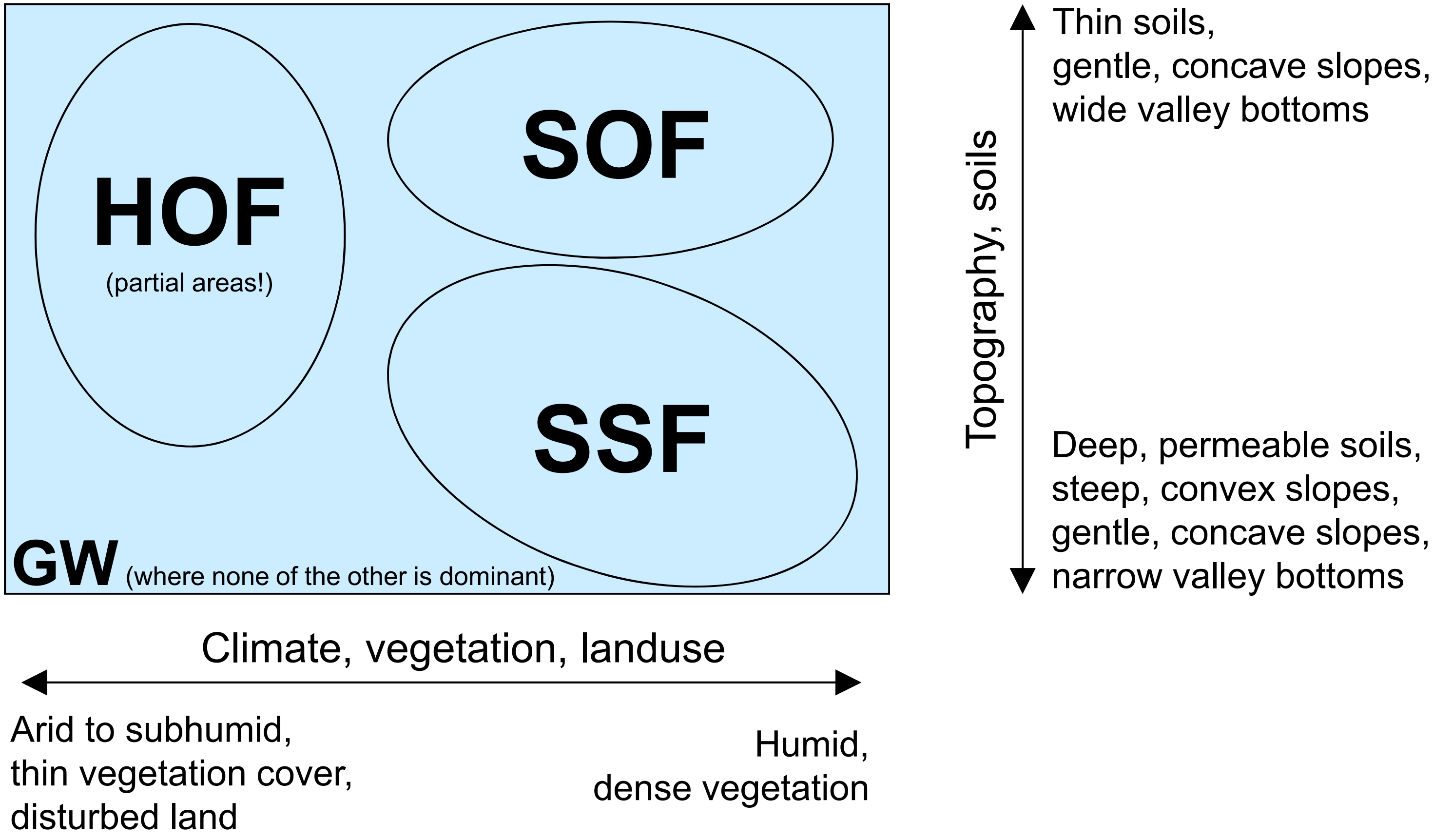


Shallow subsurface flow





Dominant Runoff processes



HOF

(partial areas!)

SOF

SSF

GW (where none of the other is dominant)

Climate, vegetation, landuse

Arid to subhumid,
thin vegetation cover,
disturbed land

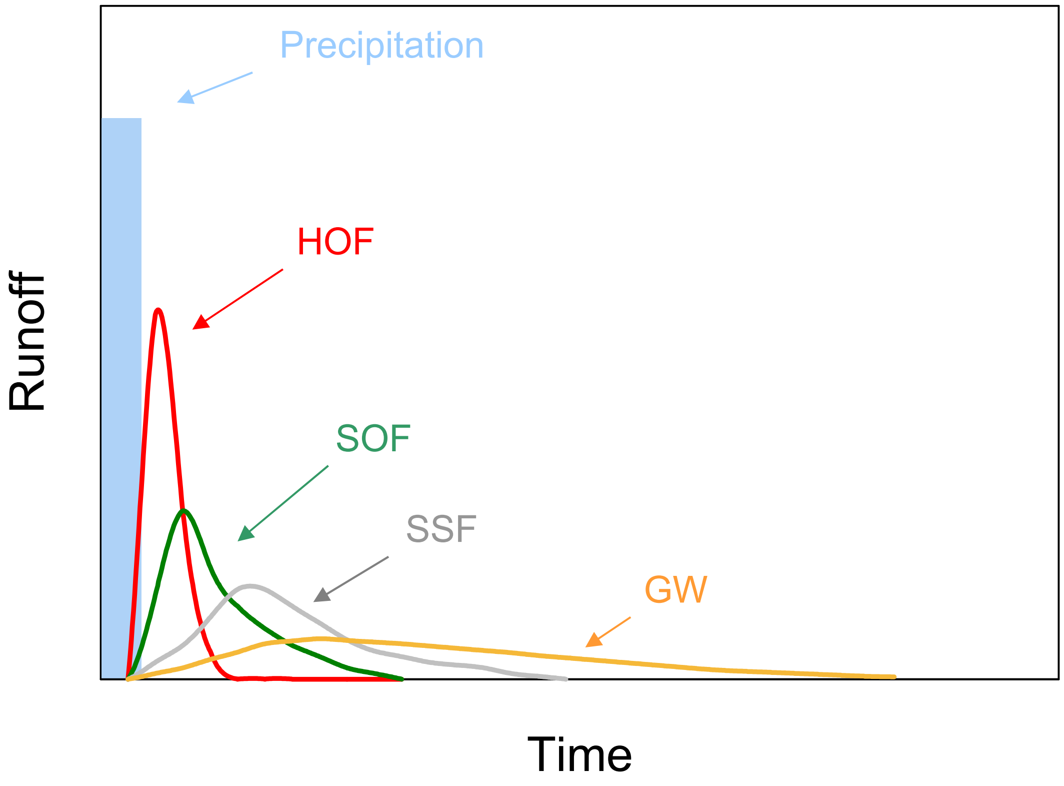
Humid,
dense vegetation

Topography, soils

Thin soils,
gentle, concave slopes,
wide valley bottoms

Deep, permeable soils,
steep, convex slopes,
gentle, concave slopes,
narrow valley bottoms

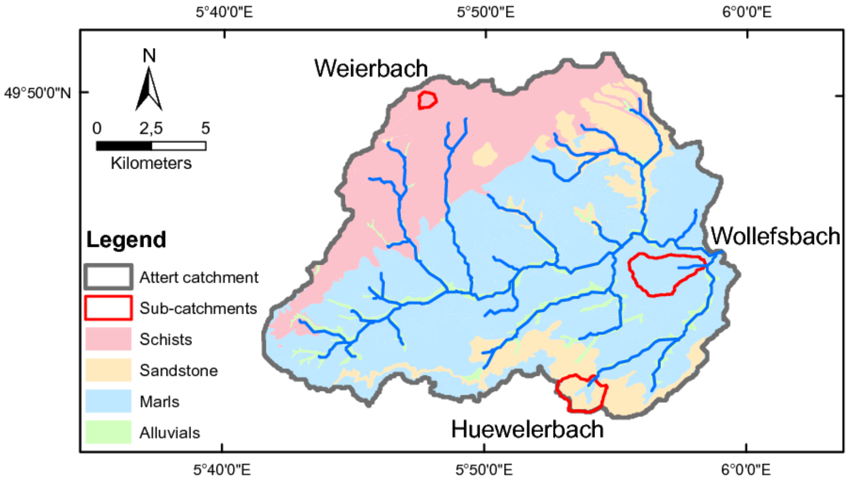
Flowpath timescales



Case study in Luxemburg

<u>3 catchments:</u>

- Huewelerbach
  - 2.7 km^2,
  - Forest
  - Sandstone
- Weierbach
  - 0.42 km^2
  - Forest
  - Schist
- Wollefsbach
  - 4.5 km^2
  - Pasture
  - Marl



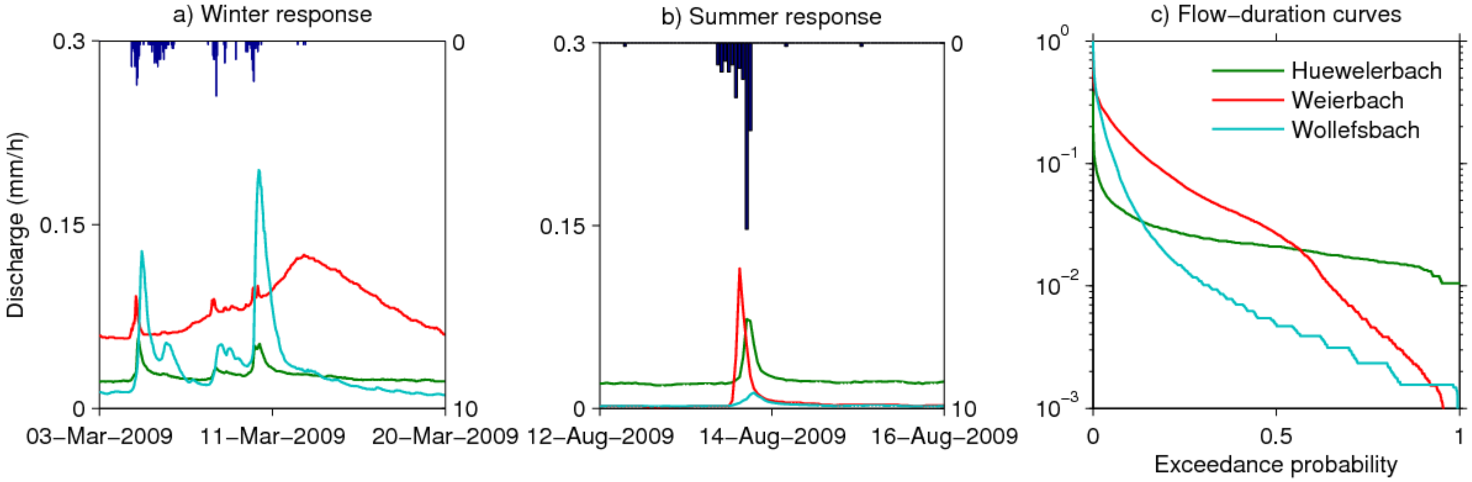
Case study in Luxemburg

Huewlerbach - Sandstone

Weierbach - Schist

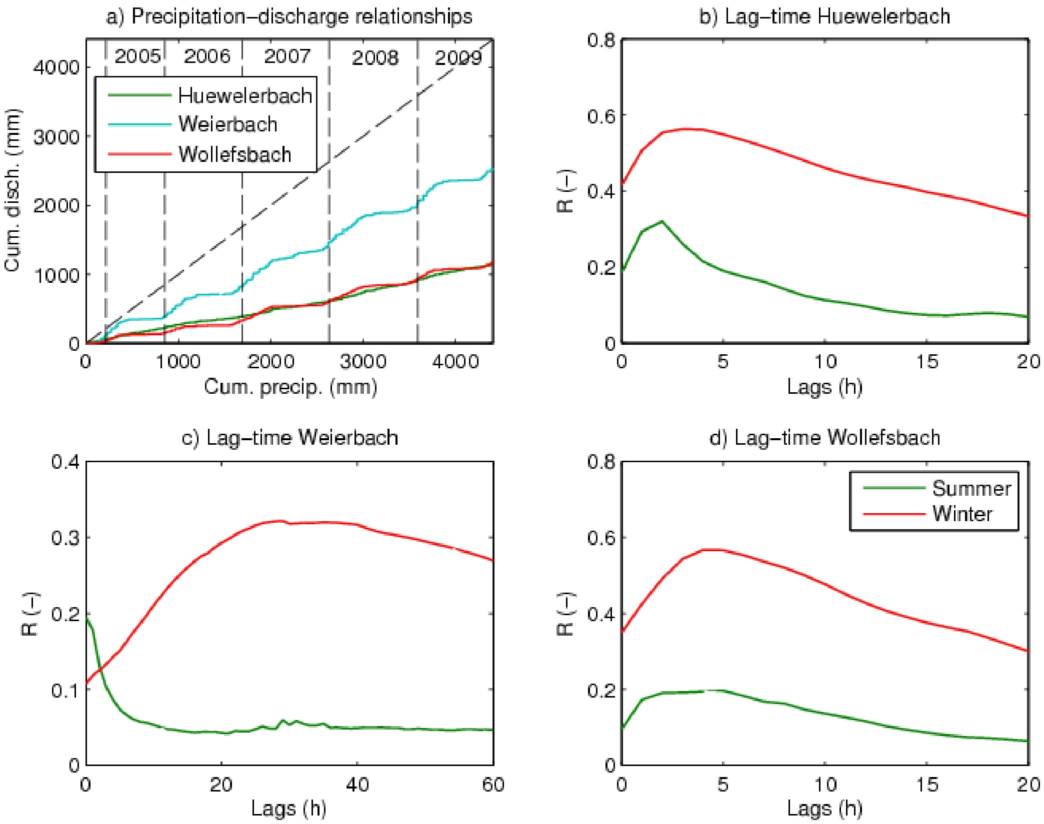
Wollefsbach - Marl

Case study in Luxemburg



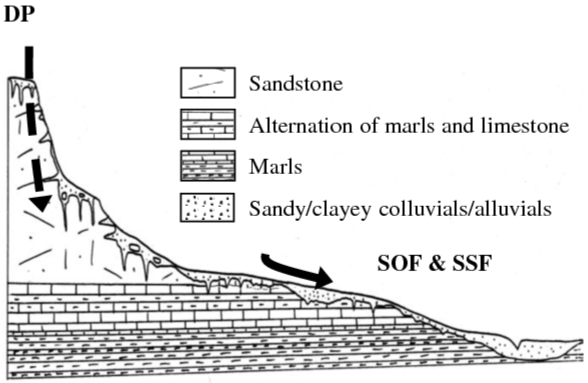
- Huewelerbach: constant baseflow
- Weierbach: delayed peaks in winter, threshold behaviour
- Wollefsbach: fast response, threshold behaviour

Case study in Luxemburg

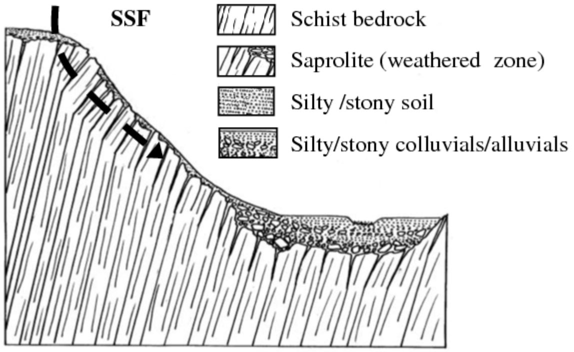


- Linear P-Q relation at Huewelerbach
- Threshold P-Q relation at Weierbach and Wollefsbach
- Different lags in runoff for wet and dry periods at Weierbach

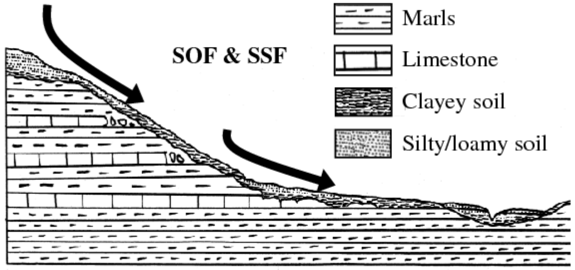
Case study in Luxemburg



a) Huewelerbach catchment (sandstone lithology)



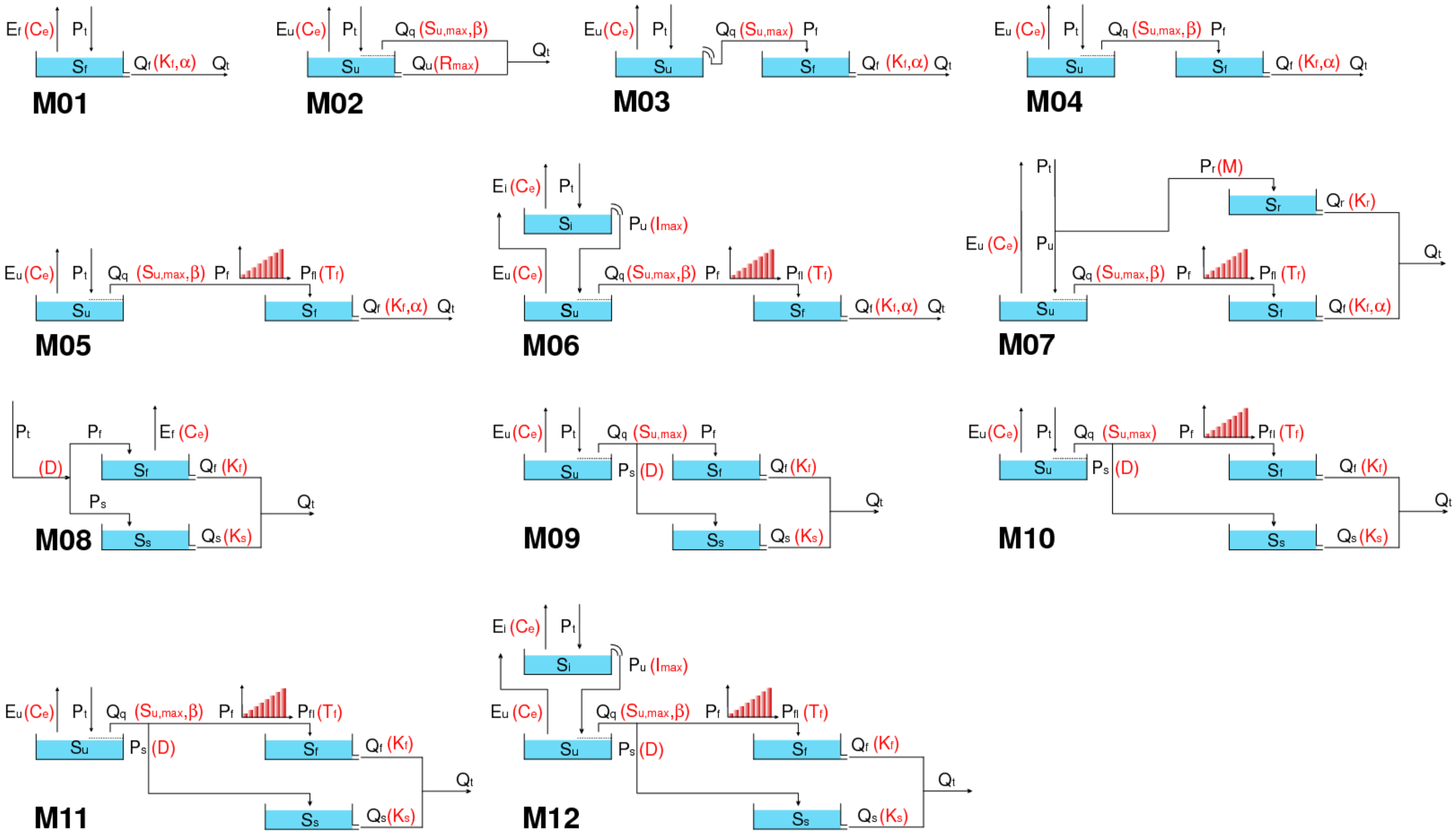
b) Weierbach catchment (schistose lithology)



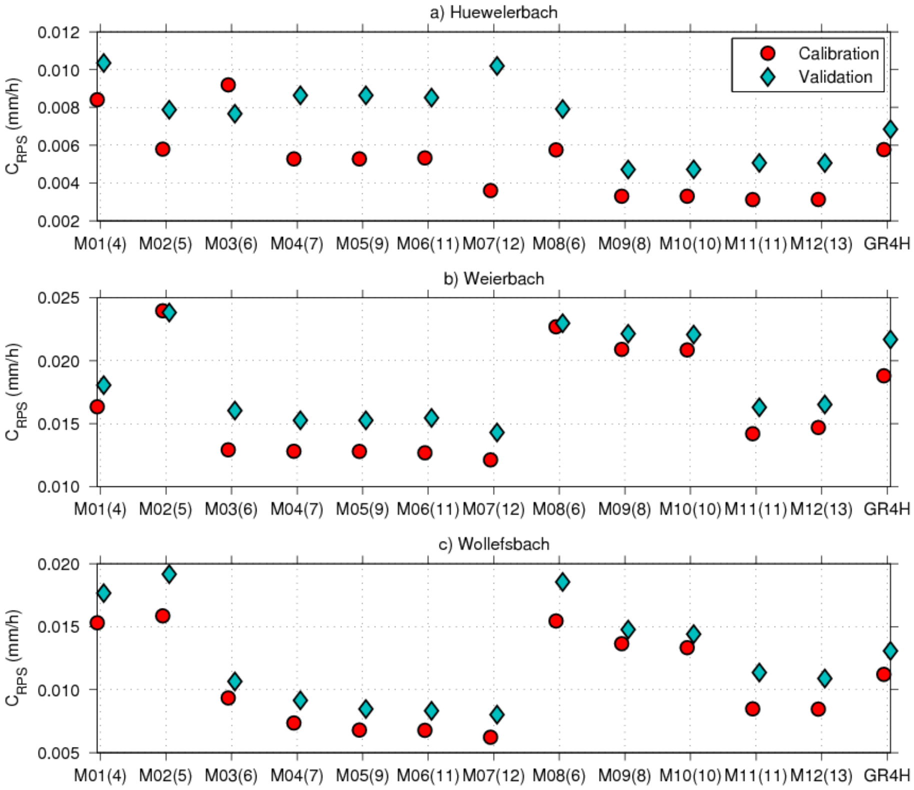
c) Wollefsbach catchment (marly lithology)

SOF: Saturated Overland Flow
SSF: Subsurface Flow
DP: Deep Percolation

Case study in Luxemburg



Case study in Luxemburg



- Huewelerbach: vertical model strucutres and linear models
- Weierbach, Wollefsbach: horizontal structures and threshold models

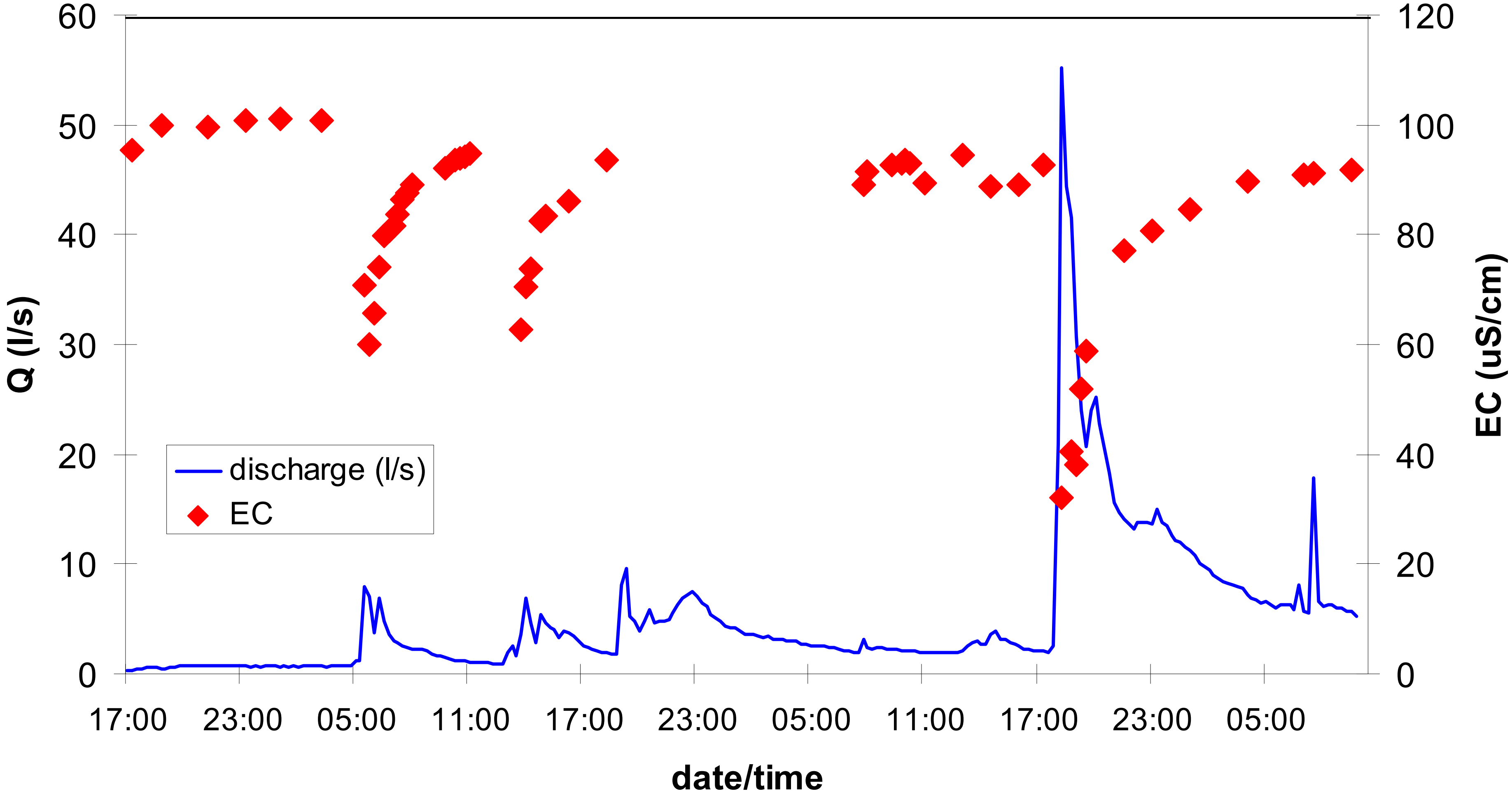
Tracers in Hydrology

Tracers

Tracers

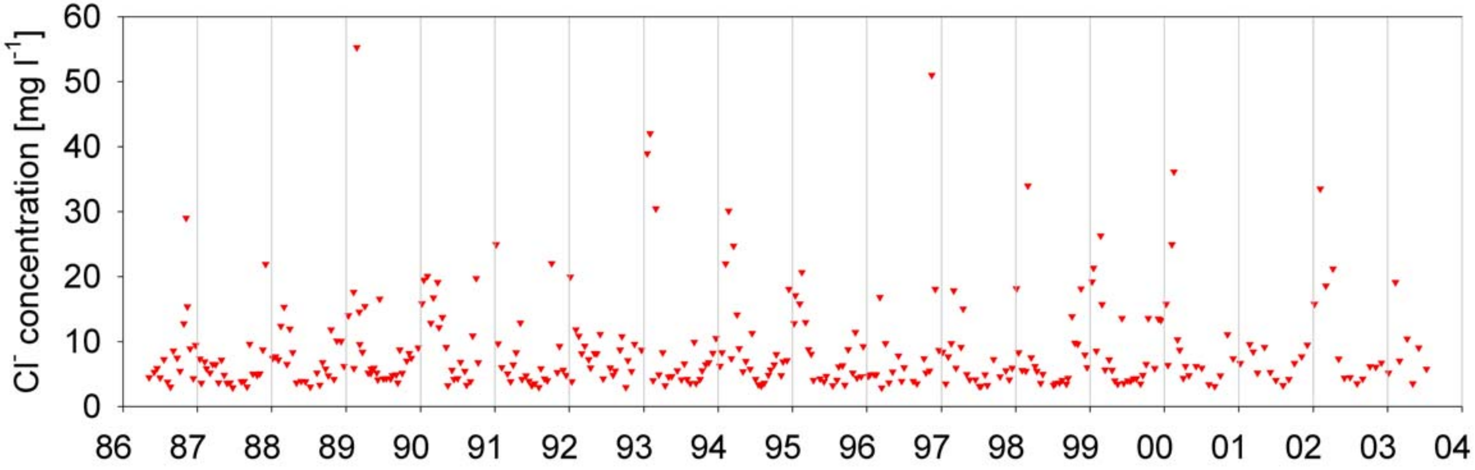
In situ	**Atmospheric**	**Artificial**
Si^+ Ca^{2+} ANC EC Temperature	Stable isotopes (^2H, ^{18}O) Cl^-	Dye tracers (Rhodamine, Uranin, Brilliant Blue) “Smart tracers” (Resazurin)
↓	↓	↓
Origin of water	Age of water	Origin/age of water

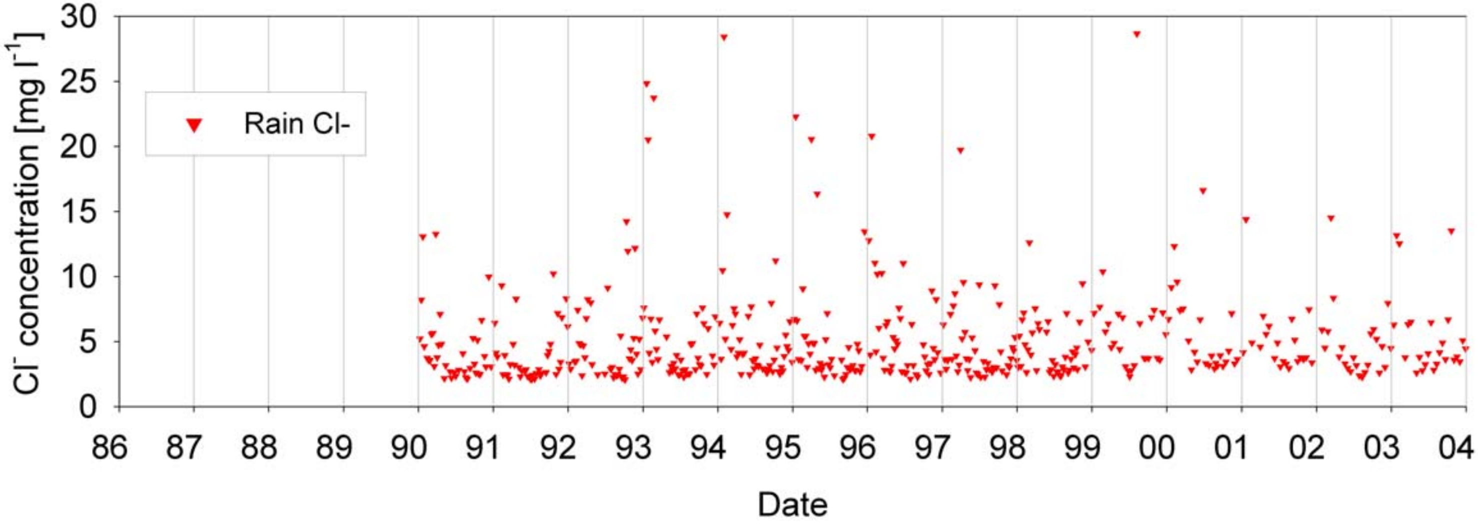
Tracers



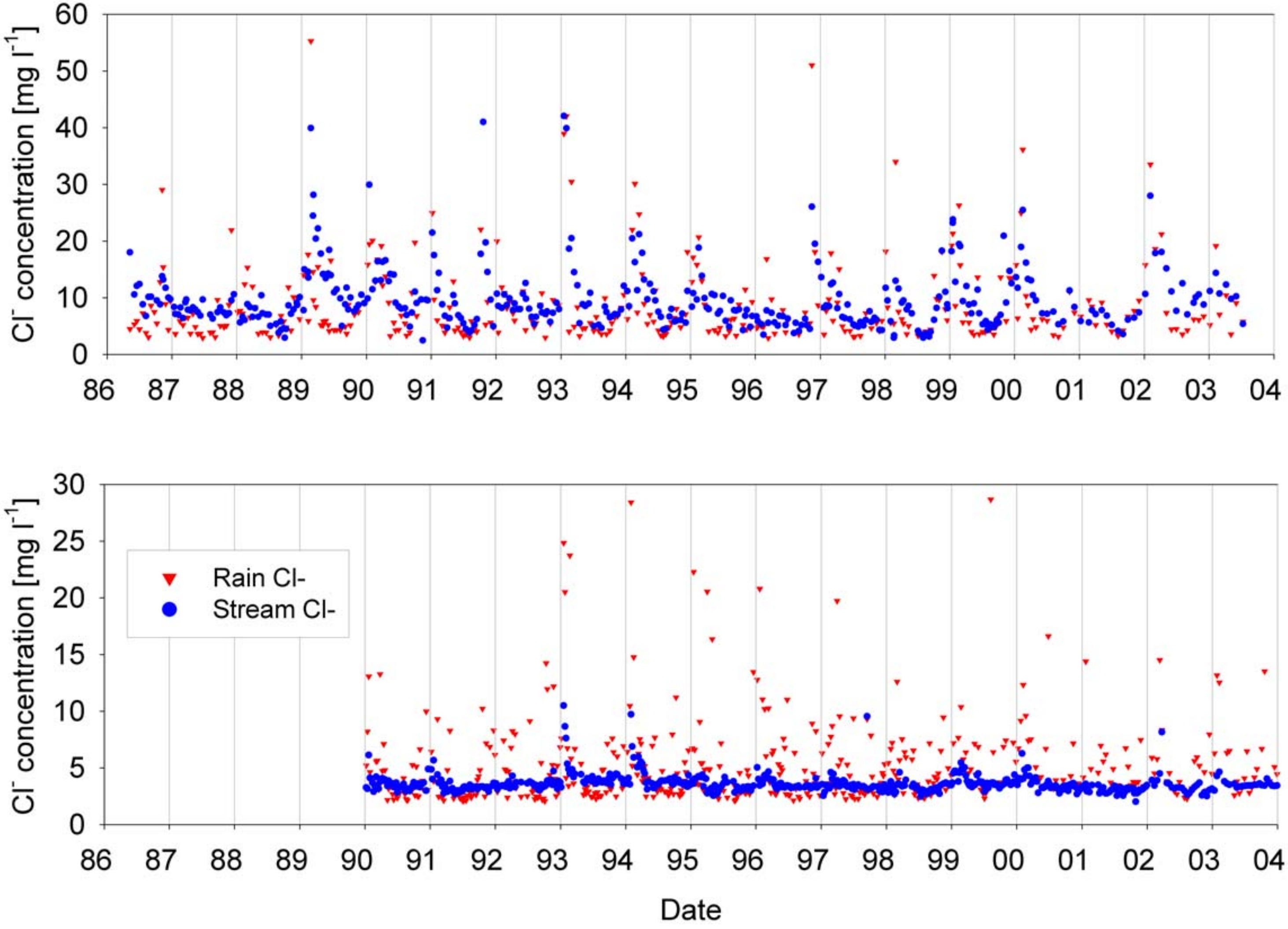
60
50
40
30
20
10
0
Q (l/s)
120
100
80
60
40
20
0
EC (uS/cm)
17:00
23:00
05:00
11:00
17:00
23:00
05:00
11:00
17:00
23:00
05:00
date/time
discharge (l/s)
EC

Tracers


Cl$^-$ concentration [mg l^{-1}]
60
50
40
30
20
10
0
86
87
88
89
90
91
92
93
94
95
96
97
98
99
00
01
02
03
04


Cl$^-$ concentration [mg l^{-1}]
30
25
20
15
10
5
0
Rain Cl-
86
87
88
89
90
91
92
93
94
95
96
97
98
99
00
01
02
03
04
Date

Tracers


Cl⁻ concentration [mg l⁻¹]
60
50
40
30
20
10
0
86
87
88
89
90
91
92
93
94
95
96
97
98
99
00
01
02
03
04
Cl⁻ concentration [mg l⁻¹]
30
25
20
15
10
5
0
Rain Cl-
Stream Cl-
86
87
88
89
90
91
92
93
94
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96
97
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02
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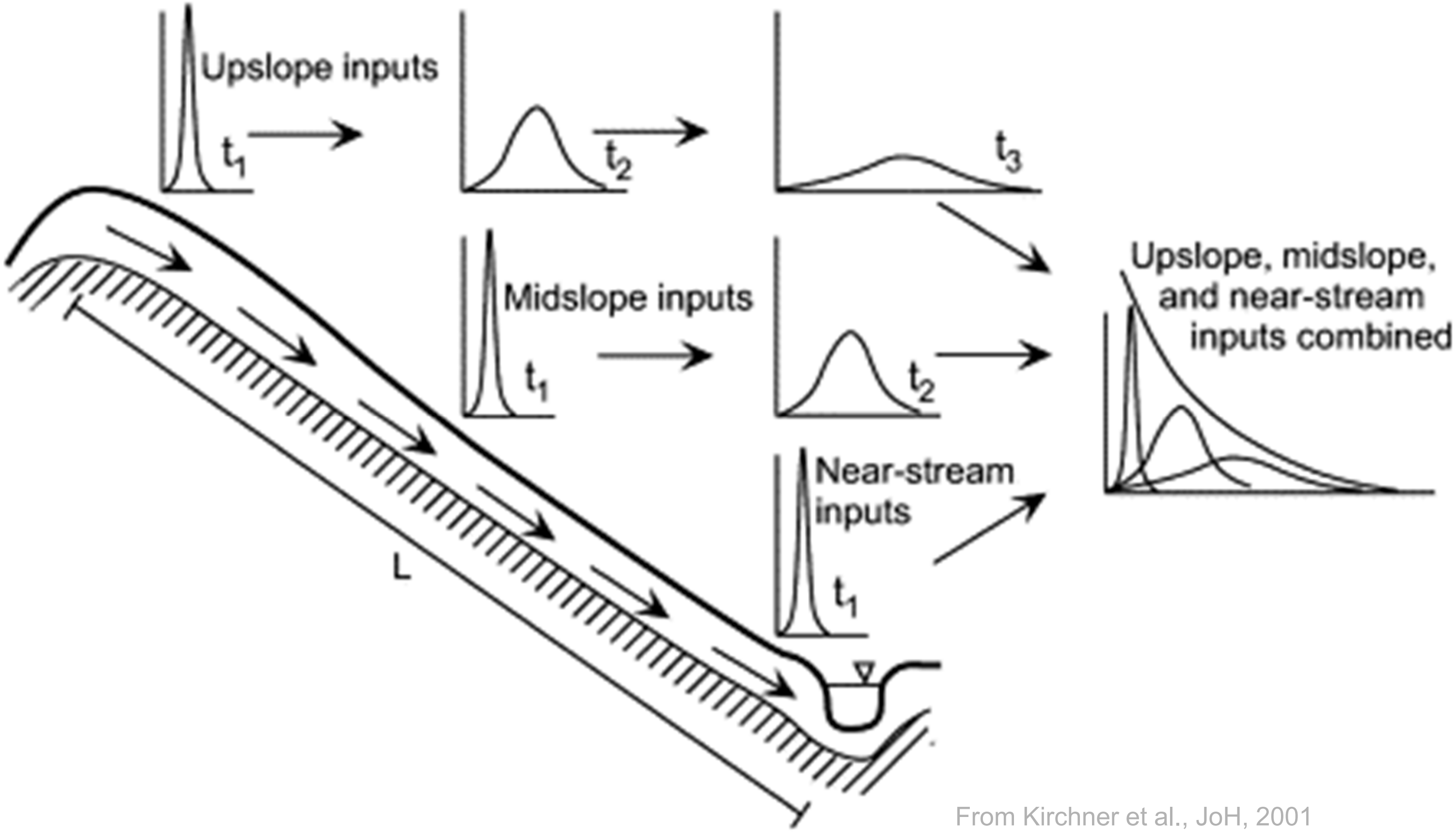
04
Date

Tracers



From Kirchner et al., JoH, 2001

Take home message

- Tracers are components or characteristics of water, which, when acting conservatively, give us additional information on the origin and the age of water.
- In-situ, atmospheric and artificial tracers
- Mixing analysis to determine origin of water
- Convolution integral to estimate age of water