Models in Hydrology

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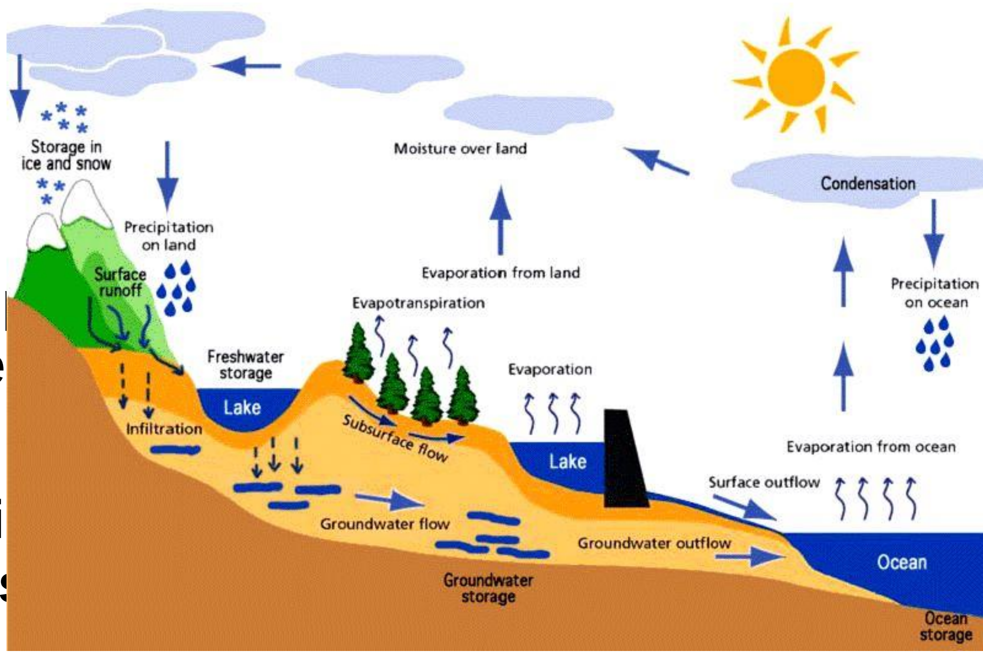
After this lecture you will

- know **what** a hydrological model is
- know **why** hydrological models are important
- be able to **identify and classify** different types of models
- be able to **describe** what conceptual hydrological models are based on
- be able to **identify** data requirements
- be able to **formulate and apply** a simple conceptual rainfall-runoff model

What is hydrology?

- hydōr (ύδωρ) = greek for water
- logos (λόγος) = greek for word, ratio, study

→ **Hydrology** is the study of the movement and distribution of water throughout the Earth in general and within the hydrologic cycle, in particular



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  perce…
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Hydrological cycle

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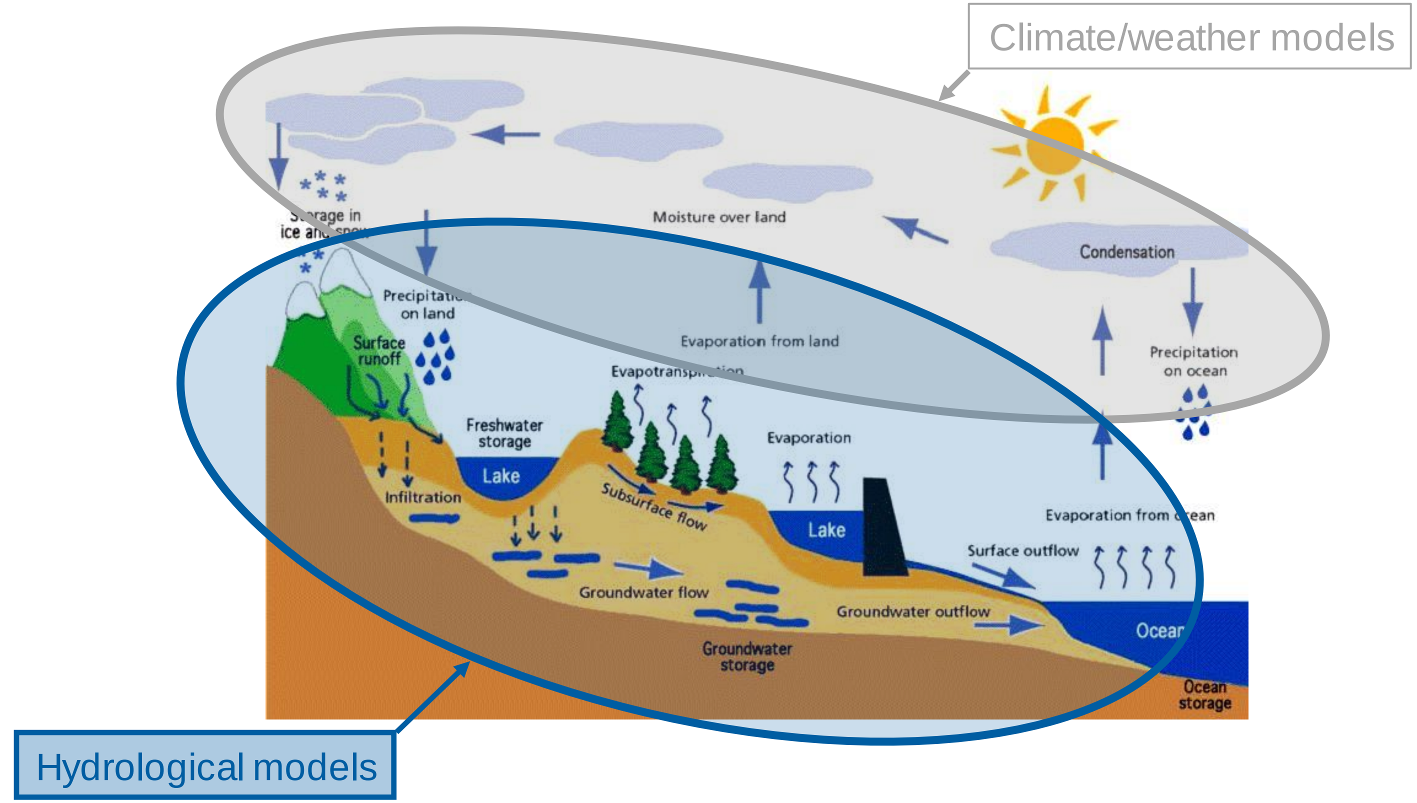


Why are hydrological models important?

- To encapsulate our knowledge
  - to prove a hypothesis wrong
- Extrapolate in time (forecast) and/or space (ungauged basin)
  - otherwise it is curve fitting
- As a mathematical laboratory
  - “virtual reality”

Hydrological Model

Purpose:

Establish a quantitative link between

(1) System input, i.e. climatic drivers (precipitation, energy supply)

(2) System state, i.e. water storage (e.g. groundwater, soil moisture)

(3) System output, i.e. hydrological response (e.g. stream flow, groundwater table fluctuations)

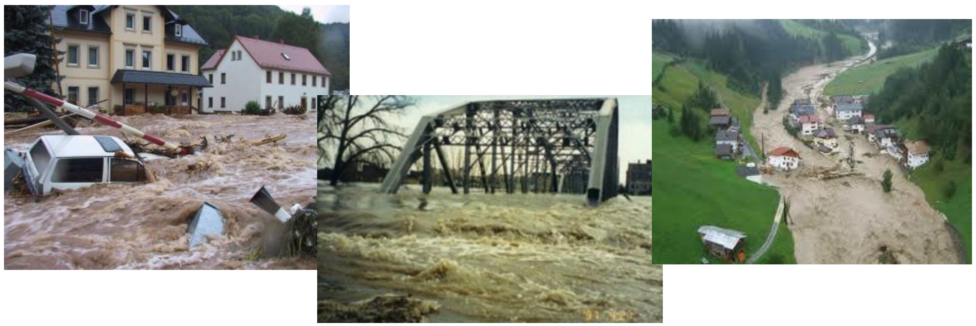
Challenge:

Identify a quantitative, functional relationship that reflects the time lags between input and output as a result of the boundary conditions of the system (e.g. geology, topography).

Definition:

A hydrological model is a simplified and abstract representation of the movement of water in the hydrological cycle, as we perceive it

Why are hydrological models important?



	What can we model?	Why?
quantitative	Floods	• Flood protection • Erosion control • Landslide management
quantitative	Low flows	• Water supply • Ecosystem stability • Food security
qualitative	Contaminants Temperature Turbidity	• Drinking water security • Ecosystem stability • Food and resources security

Modeling Process

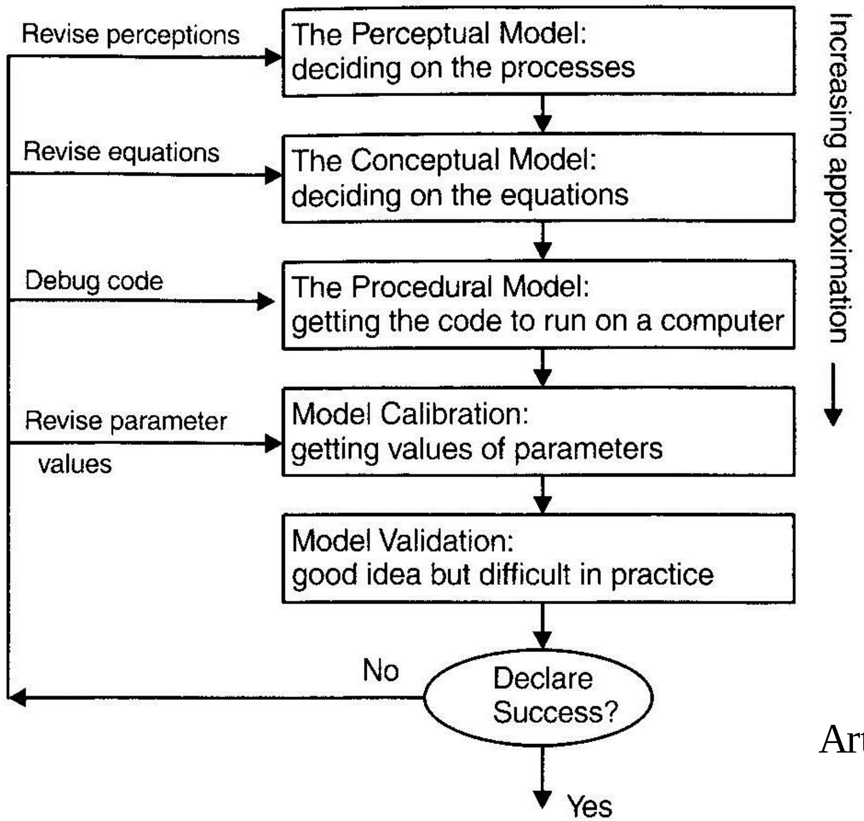


Figure 1.2 *A schematic outline of the different steps in the modelling process*

Art versus Science!!

Modeling Process

We can define a Hydrological Model as a simplified and abstract representation of the movement of water in the hydrological cycle, as we perceive it:

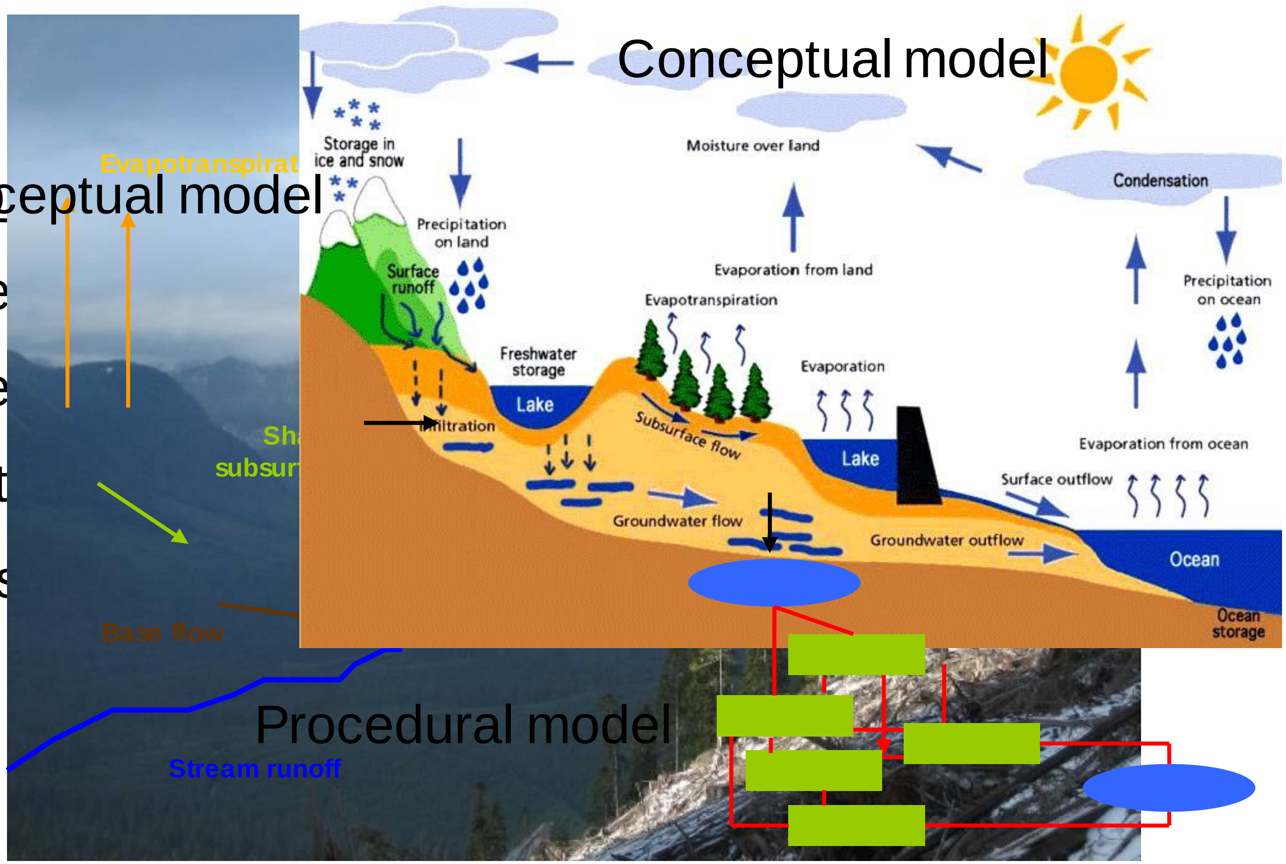
Hydro

1) pre

2) pre

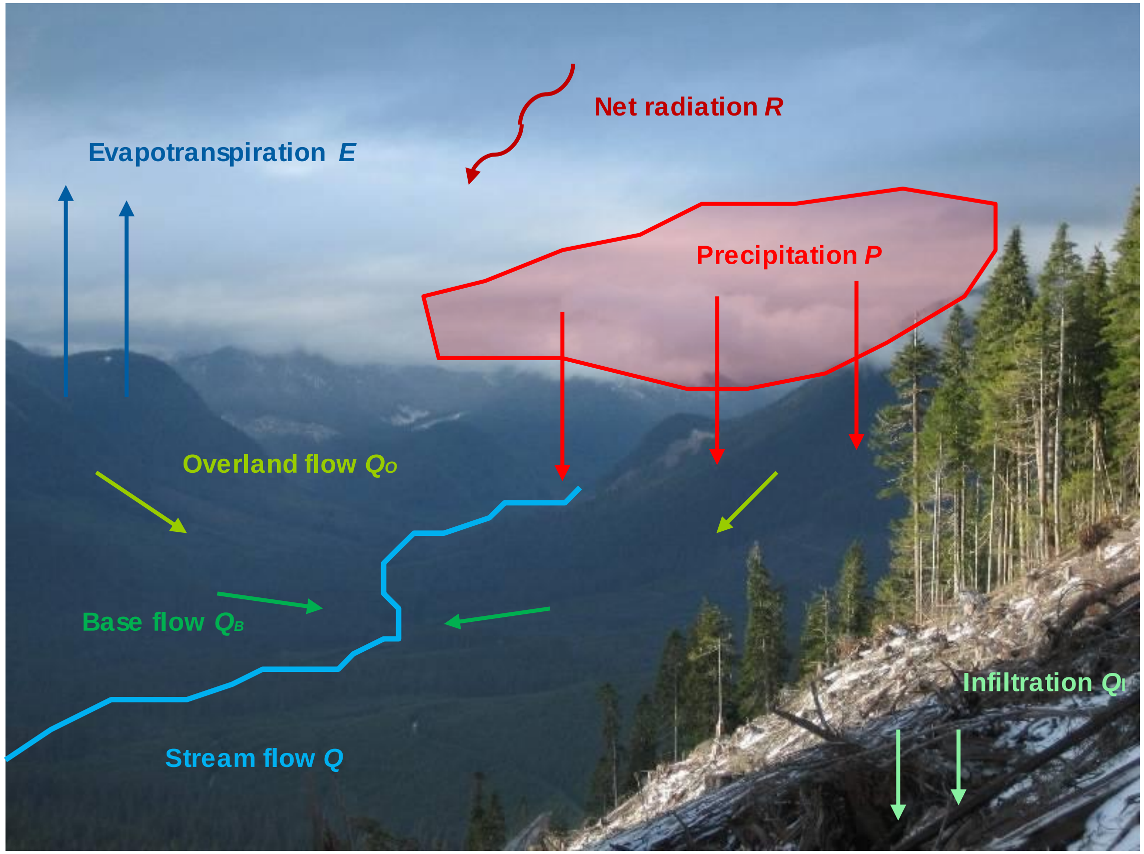
3) get

→ Bas



Perceptual Model

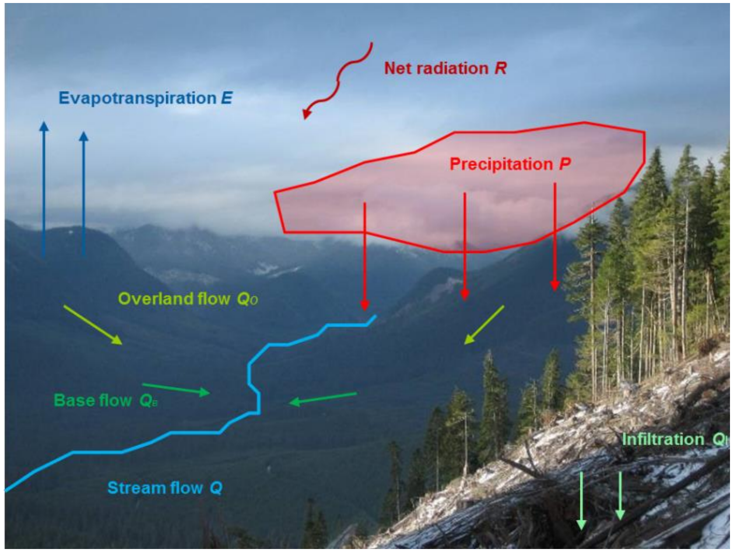
<u>What do we know/see?</u>



- ✓ Objectives
- ✓ What is a hydrological model ?
- ✓ Why do we care?
- **<u>Modeling Process</u>**
- Problems
- What types of models are out there?
- Flow Processes
  - a) Groundwater
  - b) SOF
  - c) HOF
  - d) SSF
  - e) Interception
- What does a model look like?
- Step-by-step
- Example model
- What have we learned?

Conservation laws

What do we know?



red – system input
blue – system output
green – transfer within the system

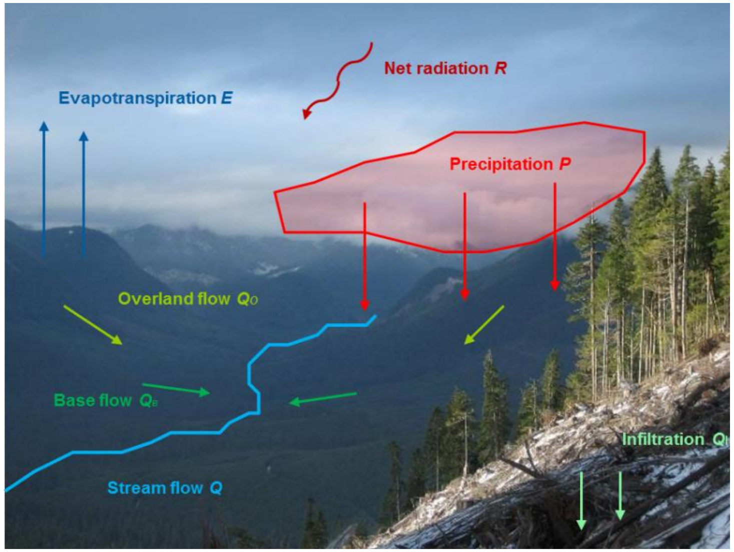
(1) Conservation of mass: $\frac{dS}{dt} = Input(t) - Output(t)$

here: Water balance $$\frac{dS}{dt} = P(t) - Q(t) - E(t)$$

Needs to be satisfied!

Conservation laws

What do we know?



red – system input
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(1) Conservation of mass: $\frac{dS}{dt} = Input(t) - Output(t)$

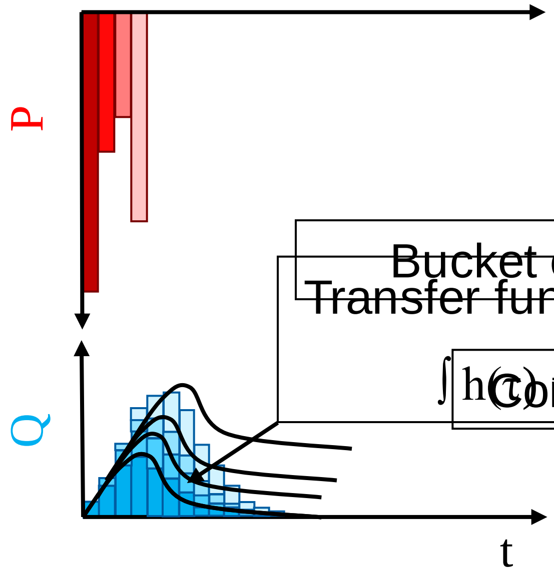
(2) Conservation of energy

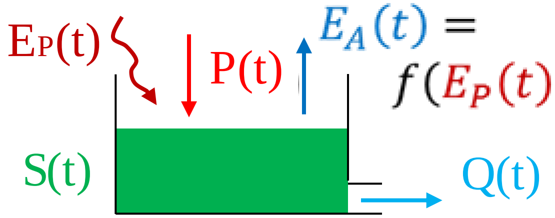
here: partitioning between stream flow and evapotranspiration, i.e. $^{Q(t)}/_{E(t)}$, needs to reflect reality

Dispersion

Observations required and typically available:

Time series of
(1) Input: (a) Precipitation P
(b) Energy input, e.g. radiation, temperature
→ potential evaporation E_P
(2) Output: (c) Stream flow Q (needed for model evaluation – inverse problem!)
(d) Actual evaporation E_A (typically not available)





$$E_A(t) = f(E_P(t), S(t))$$

Bucket outflow

$$Q(t) = f\big(P(t), S(t)\big)$$

Transfer function $h(\tau)$

$\int h(\tau) = 1$

Convolution integral

$$Q(t) = P * h = \int_0^t P(t-\tau)h(\tau)d\tau$$

Art of Modeling

- Creativity: figuring out how it works
- Experience: know how
- Insight
- Intuition
- Artful design of experiments

Basic Rules of Modeling

1. Make sure you use correct dimensions in the equations, e.g.: include d*t*

2. make a schematic picture of the conceptual framework (different ways to close a balance)

3. distinguish between stocks and fluxes

4. test and evaluate your model

What does a Model consist of?

- equations, procedures and rules
  - differential equations
  - boundary conditions (fluxes, states, geometry)
  - initial conditions
- time-varying input: drivers and boundary conditions (e.g. atmospheric fluxes)
- fixed input: geometry (boundary conditions)
- model parameters (generally calibrated):
  - time invariant (e.g. conductivity, porosity)
  - time variant (e.g. interception capacity)
- state variables (stocks and fluxes) : internal and external (output)

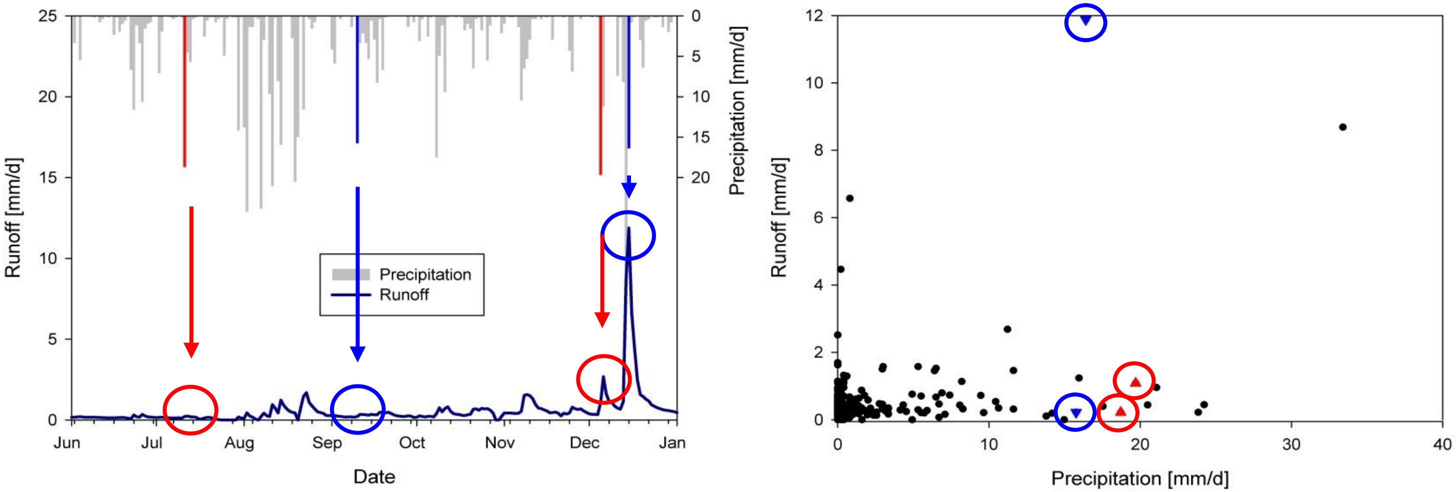
Determination of Model Parameters

- from the literature (science)
- from experience (art)
- through calibration (art or science?)
  - manual
  - automatic
  - stepped (Fenicia *et al*., 2007)

Main Issues

- Non-linearity
- Heterogeneity
- The issue of scale
  - the problem of the ant
- Equifinality
  - infinite parameter sets perform equally well
- Physically based or conceptual?
- Lumped or distributed?

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 → **"Nonlinearity"**

Non-Linearity

- Non-linear differential equations
- Hysteresis
  - flood wave
  - soil wetting and drying (pF-curve)
- Threshold behaviour
  - ANN's are not capable of mimicking hydrological models

Non-linearity

- Linear threshold process
- Plus probability distribution of system driver (e.g. rainfall)
- Plus probability distribution of threshold
- Results in non-linear behaviour

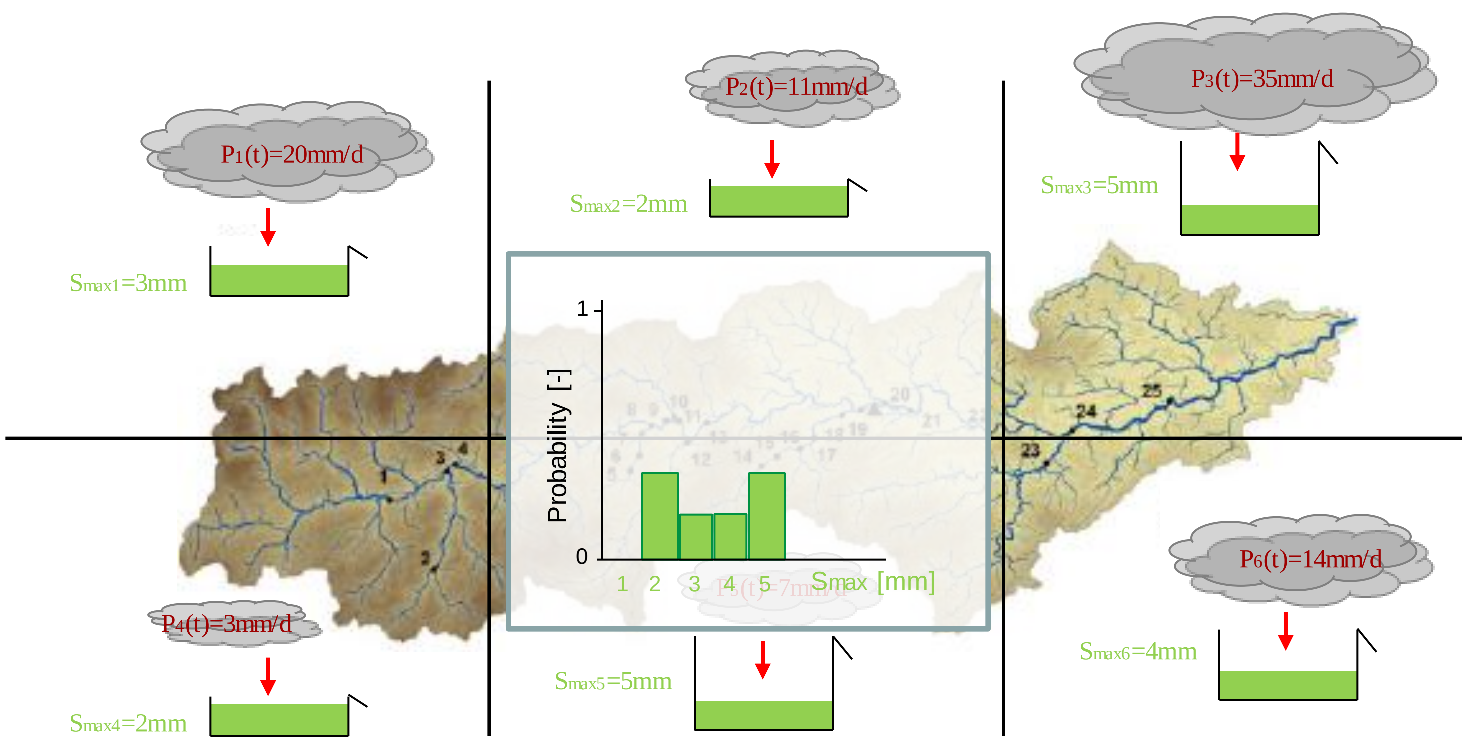
Heterogeneity

- "het meeste valt ernaast"
  - spatial distribution of rainfall
- spatial distribution of topography
- spatial distribution of soil depth
- spatial distribution of land cover

Non-linearity and heterogeneity

Sources of non-linearity:

- Linear threshold process
- Probability distribution of threshold due to natural heterogeneity of landscape (e.g. vegetation, soils,…)
- Probability distribution of system driver (e.g. rainfall)



✓ Objectives

✓ What is a hydrological model ?

✓ Why do we care?

✓ Modeling Process

Problems

What types of models are out there?

Flow Processes

a) Groundwater

b) SOF

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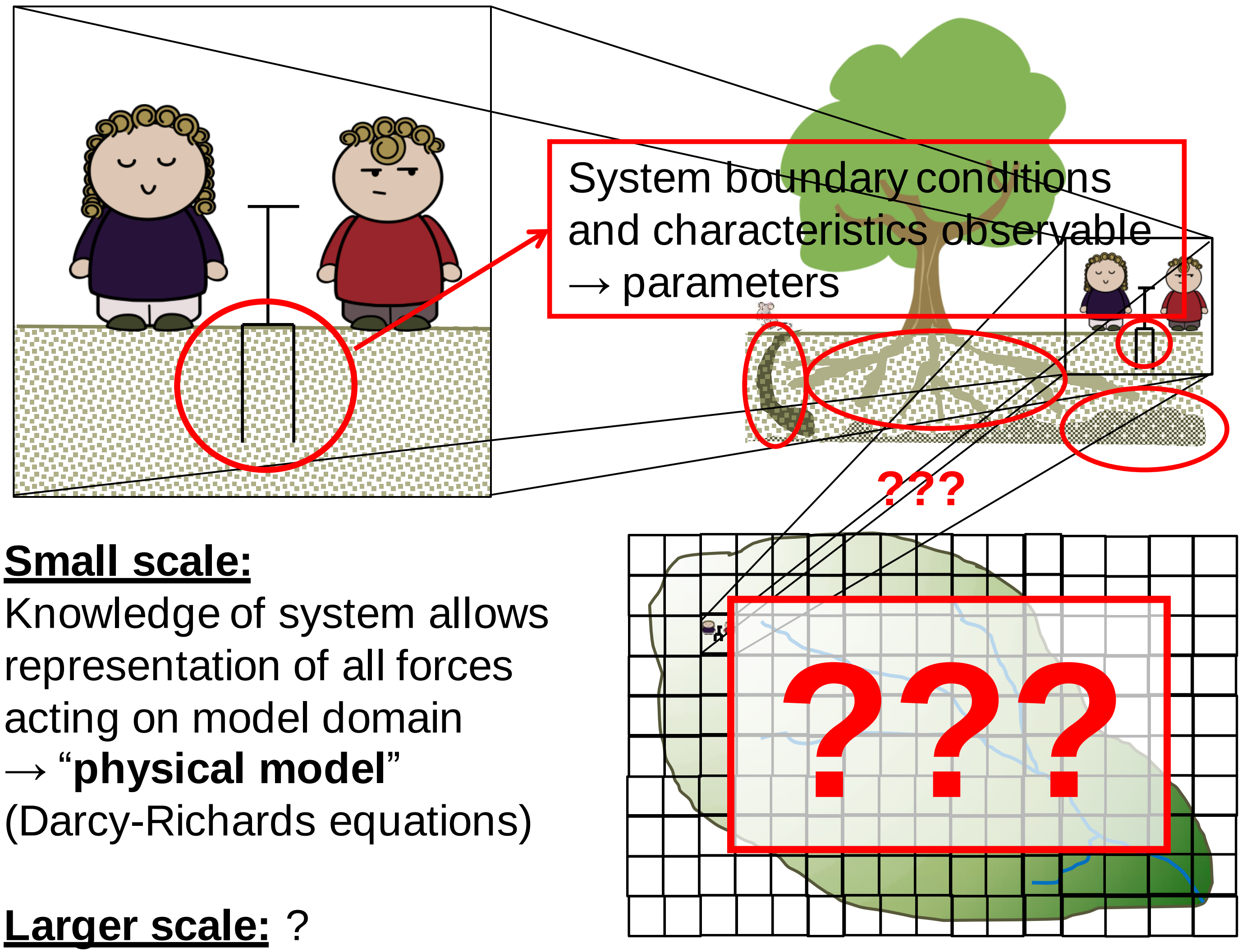
What does a model look like?

Step-by-step

Example model

What have we learned?

Modelling scale and heterogeneity



Small scale:
Knowledge of system allows representation of all forces acting on model domain
→ “**physical model**”
(Darcy-Richards equations)

Larger scale: ?

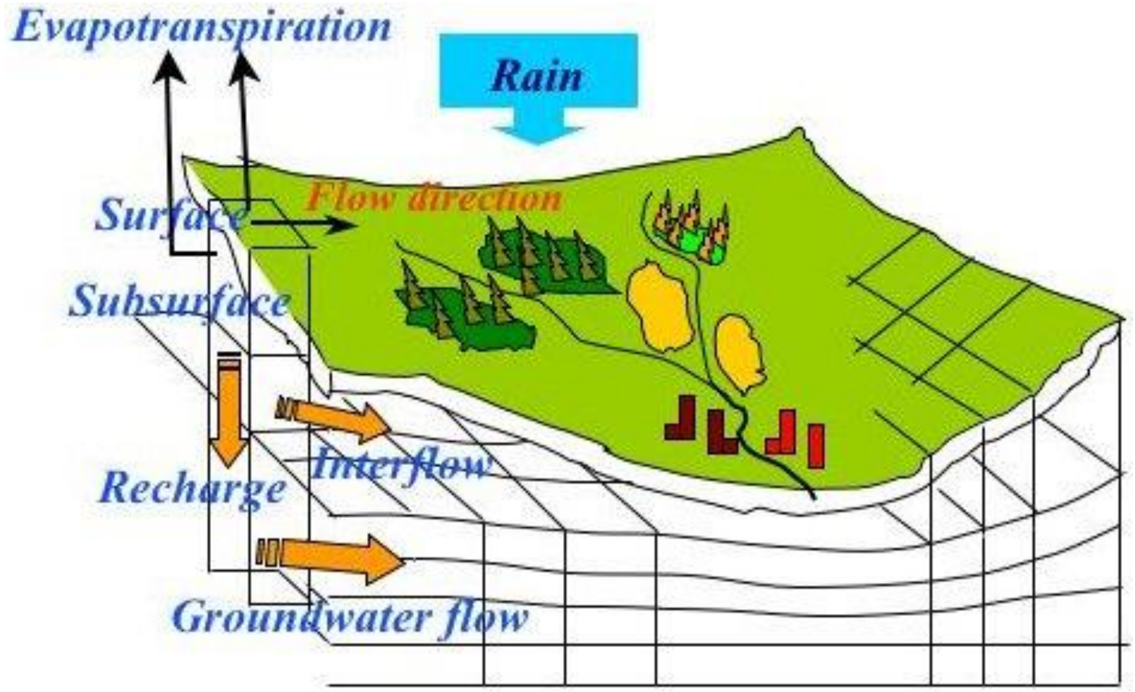
Parameter Equifinality

- makes validation and evaluation difficult
- is the result of over-parameterization
- the “curse” of distributed and physically based modelling
- asks for parsimonious conceptual models
- “equifinality is a blessing in disguise”
  - the world is simpler than we think

Types of hydrological models

Perceptual models

Types of hydrological models



- All distributed models are lumped to a certain extent
- All physically based models are conceptual to a certain extent

Types of hydrological models

Perceptual models

Lumped / distributed

low

Complexity

Data requirements

Resource / time requirements

high

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Types of hydrological models

Physically-based models (Bottom-up models)

- Full description of forces acting on a control volume
- Based on the **Navier-Stokes equations** of fluid movement, different formulations of water fluxes:
  (a) Darcy
  (b) Richa… …dia)
  (c) Kine…
  (d) Sain…

BUT…

- Explicit treatment of conservation equations:
  (a) Mass balance ("continuity")
  $$\frac{\partial p}{\partial t} + \frac{\partial(\rho v_x)}{\partial x} + \frac{\partial(\rho v_y)}{\partial y} + \frac{\partial(\rho v_z)}{\partial z} = 0$$
  (b) Momentum balances (here shown: X-momentum, equivalent for Y and Z)
  $$\frac{\partial(\rho v_x)}{\partial t} + \frac{\partial(\rho {v_x}^2)}{\partial x} + \frac{\partial(\rho v_x v_y)}{\partial y} + \frac{\partial(\rho v_x v_z)}{\partial z} = -\frac{\partial p}{\partial x} + \frac{1}{R_e}\left[\frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z}\right]$$
  (c) Energy balance
  $$R_n = \rho\lambda E_a + H + G$$

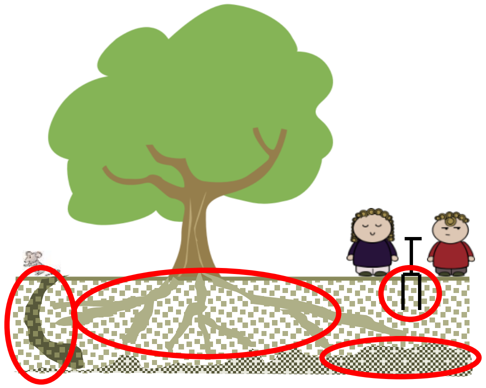
t=time, p=pressure, v=velocity, ρ=density, τ=stress, Rn=net radiation, λ=latent heat of vaporization, H=sensible heat flux, G=ground heat flux

Types of hydrological models

Physically-based models (Bottom-up models)

Critical **assumptions** required:
- "small" control volumes (in theory infinitesimal)
- each control volume is a continuum (i.e. without structure and thresholds)

Problem:
may hold for point or plot scales but is violated on hillslope and catchment scales where modelling grid is often > 10 m: the larger the scale the more structure and thresholds characterize the control volume, i.e. breaks in the continuum, such as preferential flow features



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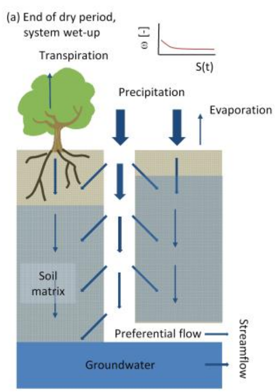
Dry period:
most precipitation is adsorbed in small pores ("matrix") from where it is only slowly released.



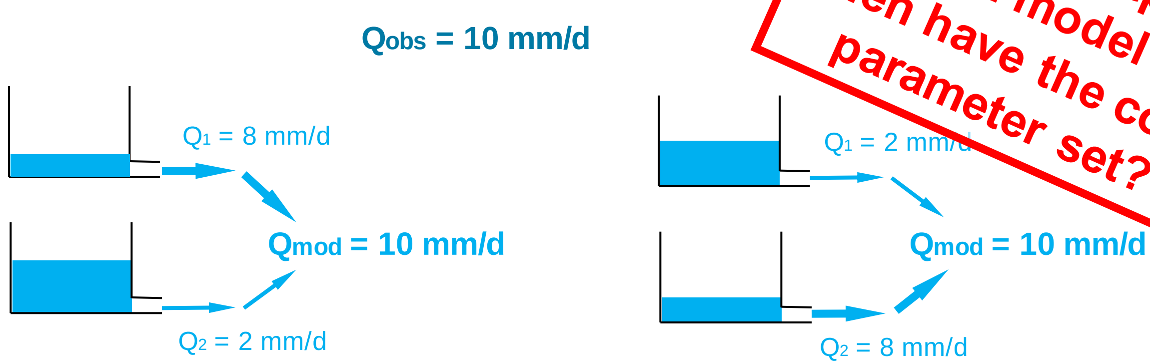
Wet period:
when matrix is filled, i.e. storage threshold exceeded, most water bypasses matrix and is released through preferential flow features.

Types of hydrological models

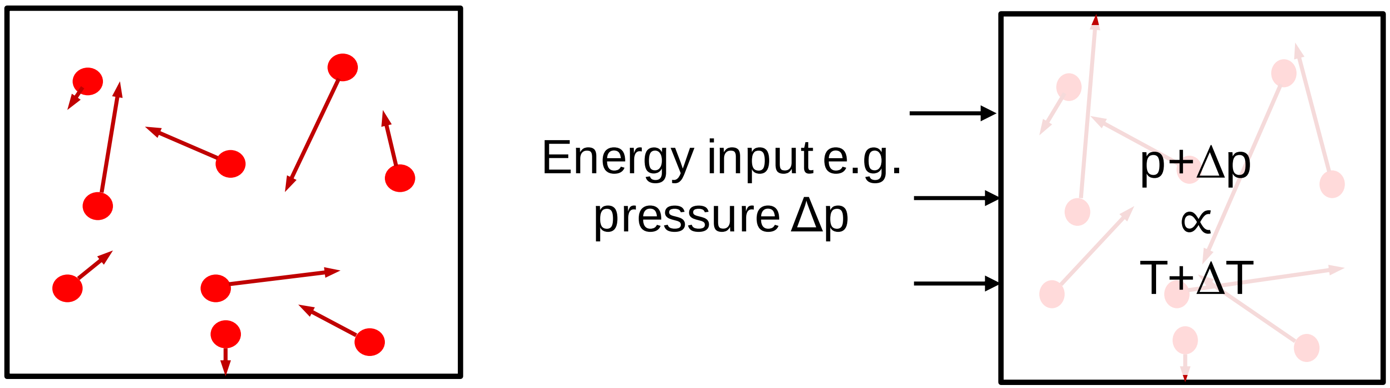
Physically-based models (Bottom-up models)

The problem of calibration:
High level of spatial and process discretization requires a LOT of parameters.
-High computational cost
-Elevated degrees of freedom in model
→ Parameters compensate uncertainties in other parameters, model structure and data: "**equifinality**" (different parameter sets give similar model performance).
Does the chosen parameter set then really represent reality or does is it merely provide a good fit?

Different models, same output. Which model does then have the correct parameter set???



Zooming out and macroscale physics

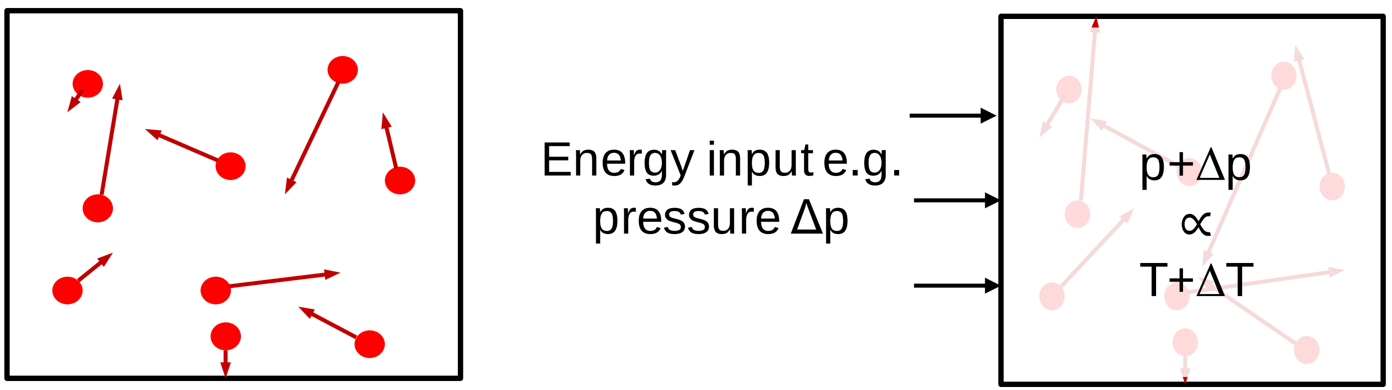


What happens if energy is increased or decreased?

Speed, trajectories and interactions of molecules will change. How and how much? This could in theory be calculated. In reality, however almost impossible due to:
(1) lack of computational power
(2) lack of observations on initial conditions.

Zoom out to the macroscale (statistical physics): a very simple but very stable relationship emerges that relates energy input to the system response: $p \propto T$ (Gas Laws!!)

Zooming out and macroscale physics



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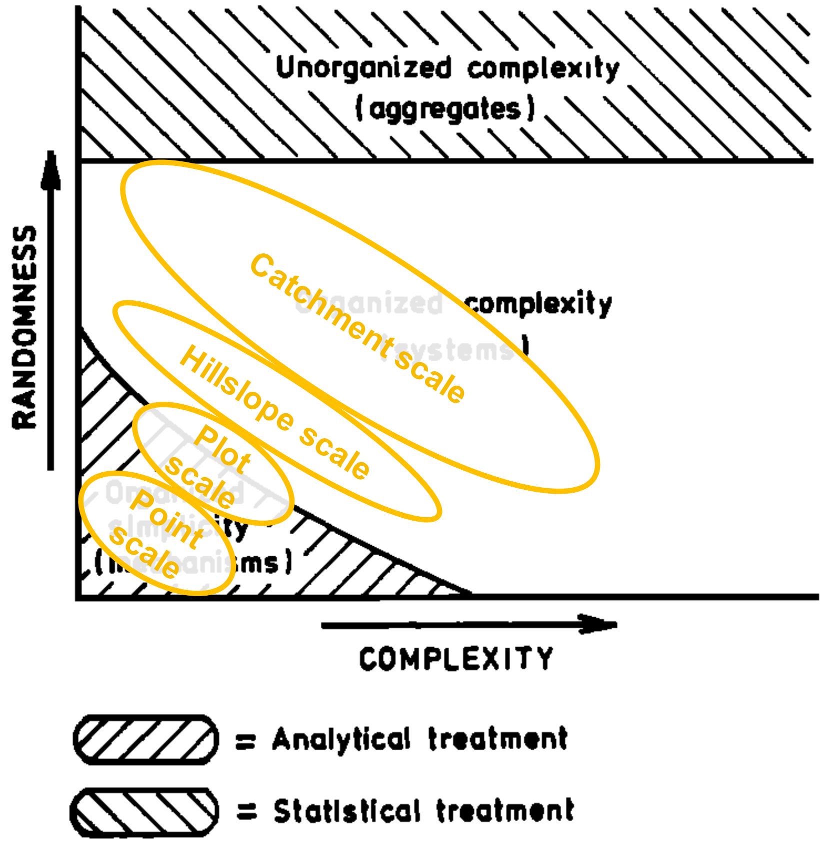
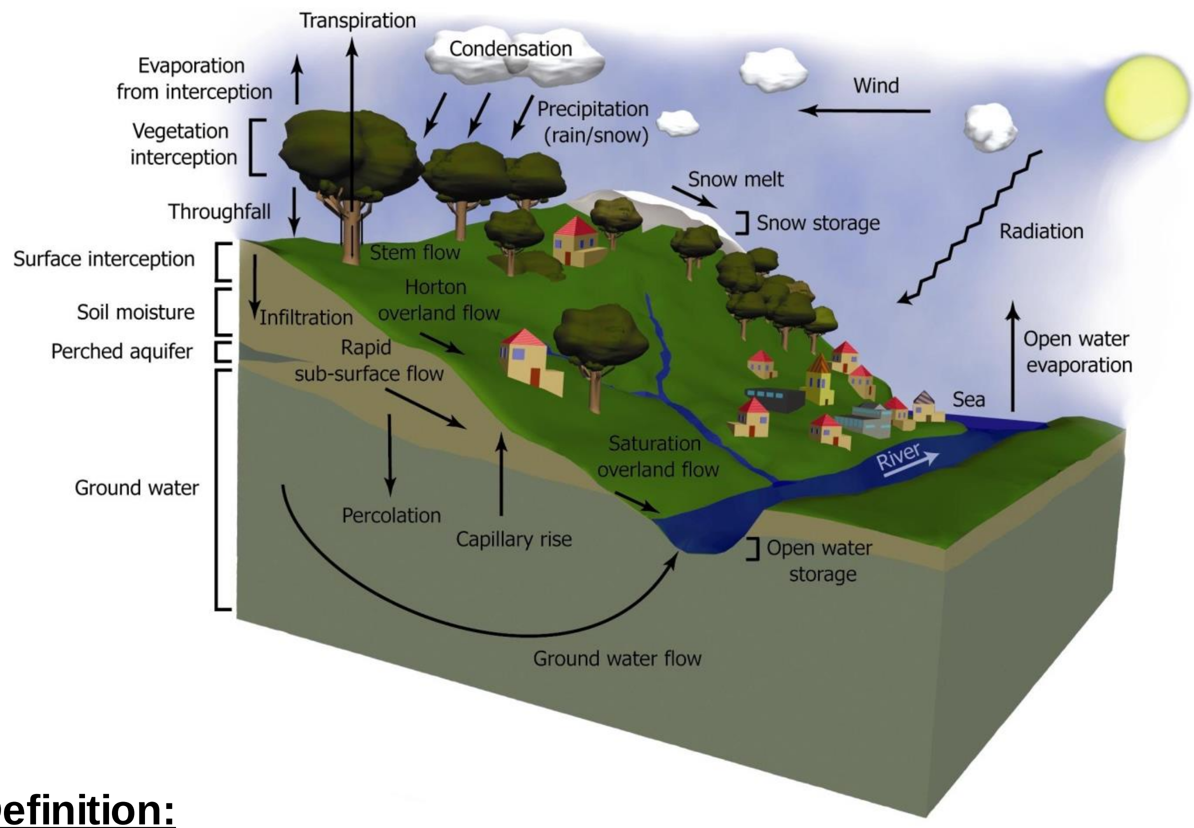
The role of organization



Organization through flow paths

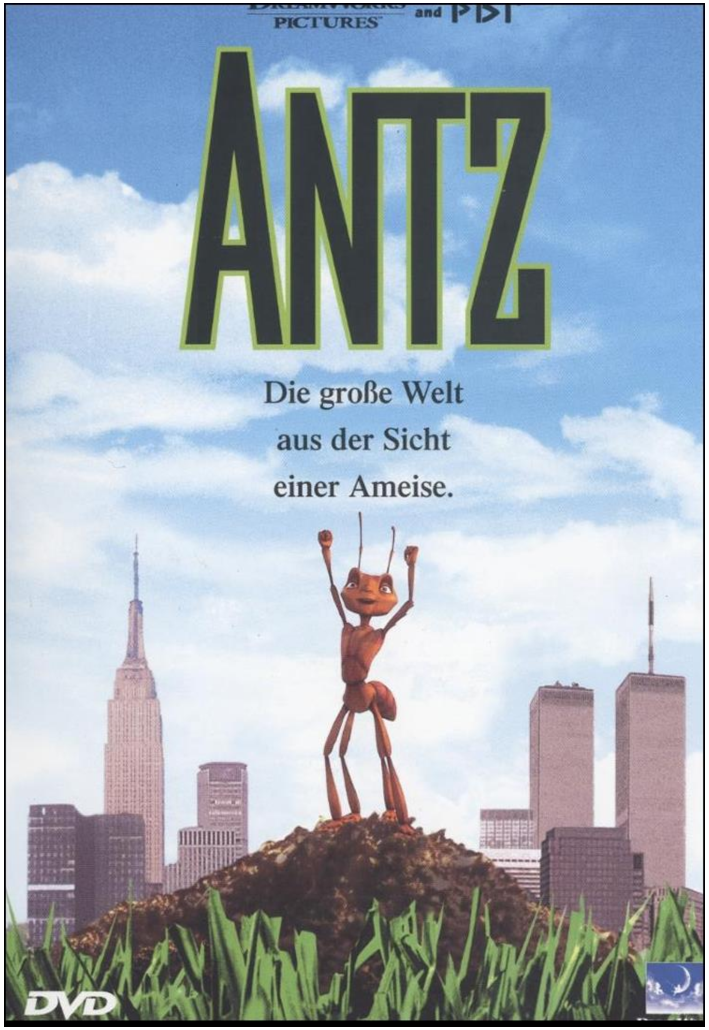


Definition:

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"

Scale

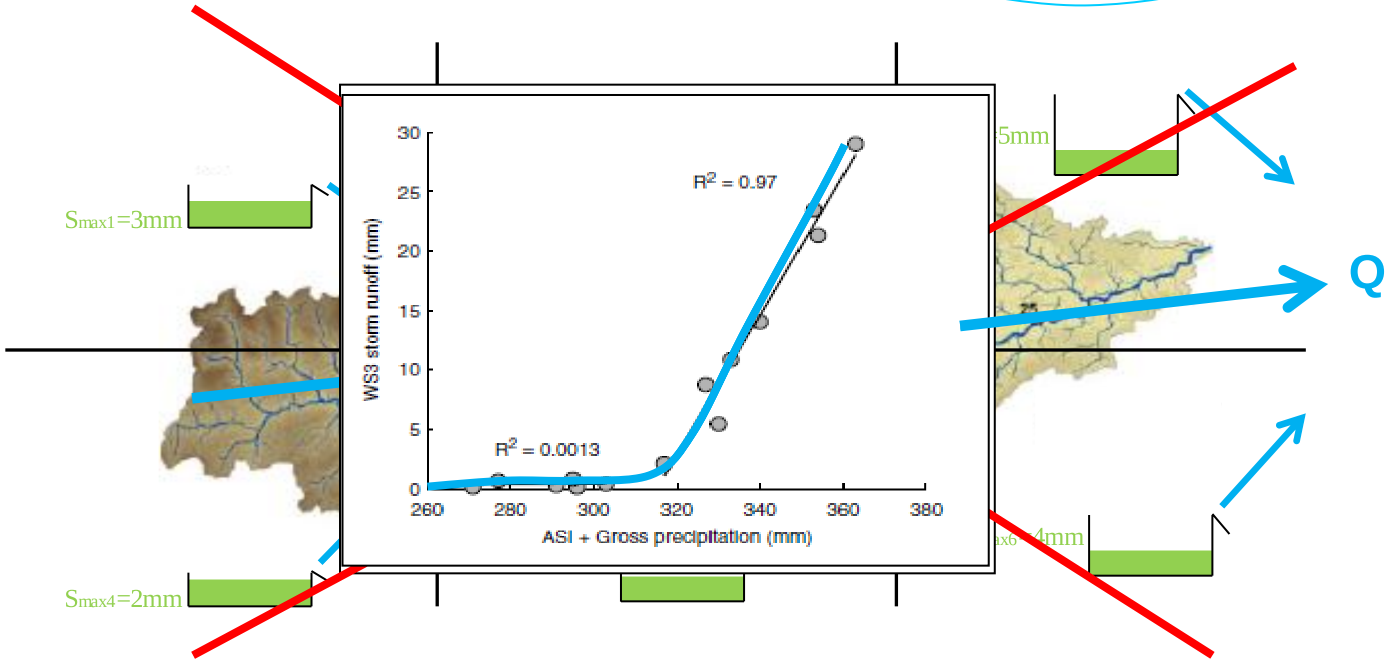


- better understanding through zooming in
  – Mainstream

- better understanding through zooming out
  – holistic empirism

The great world through the eyes of an Ant

Scale and emergent processes



Organization manifests itself by simple functional relationships **emerging at larger scales** (zooming out)

Emergent processes controlled by natural heterogeneity of thresholds (probability distributions)

In other words: how much water can be stored and how much is released from each point in the system at each time step

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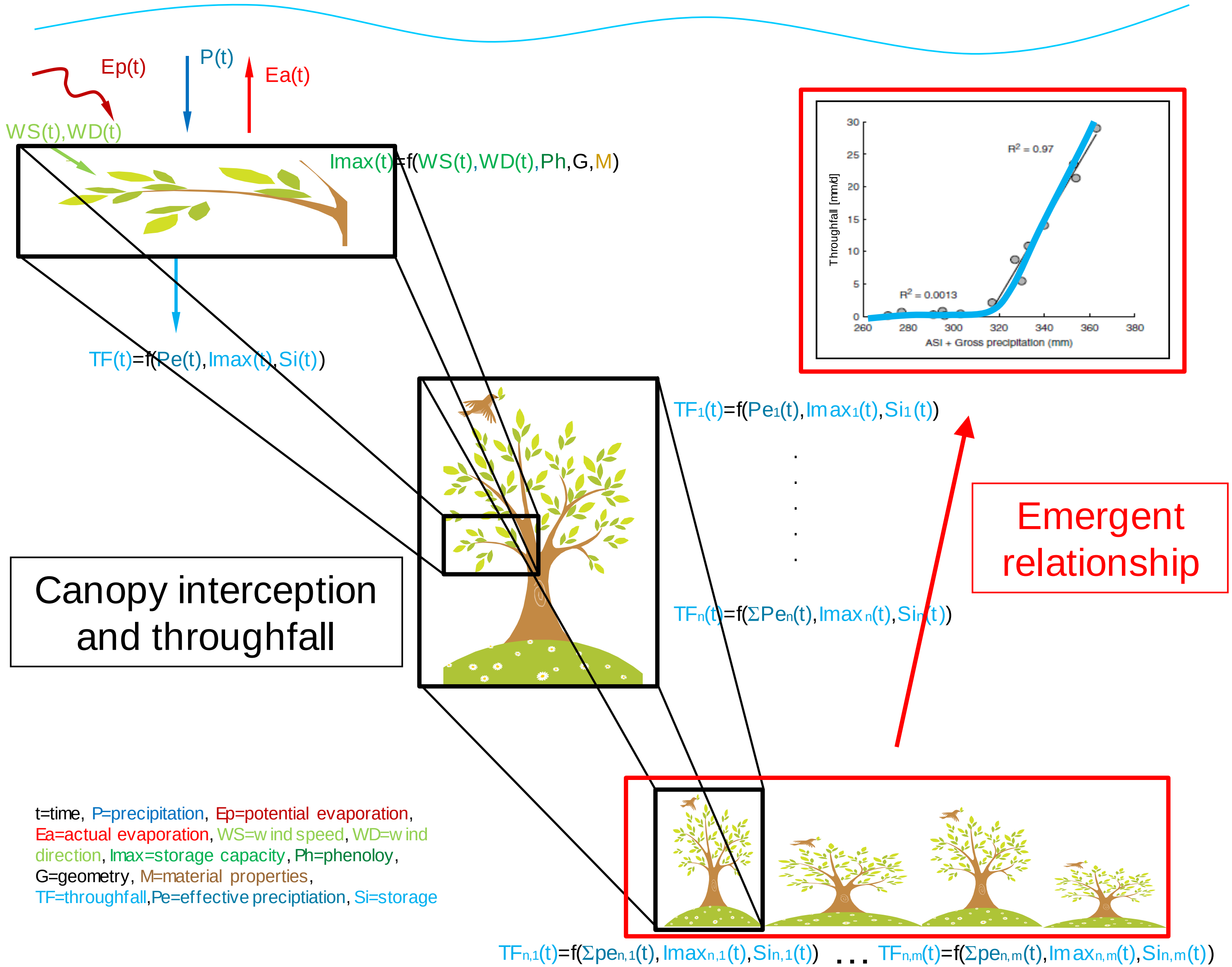
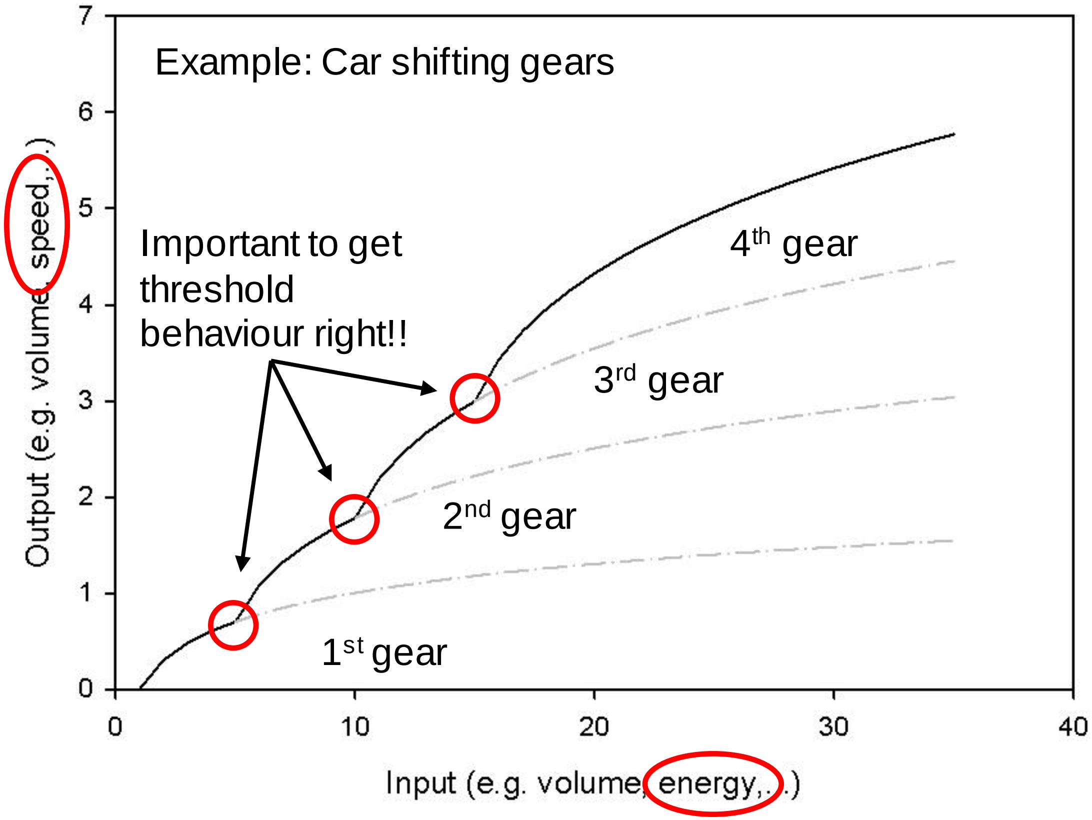
Scale and emergent processes



Feedback and thresholds

Modelling complex feedback systems can frequently result in surprising results as they are characterized by thresholds. The system response can thus tip from one regime to another with only VERY SMALL changes in the forcings and states (e.g. like horses switch gaits, cars switch gears or distinct storages in a hydrological system are activated and deactivated)



Zooming out – conceptual models

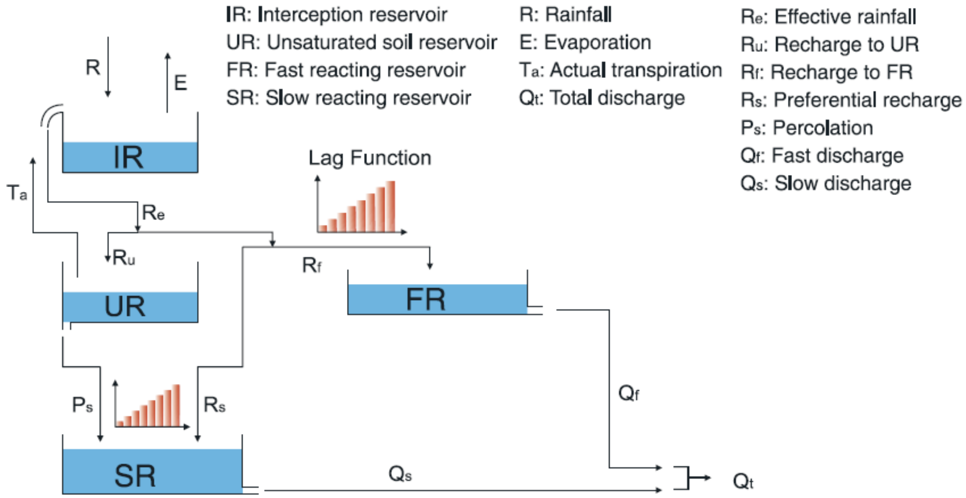


Figure 10. Structure schematization of the FLEX[B] model.

Advantages of **<u>conceptual models</u>** at the catchment scale:

-Fewer parameters

→ reduced problem of equifinality

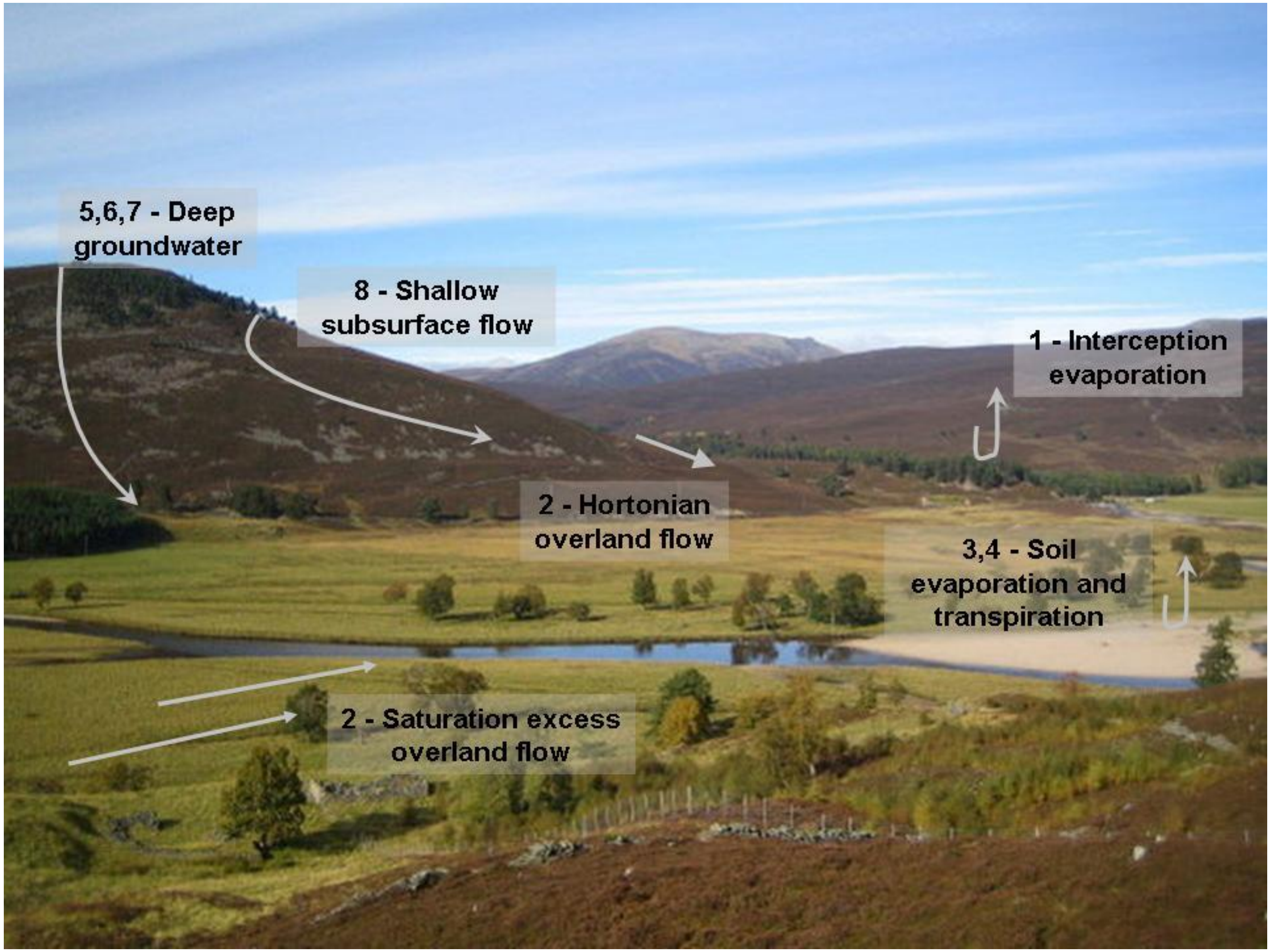
-Emergent relationships integrate natural heterogeneity ("effective parameters"!)

-Lower computational cost

Why are there so many models?

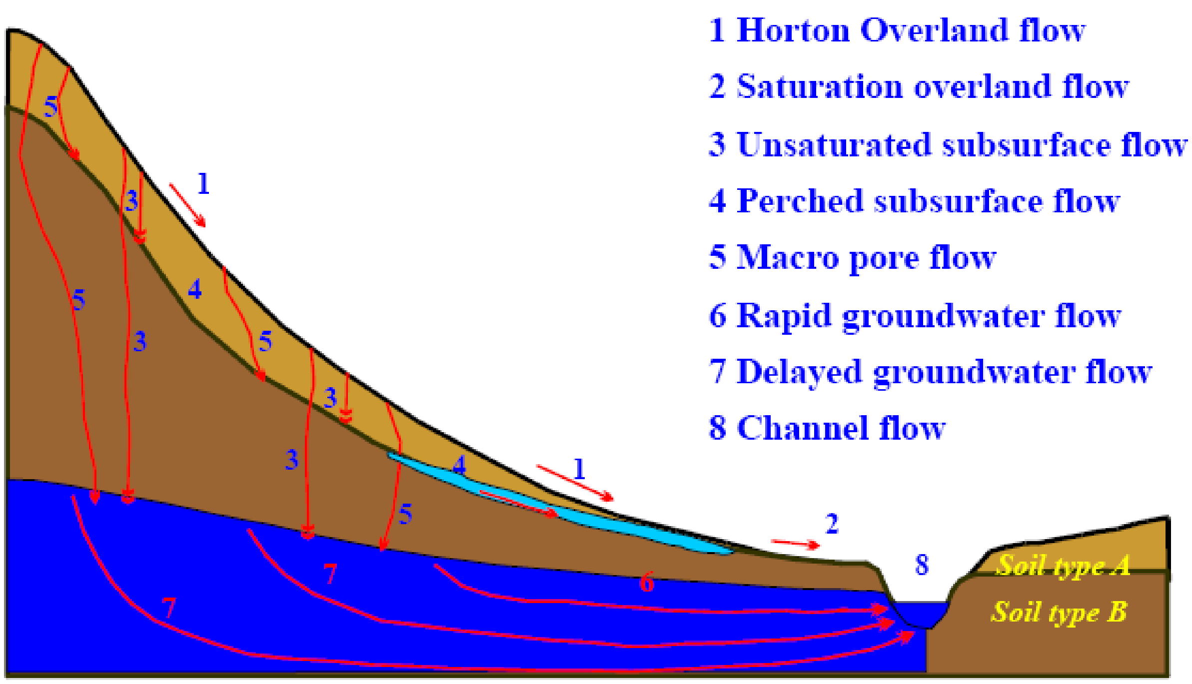
- our inability to calculate the spatial and temporal variability of the rainfall accurately (“het meeste valt ernaast”)
- our deficient ability to conceptualise (Art)
- over-parametrisation

Flow paths

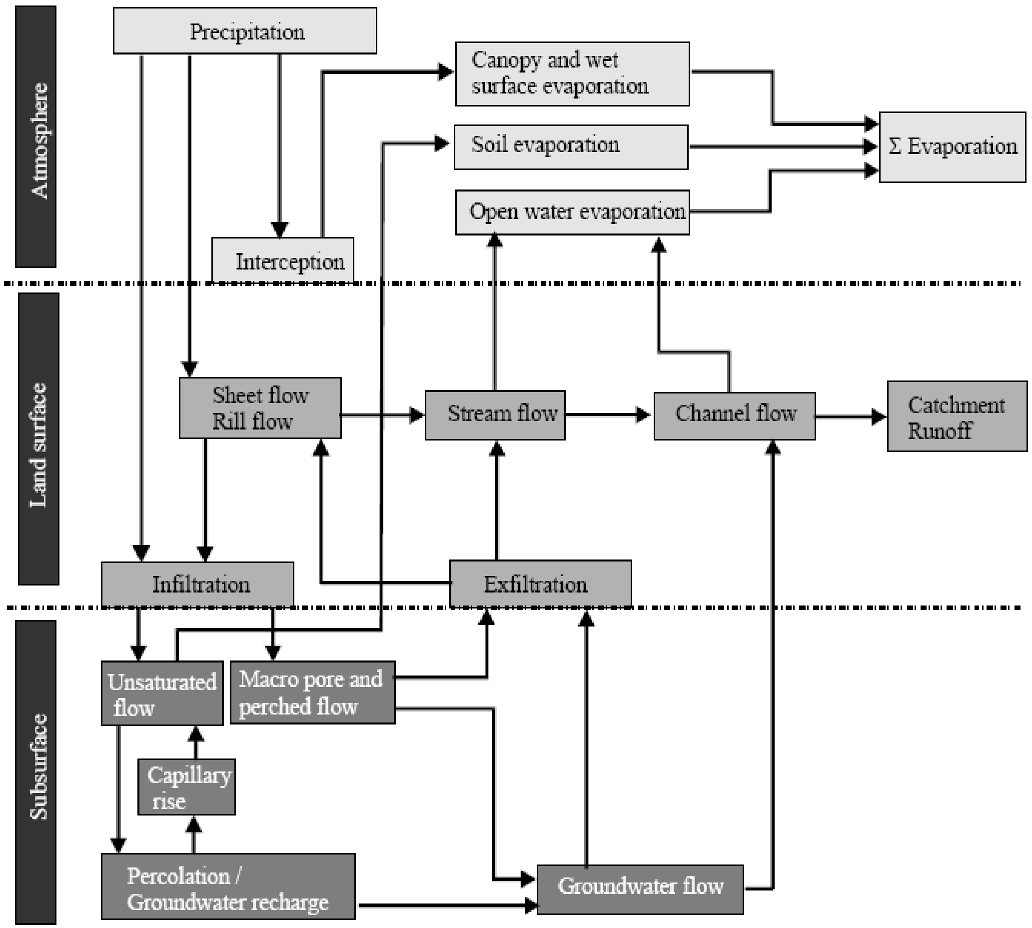


5,6,7 - Deep groundwater
8 - Shallow subsurface flow
1 - Interception evaporation
2 - Hortonian overland flow
3,4 - Soil evaporation and transpiration
2 - Saturation excess overland flow

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
Soil type A
Soil type B
1
2
3
4
5
6
7
8

Flow paths



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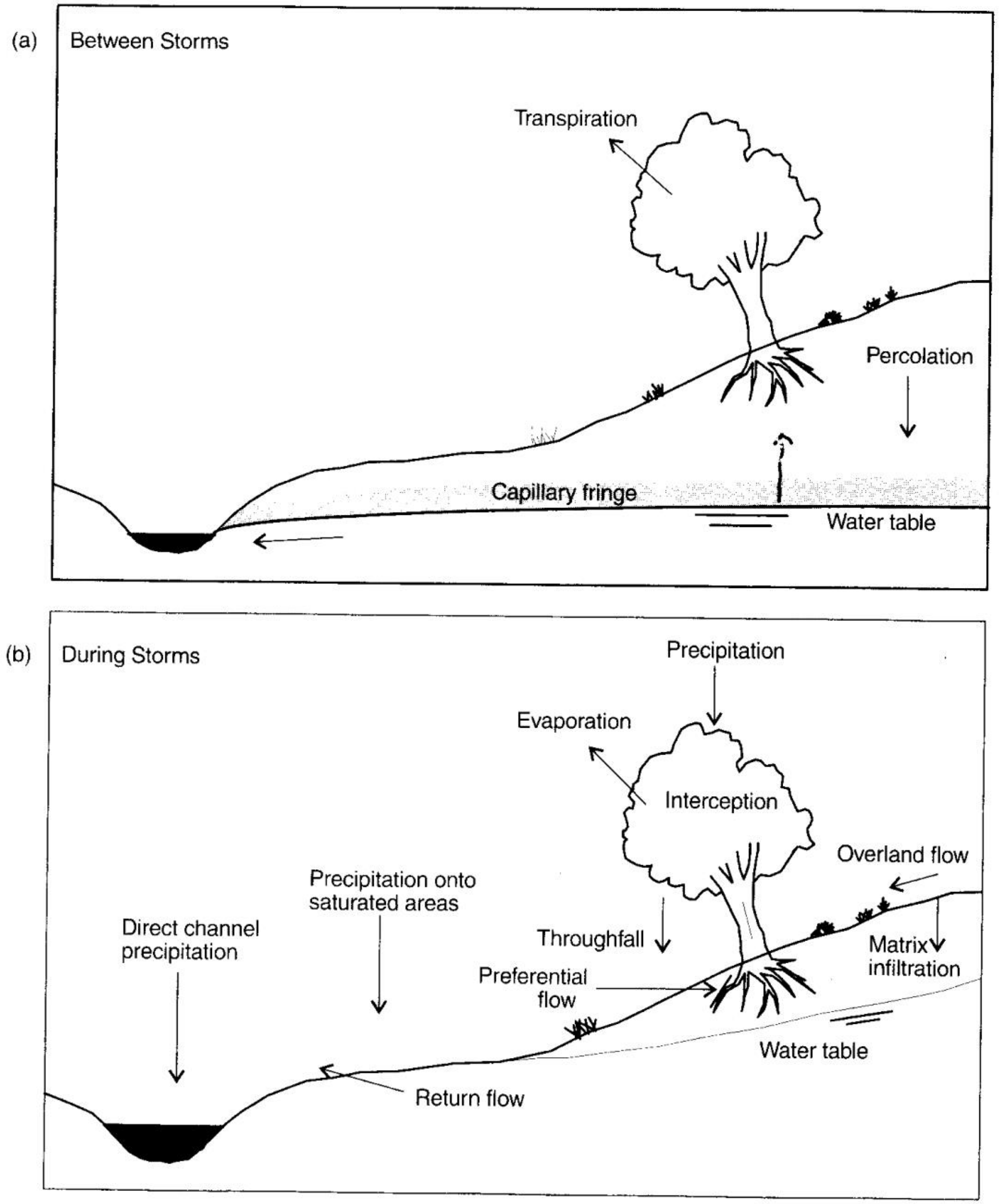
What does a model look like?

Step-by-step

Example model

What have we learned?



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Scales of flow patterns

Scales

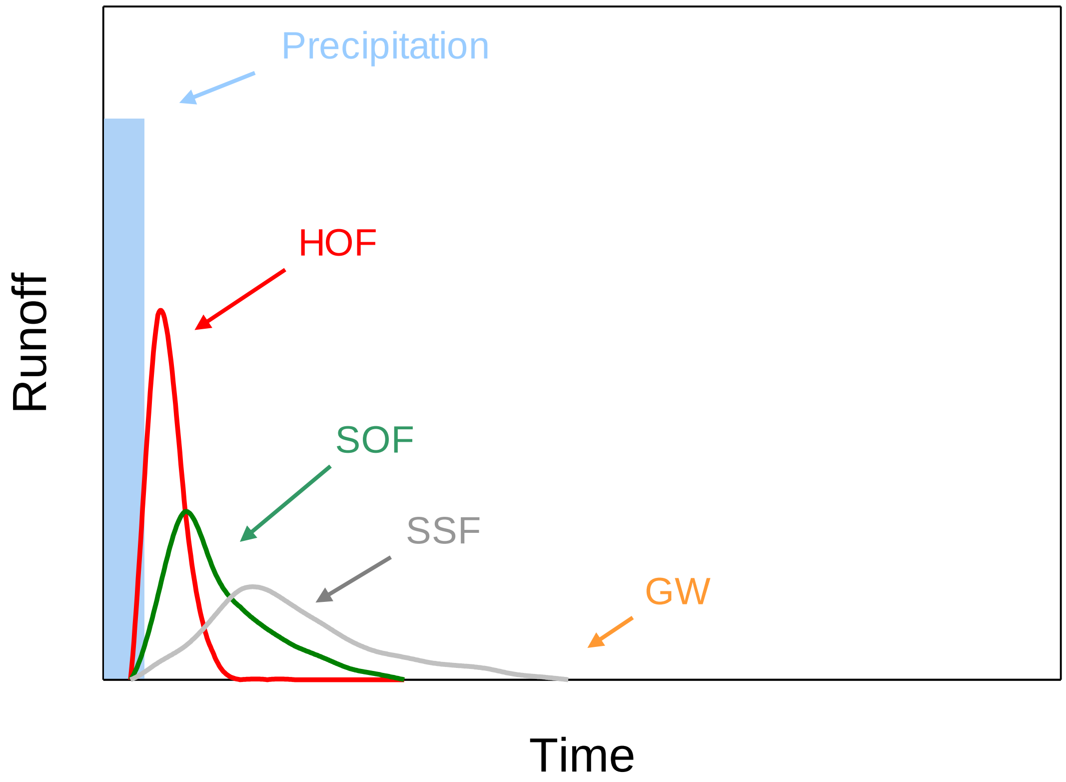
Table 12.1: *Spatial and temporal process scales of the rainfall-runoff processes*

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!

Flowpath timescales



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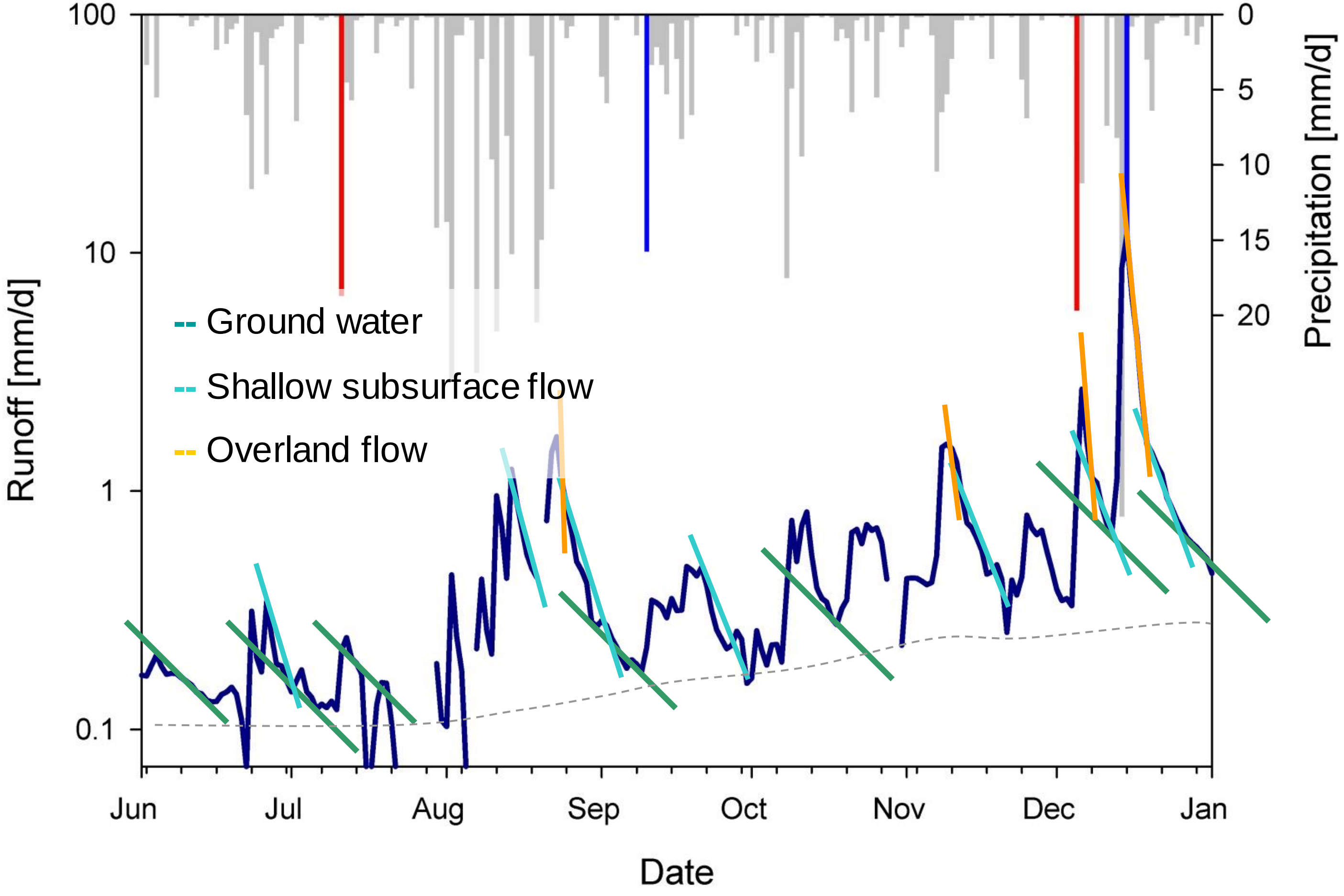
Hydrograph



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Flow Processes

- a) Groundwater
- b) SOF
- c) HOF
- d) SSF
- e) Interception

What does a model look like?

Step-by-step

Example model

What have we learned?

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

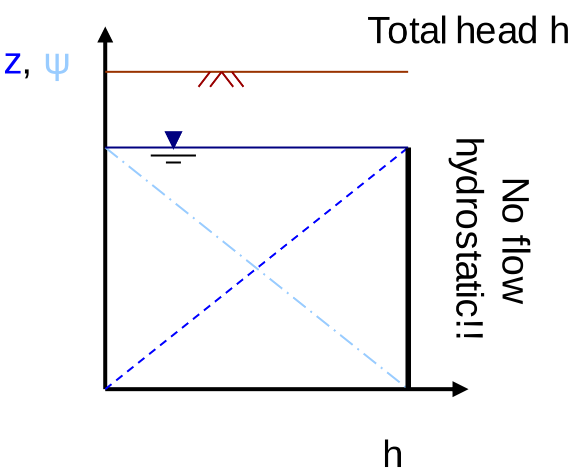
Bernoulli equation

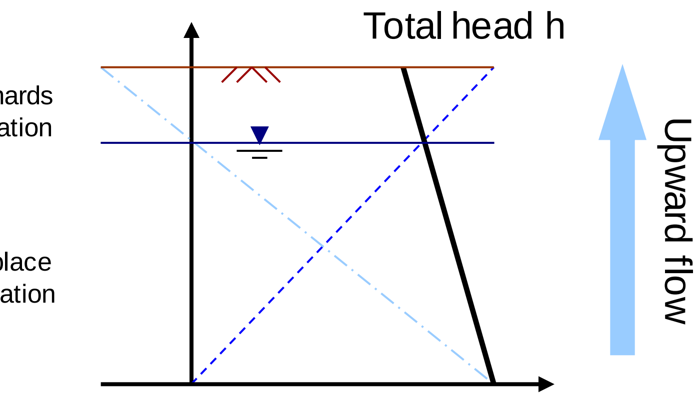
Pressure distribution

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

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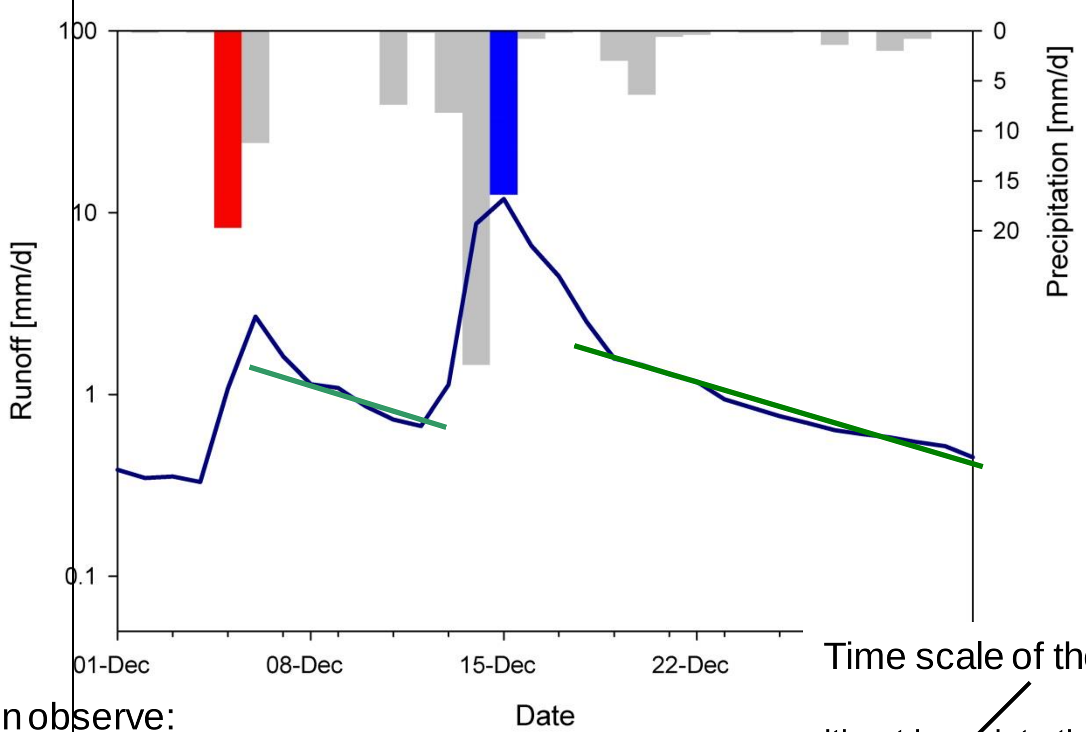


Time scale of the process!

We often observe:

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

and we know:

For deep groundwater in a dry period ~ 0

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

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

without input into this model this discharge - storage relationship is linear

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

no input inside this recession

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

Linear Reservoir

- ✓ Objectives
- ✓ What is a hydrological model ?
- ✓ Why do we care?
- ✓ Modeling Process
- ✓ Problems
- ✓ What types of models are out there?
- **Flow Processes**
  - **a) Groundwater**
  - b) SOF
  - c) HOF
  - d) SSF
  - e) Interception
- What does a model look like?
- Step-by-step
- Example model
- What have we learned?

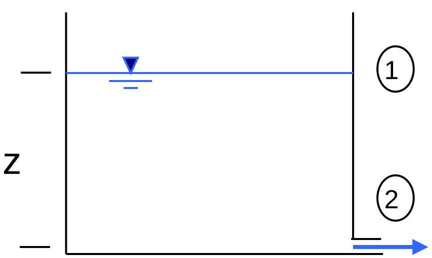
Groundwater – Linear Reservoir

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 ($A_1 >> A_2$):

S = z



Q = ?

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

Atmospheric pressure!

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

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

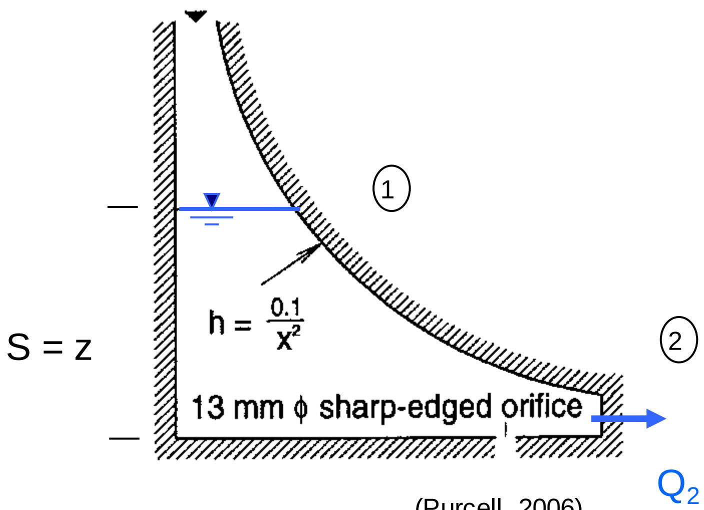
$$Q_2 = A_2\sqrt{2gS_1} = A_2\sqrt{2g}\sqrt{S_1} \qquad A_2\sqrt{2g} = \frac{1}{k}$$

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

→ ????

Groundwater – Linear Reservoir

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

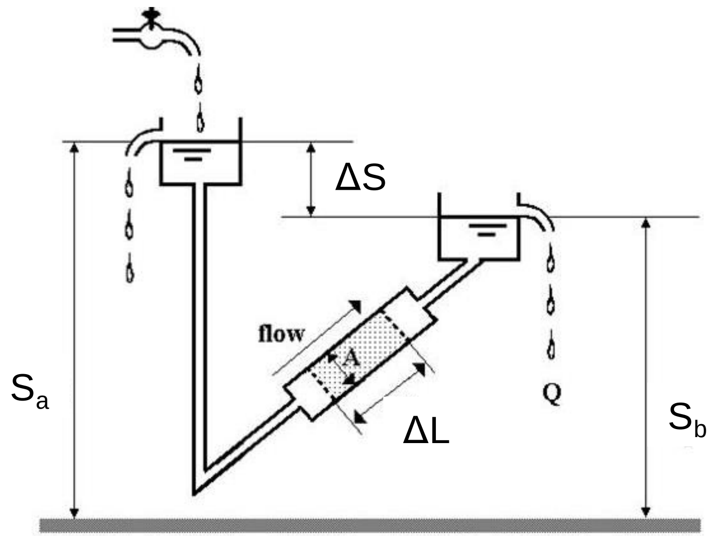


(Purcell, 2006)

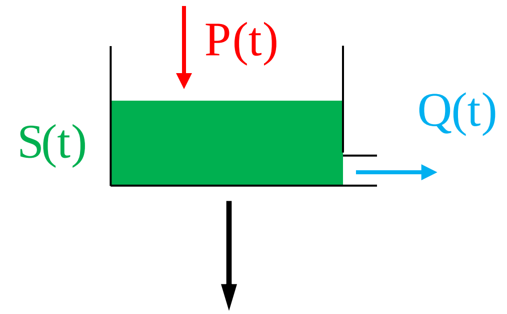
$$Q_{lin} = \frac{1}{k} S_1 \quad = \quad Q_2 = \frac{1}{k} S_1$$

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:



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

Catchment "form"

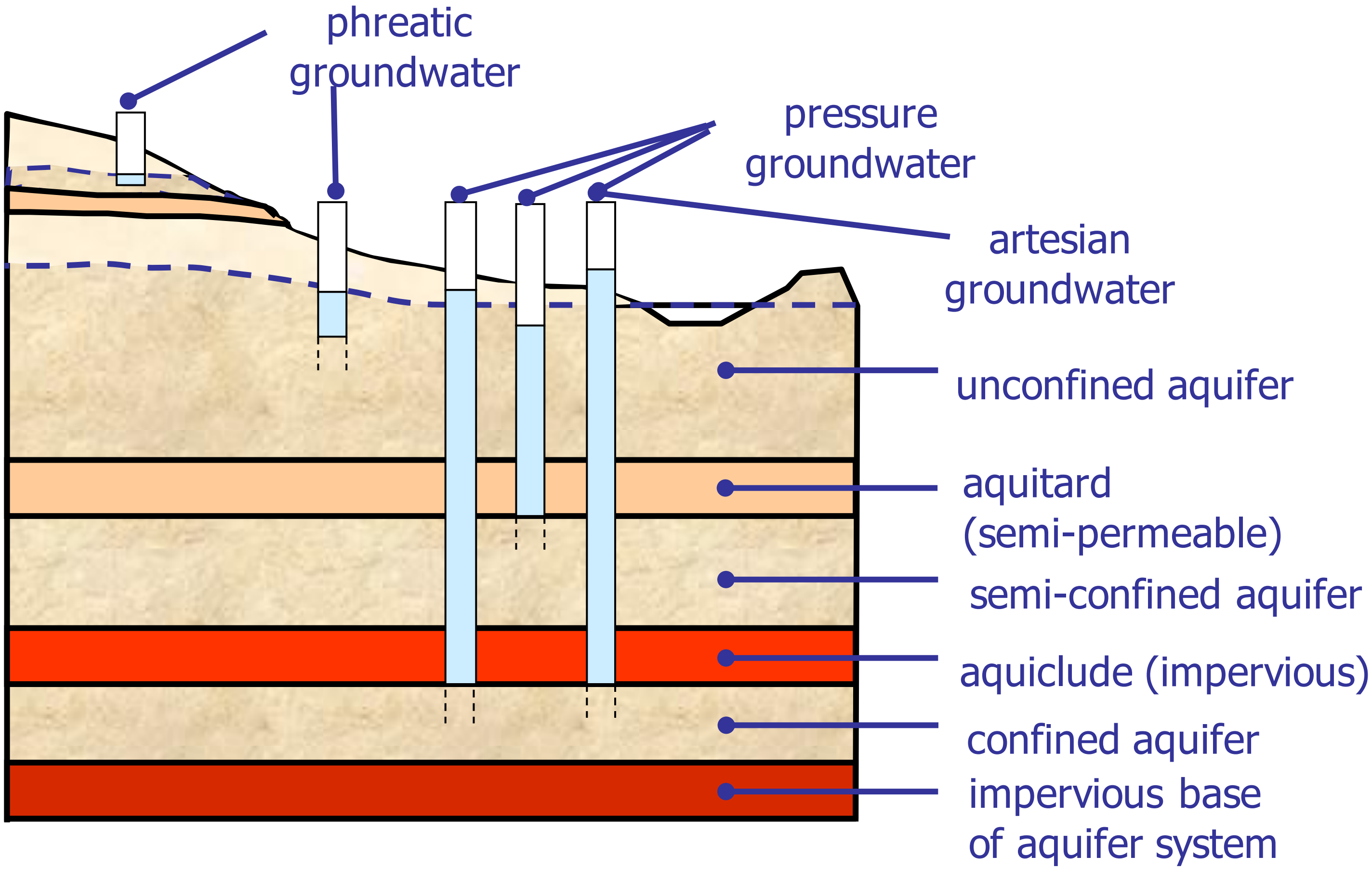
$$Q_{Darcy} = A \cdot v = A k_S \frac{dS}{dL}$$

With: $k_S \frac{A}{dL} = \frac{1}{k}$

$$dS = S_a - S_b = S$$

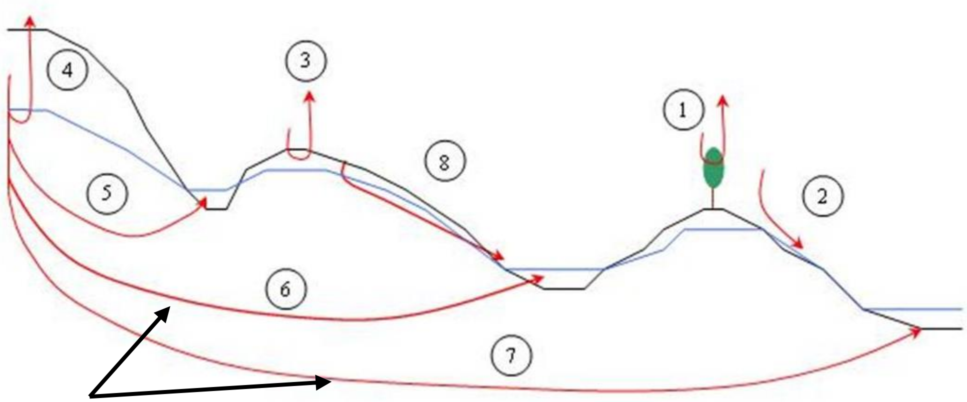
$$\boxed{Q_{Darcy}(t) = Q_{lin}(t) = \frac{1}{k} S(t)}$$

Groundwater



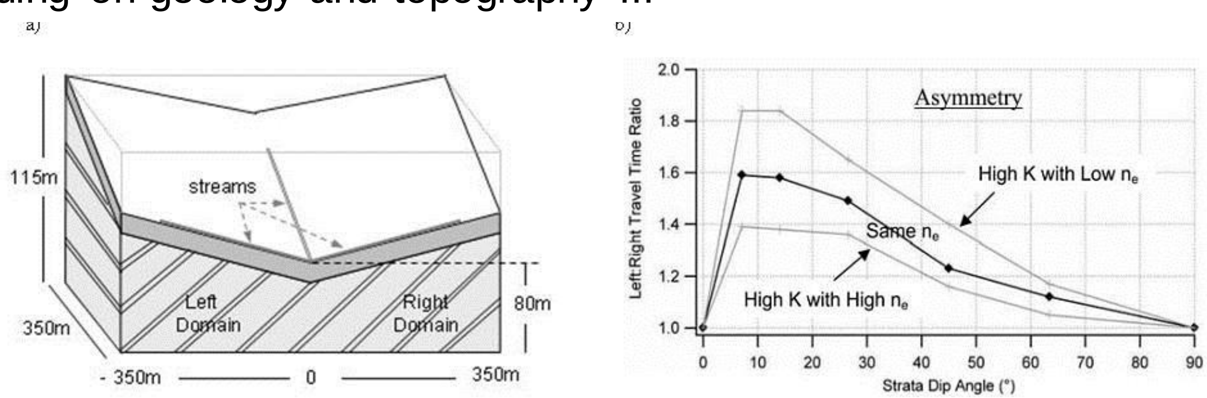
Water storage and movement in pores, fractures, solution channels and caverns (e.g. Karst)

Groundwater import and export



Regional Groundwater flow (5,6)

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



- ✓ Objectives
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Flow Processes

- **a) Groundwater**
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- c) HOF
- d) SSF
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What does a model look like?

Step-by-step

Example model

What have we learned?

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

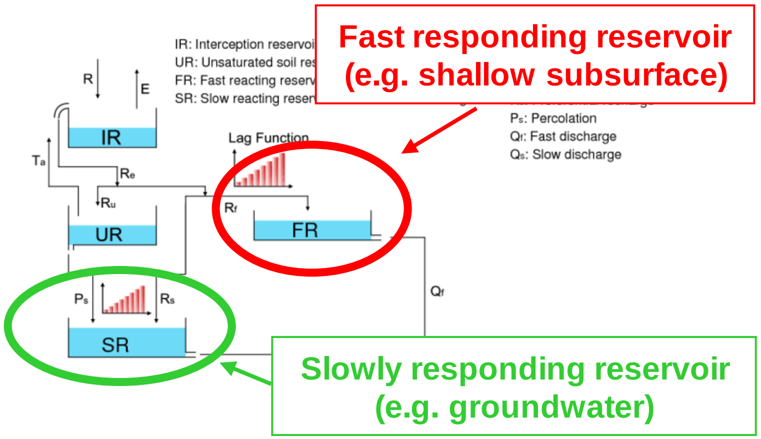
Disadvantages of groundwater resources

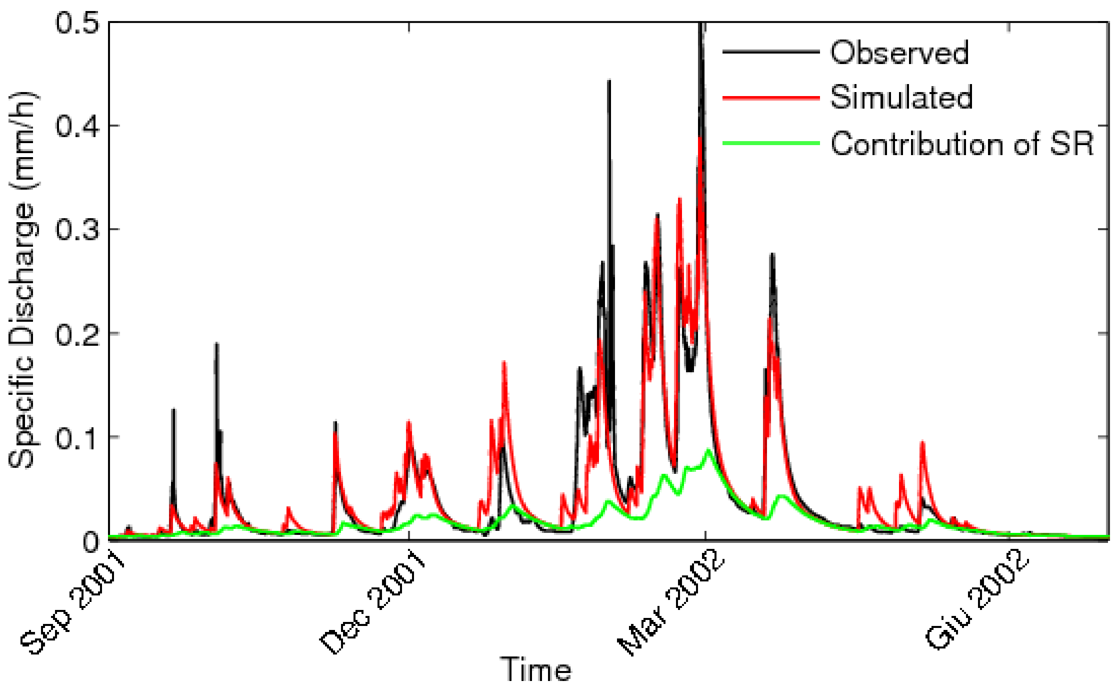
- Strongly limited resource
- Recovery is expensive due to pumping costs
- Vulnerable and sensitive to pollution
- Impact on land subsidence and/or salinization

Baseflow modeling

- Baseflow is often represented as water draining from a groundwater reservoir

- Frequently linear reservoir Q=S*k





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Flow Processes

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What does a model look like?

Step-by-step

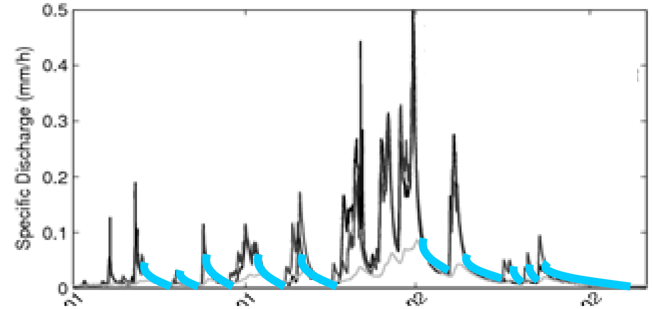
Example model

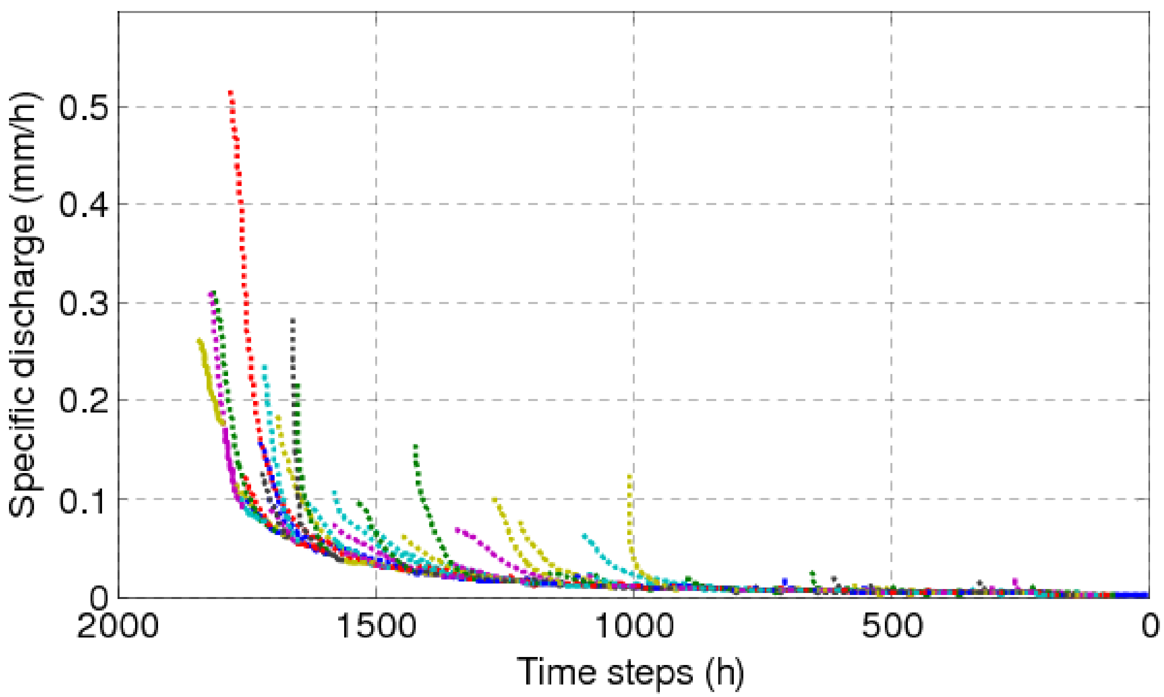
What have we learned?

Baseflow modeling

Master Recession Curve

- Obtained by combining different recession segments
- Used to “model” the catchment recession behavior

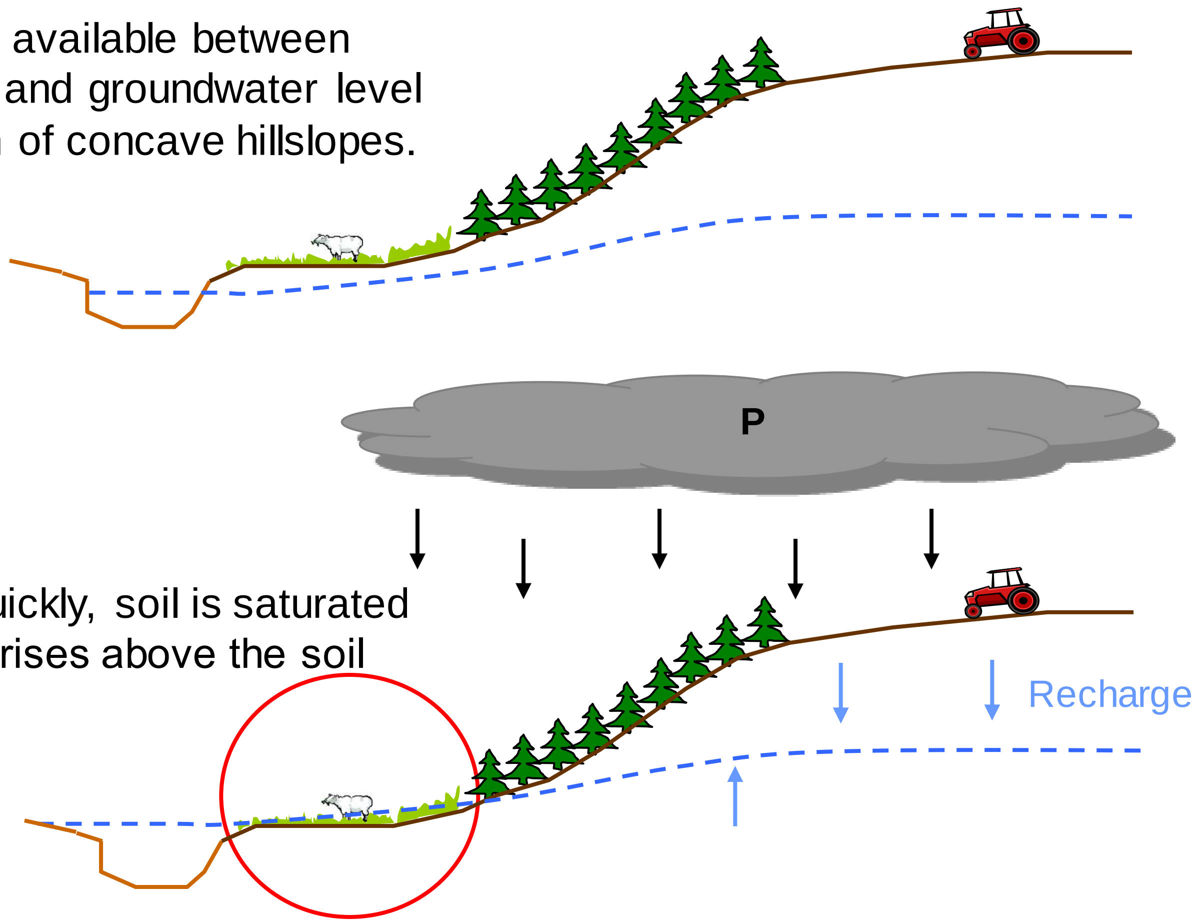




Saturation Overland Flow

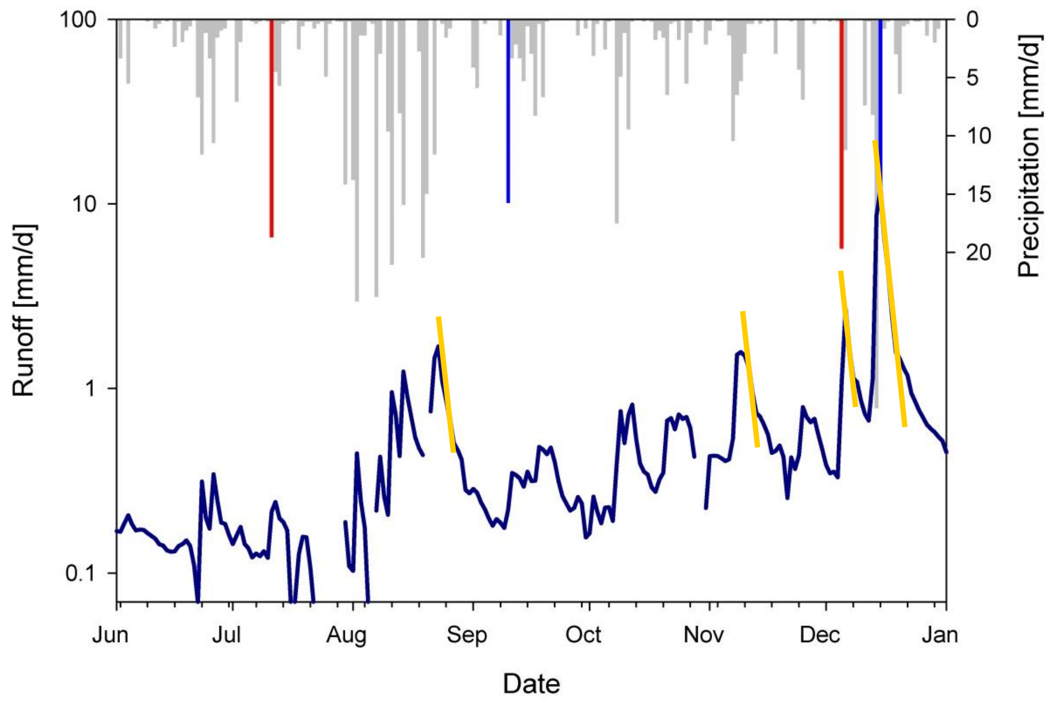
Little storage available between soils surface and groundwater level at the bottom of concave hillslopes.

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

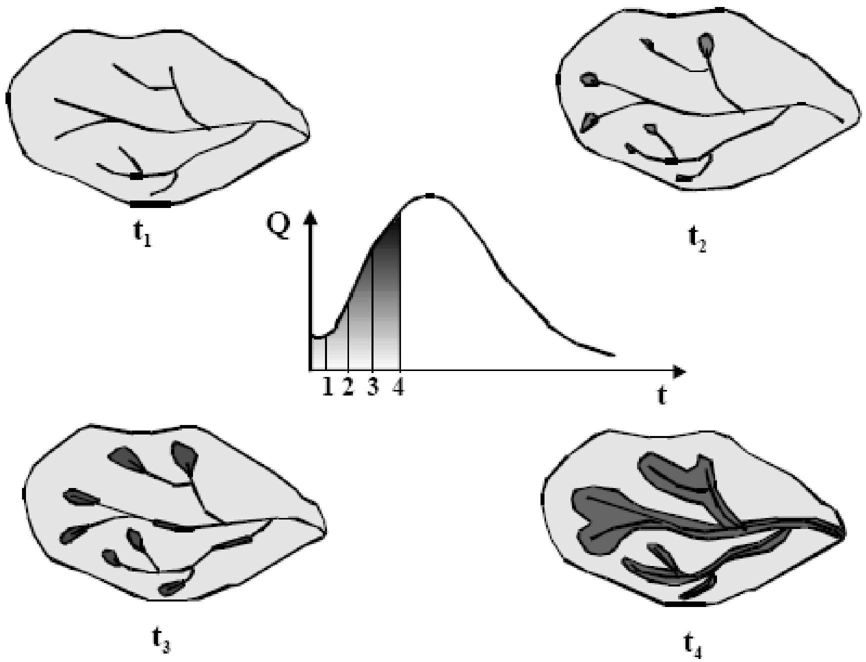
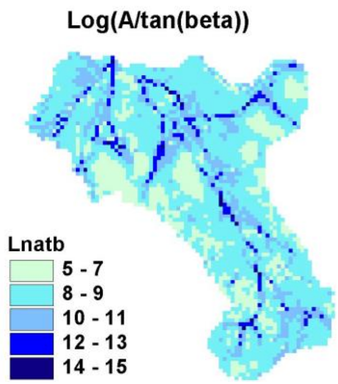


Figure 12.5: *Expansion of the saturation overland flow source area during a storm event [modified after Dunne, 1978]*

Saturation Overland Flow - TWI

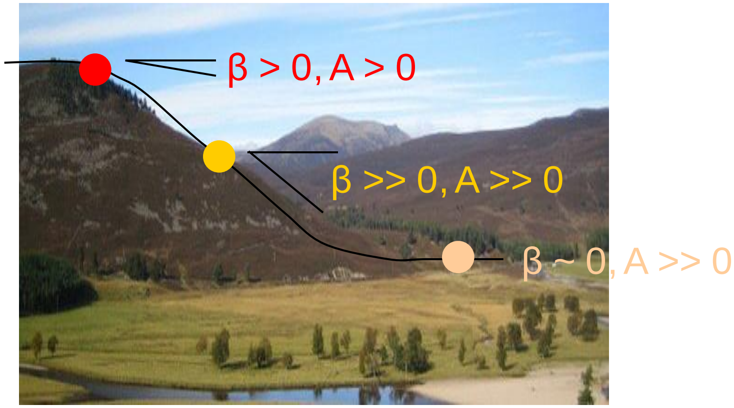
<u>Topographic Wetness Index</u> (TWI; Beven and Kirkby, 1979)

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



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

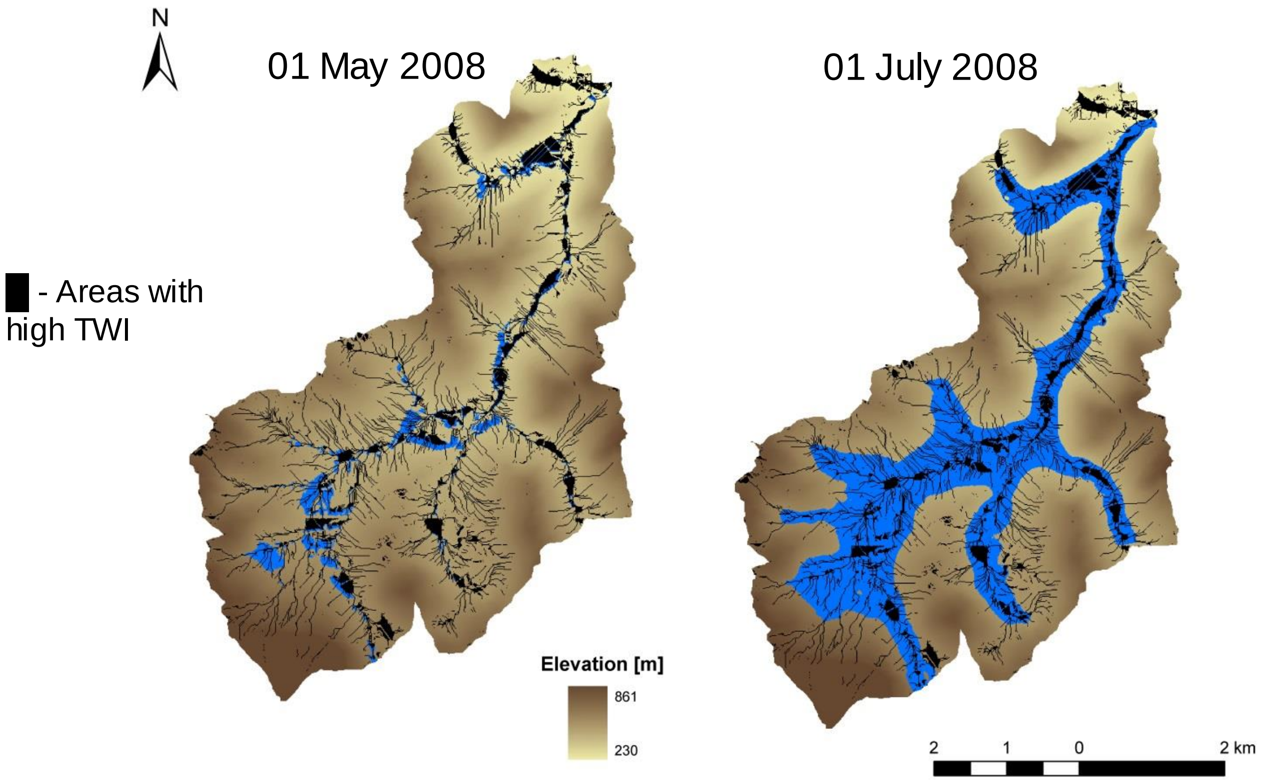


→ TWI: low

→ TWI: medium - low

→ TWI: high

Saturation Overland Flow - TWI



(Birkel et al., 2009)

- ✓ Objectives
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Flow Processes

- ✓ a) Groundwater
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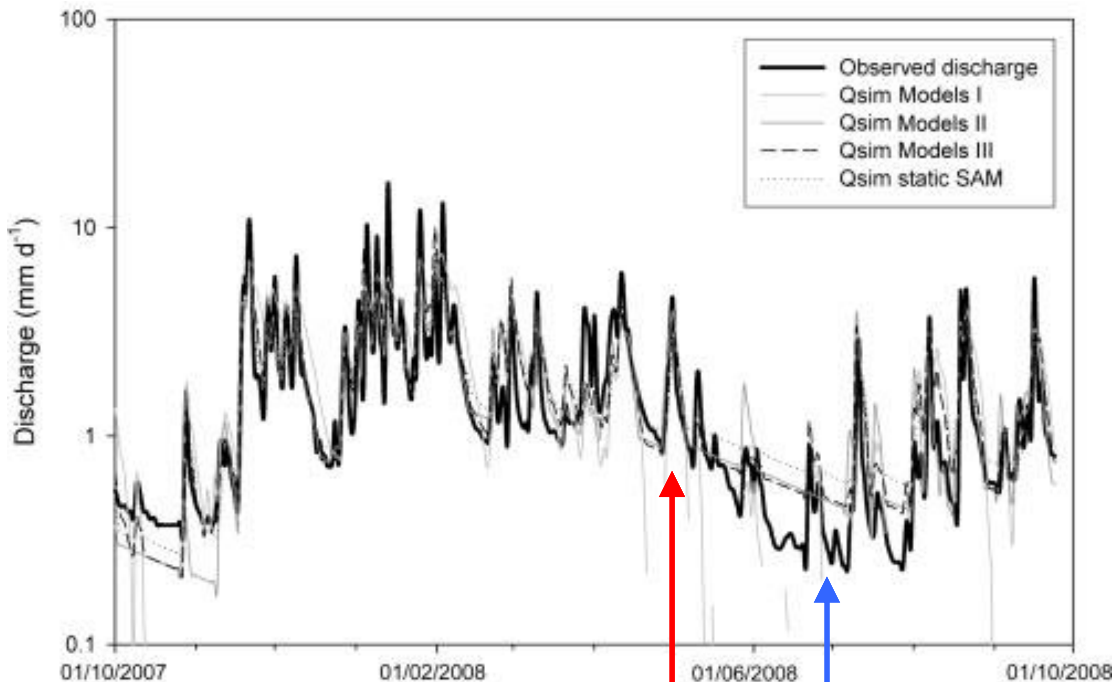
What does a model look like?

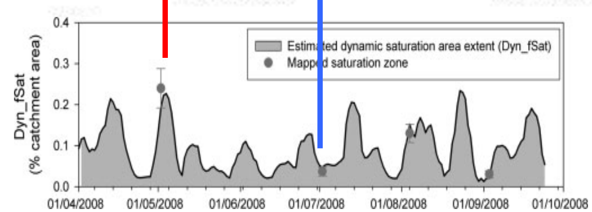
Step-by-step

Example model

What have we learned?

Saturation Overland Flow





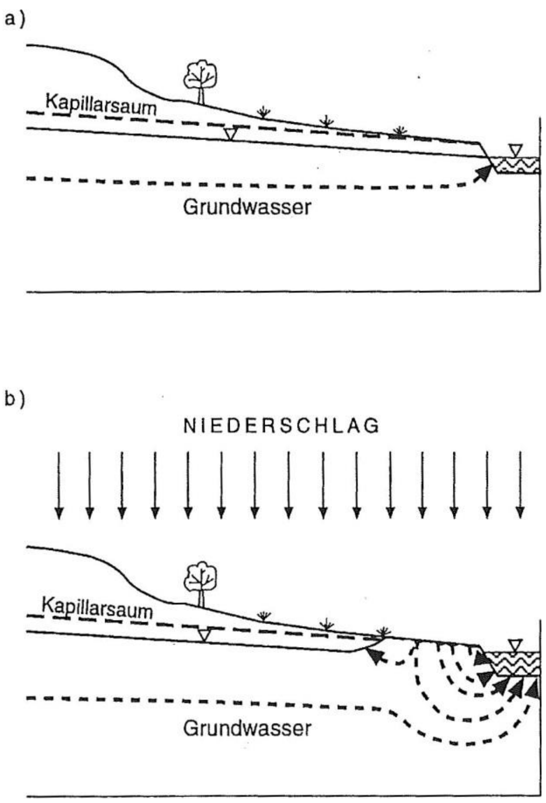
High proportions of saturated area when groundwater level is high, low proportion when groundwater level is low

(Birkel et al., 2009)

Saturation Overland Flow

<u>Groundwater Ridging:</u>

- 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

<u>Where does SOF occur?</u>

Frequently in wide valley bottoms.
Rare in steep terrain.

Indicator plants include:

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

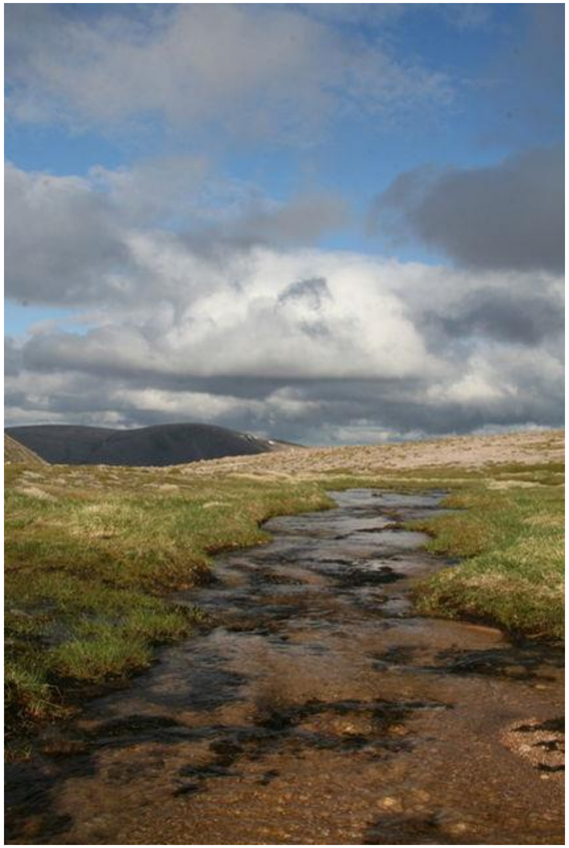
and the most other species in and around the Dutch Polder landscape

Saturation Overland Flow

Saturation Overland Flow

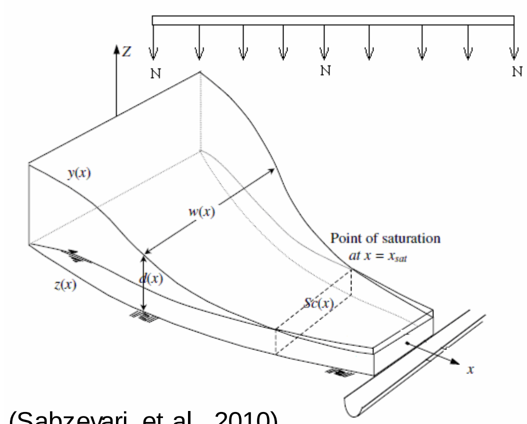


Saturation Overland Flow



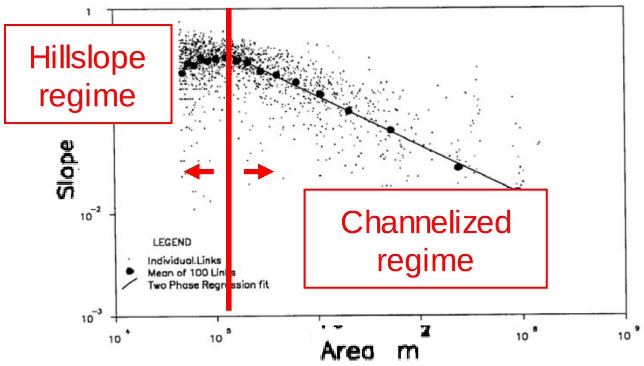
SOF can also be found in the headwaters !

Saturation Overland Flow

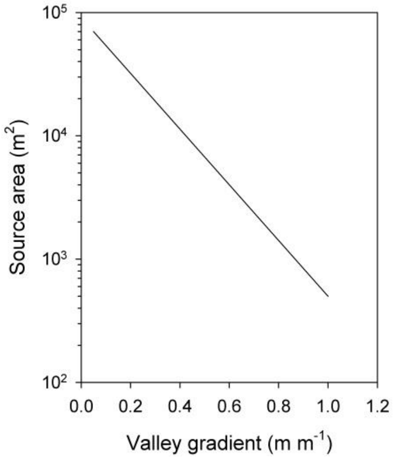


(Sabzevari et al., 2010)

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



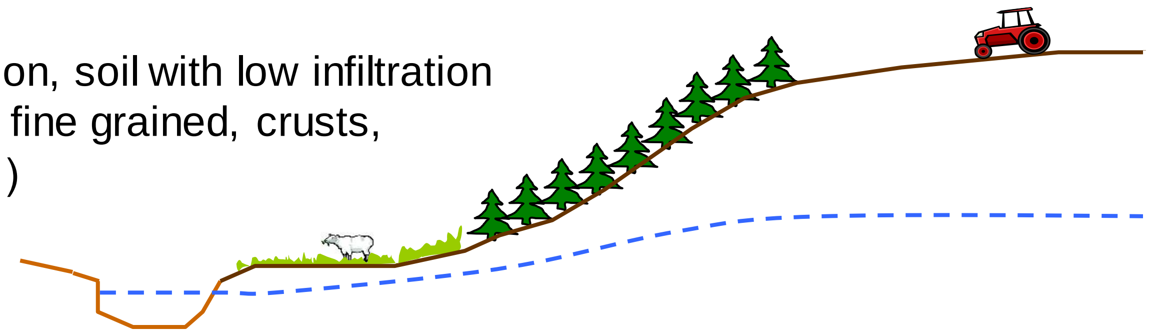
(Tarboton et al., 1992)



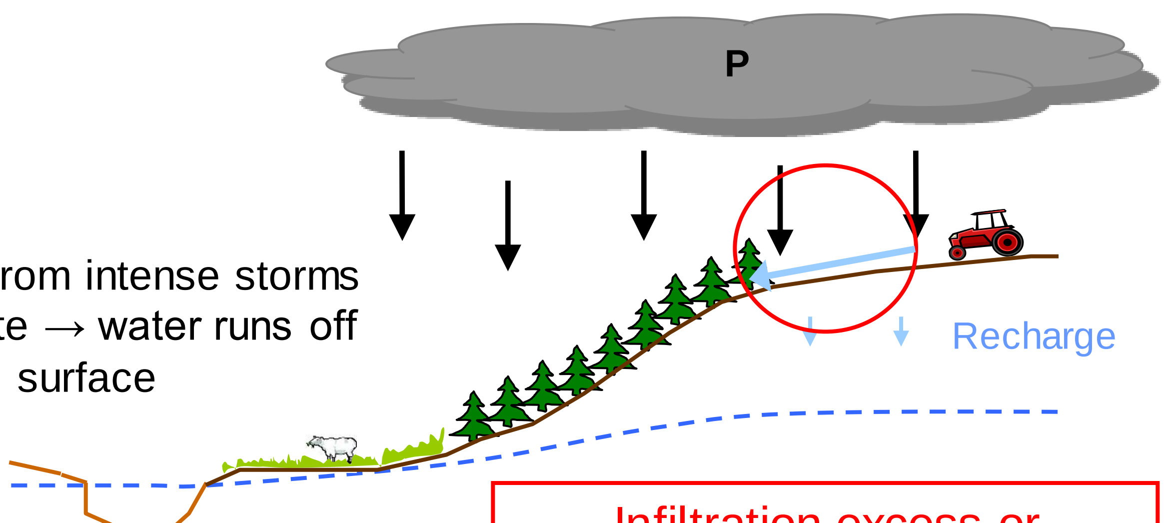
(after Montgomery and Dietrich, 1988)

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

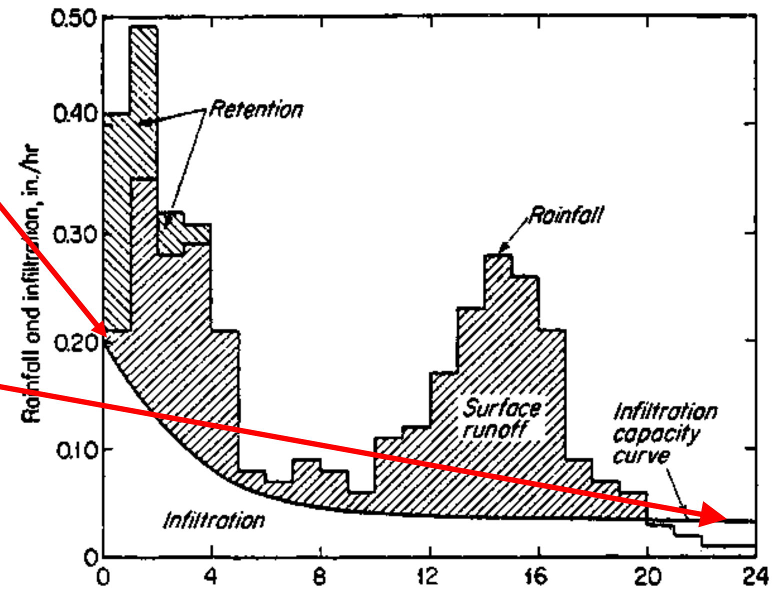


Infiltration excess or Hortonian overland flow (HOF)

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 $\mathbf{K^{sat}}$

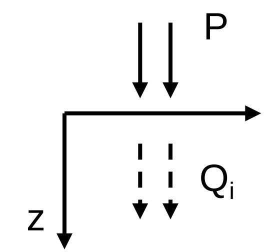
But why is $\mathbf{Q_i}$ declining when soil moisture increases ?????



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

- ✓ Objectives
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Flow Processes

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- ✓ b) SOF
- **c) HOF**
- d) SSF
- e) Interception

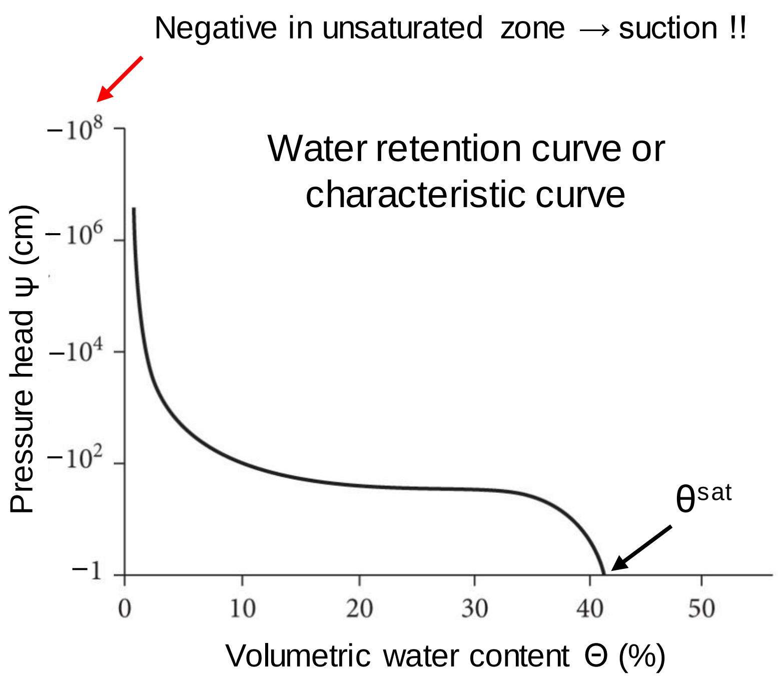
What does a model look like?

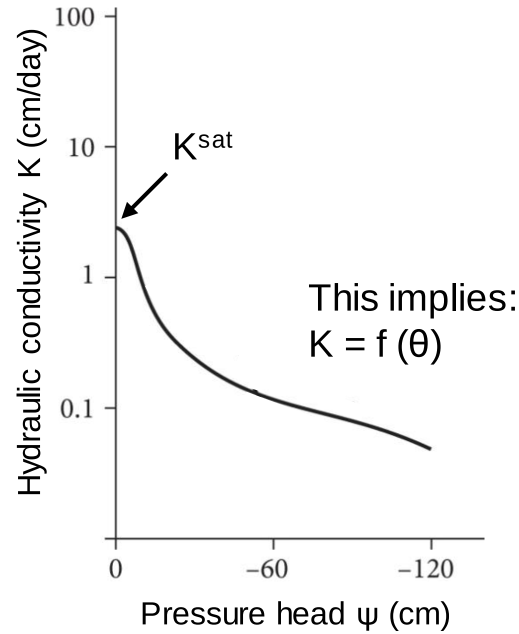
Step-by-step

Example model

What have we learned?

Infiltration





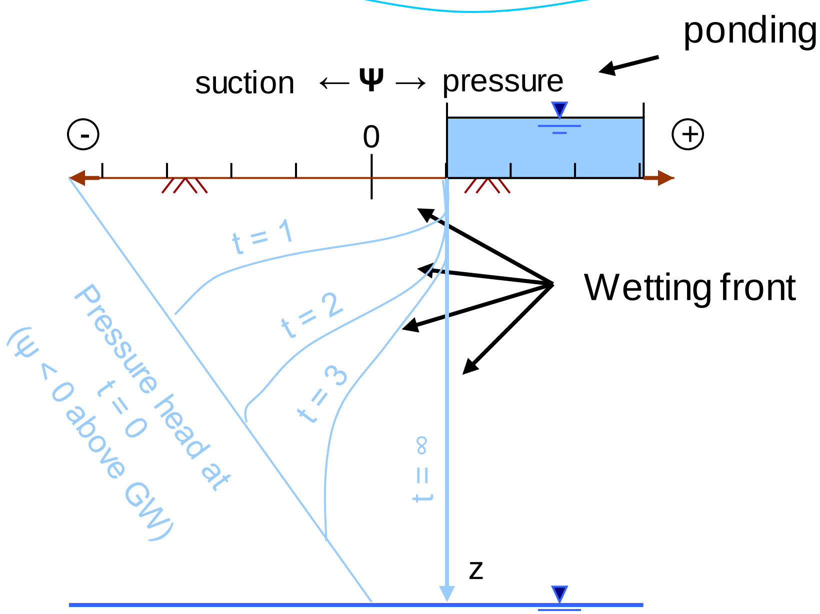
Volumetric water content $\theta = V_w/V_{total}$

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	HOF
~ limit of rainfall intensity		
Sandy soils, humid	8	SSF
Rainforest	135	SSF
Oregon coast range	> 500	SOF

However:

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

Hortonian Overland Flow

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What does a model look like?

Step-by-step

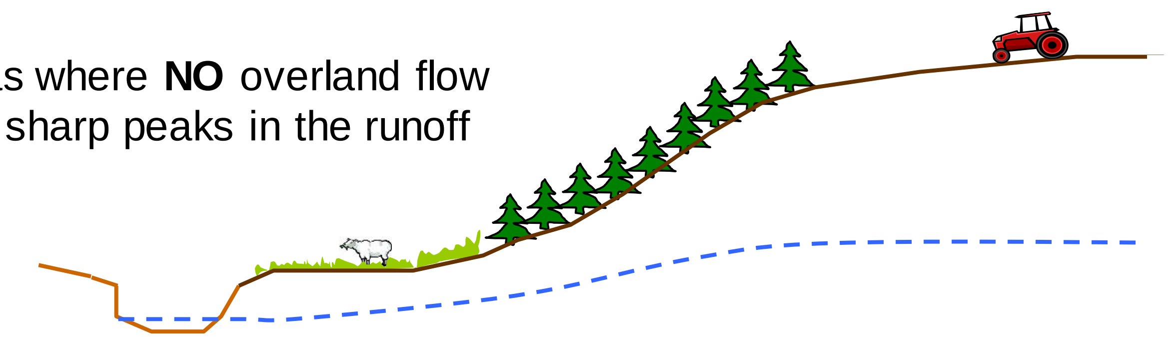
Example model

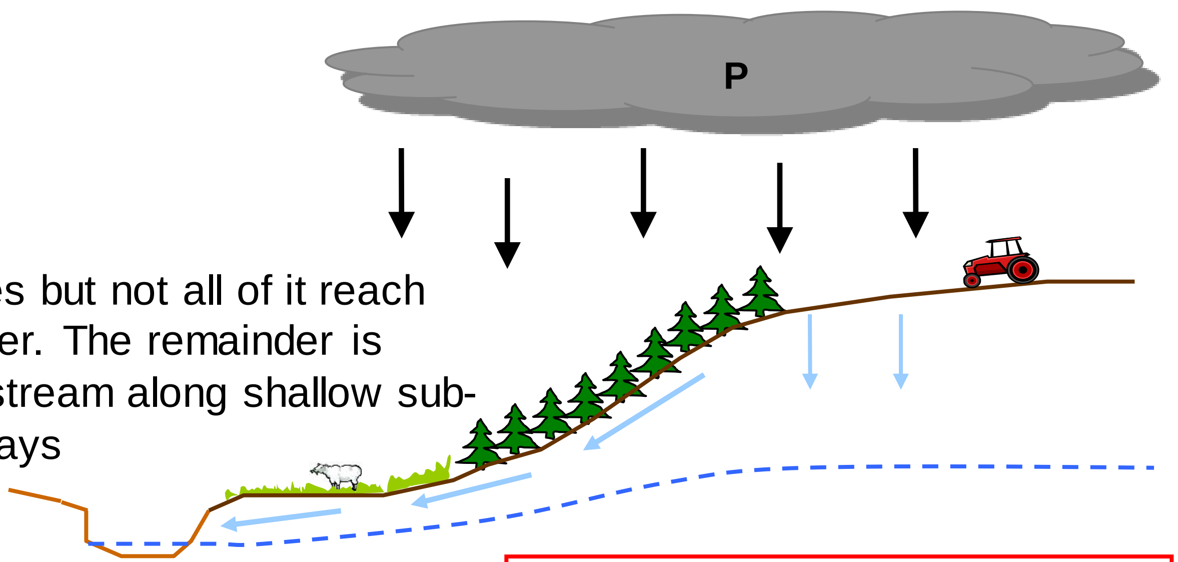
What have we learned?

Hortonian Overland Flow

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)

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What does a model look like?

Step-by-step

Example model

What have we learned?

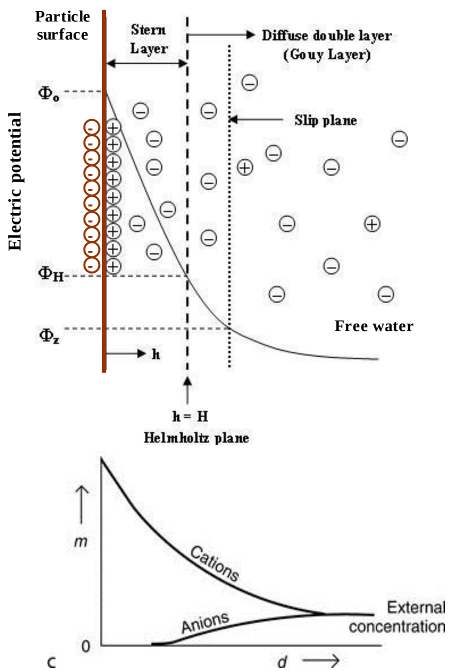
Unsaturated zone

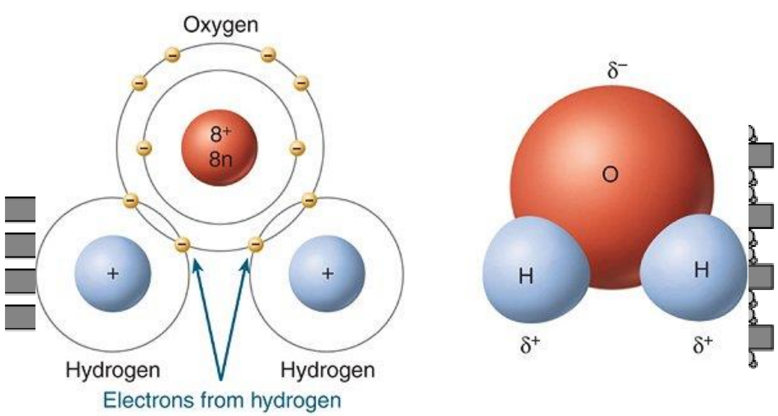
The unsaturated zone (also: vadose zone or soil moisture zone) is the zone above the phreatic groundwater table.

Pressure head $\psi < 0 \rightarrow$ 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!

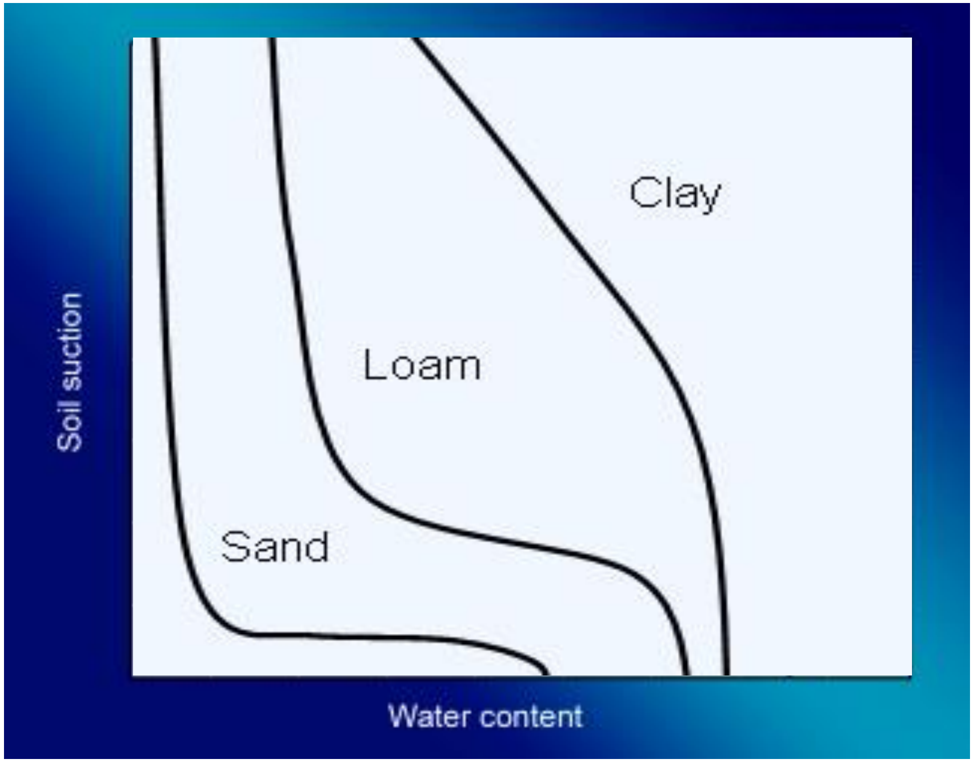
Unsaturated zone

Flow in soil with different water content:

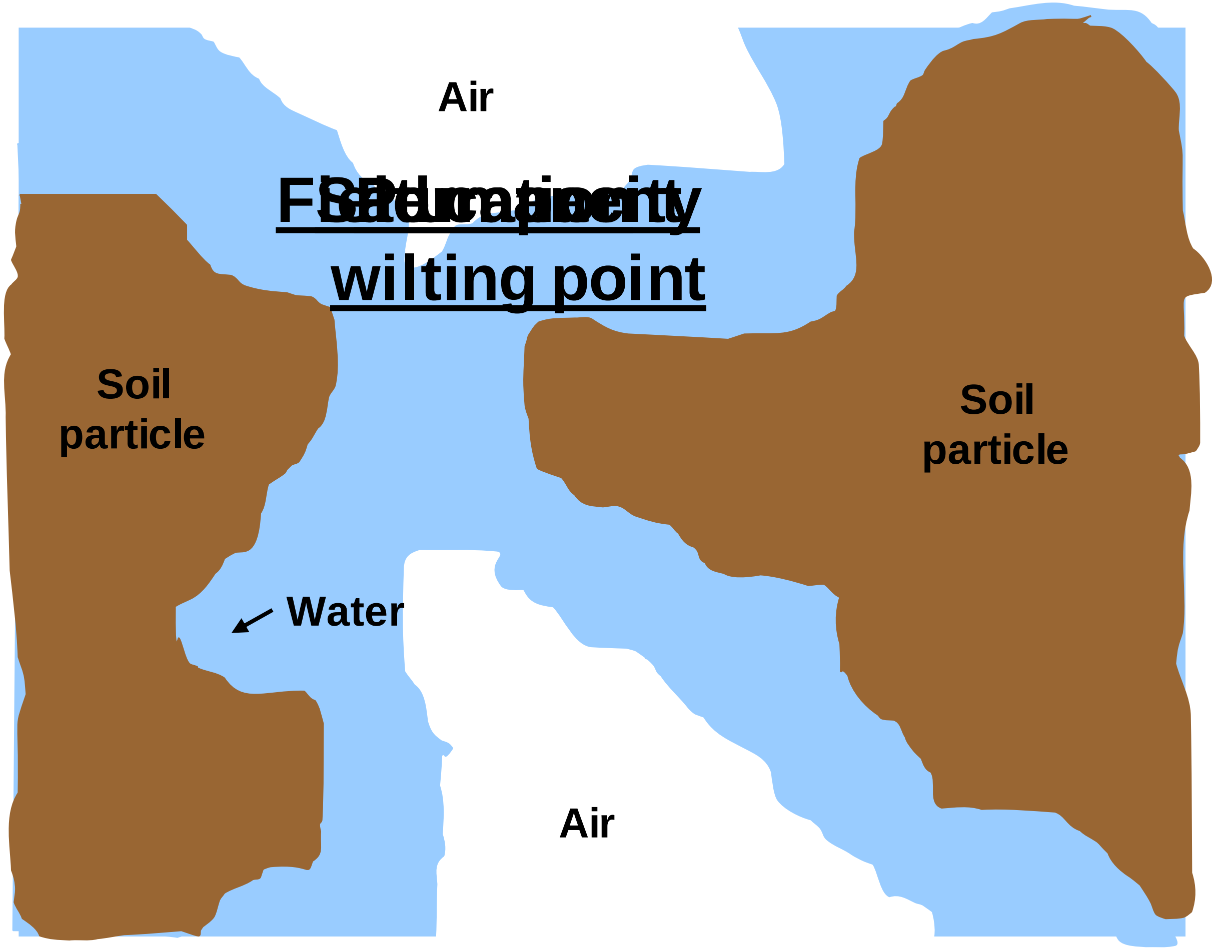
(a) at saturation building of hydrostatic pressure head → Darcy
(b) partial saturation → Richards equation
(c) No flow

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



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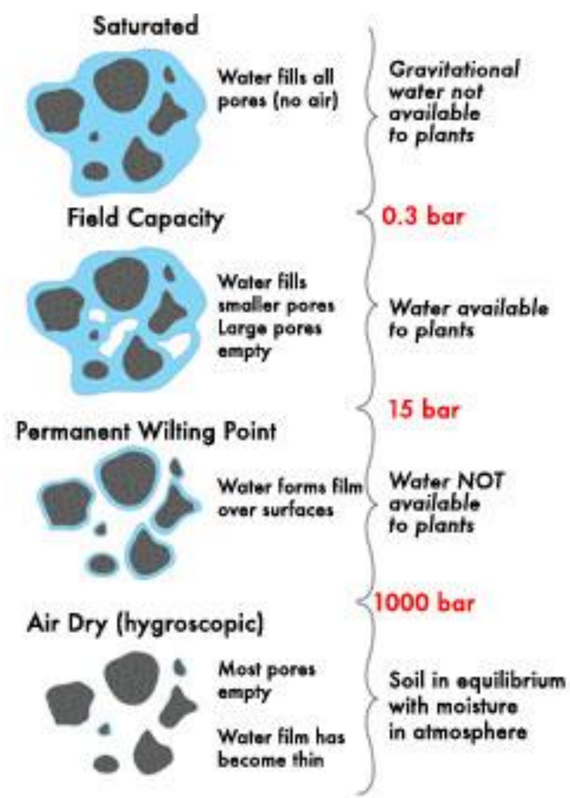
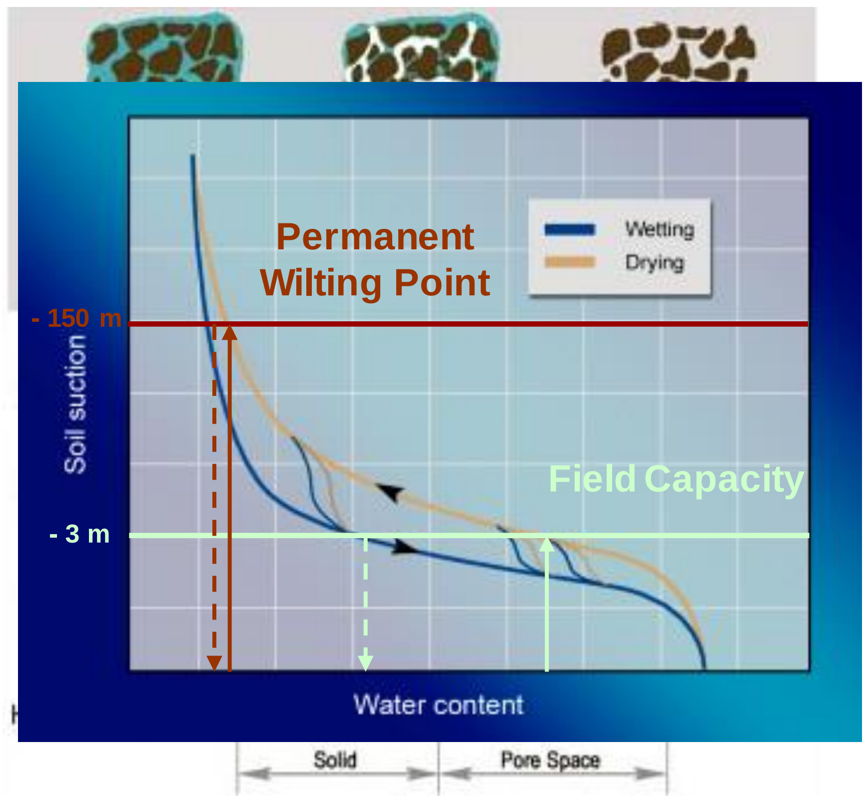
Step-by-step

Example model

What have we learned?

Unsaturated zone

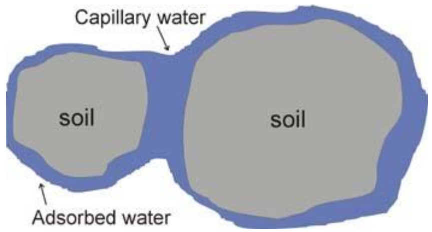


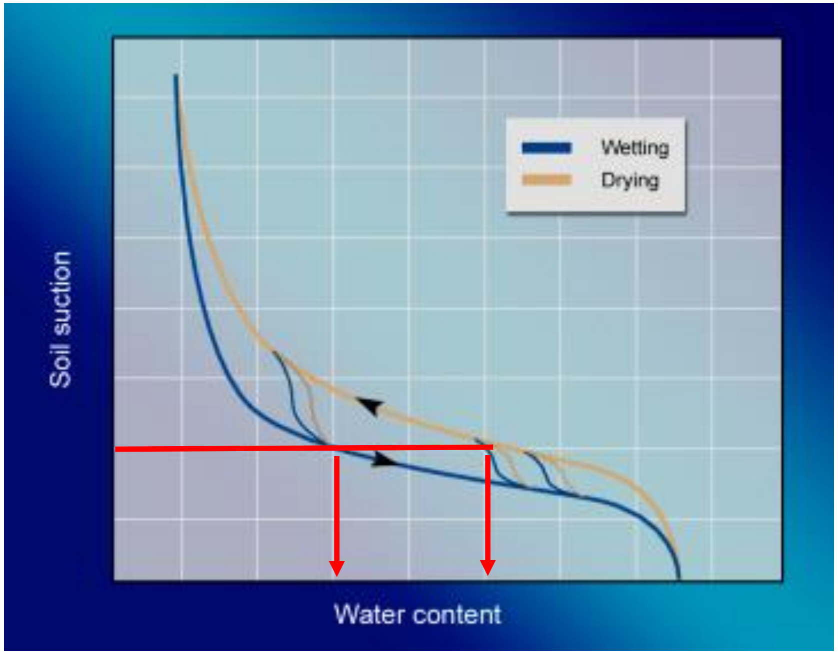


Field capacity is the amount of water that can be held **against gravity**. It is the water content held in the soil after excess water drained away. Reached ~ 2-3 days after precipitation.

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

Hysteresis - Capillarity

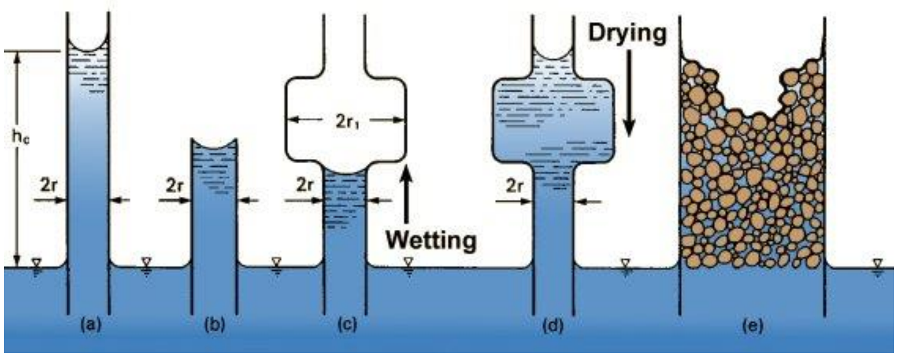




Pressure head different at equal water content for wetting and drying → Hysteresis

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



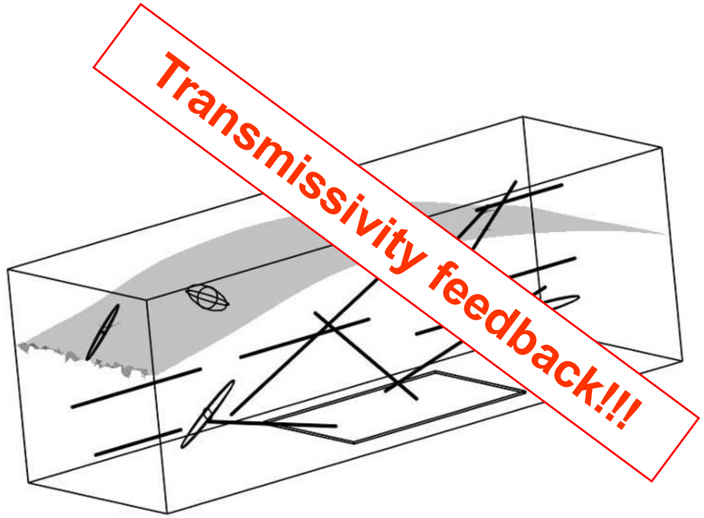
$$h_c = \frac{2\gamma \cos\beta}{\rho g r}$$

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

SSF - Macropores

How can shallow subsurface flow be explained?

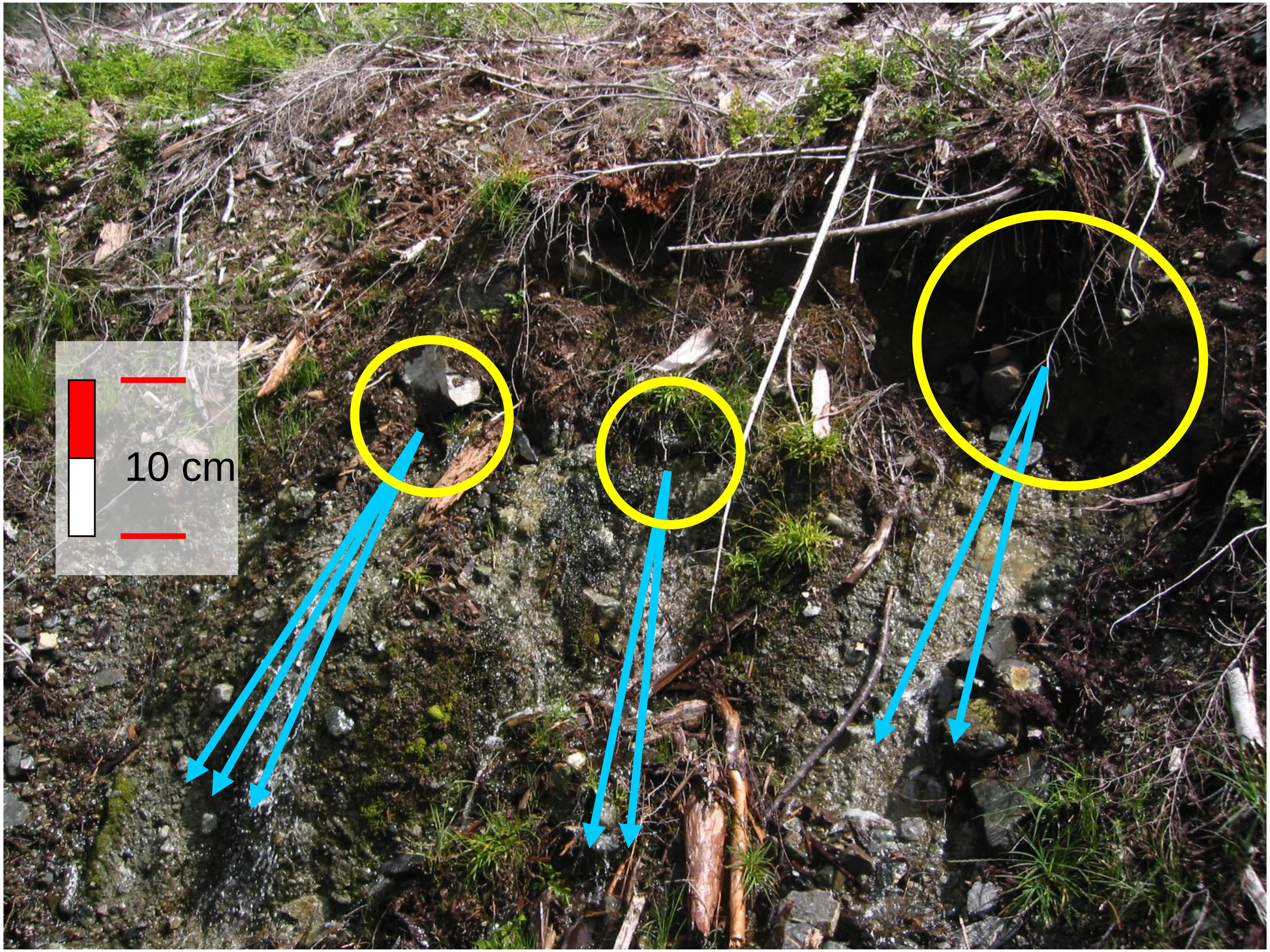
For example:
(1) by macropores or
(2) by the Fill-and-Spill Theory



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

- 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

Macropores



- ✓ Objectives
- ✓ What is a hydrological model ?
- ✓ Why do we care?
- ✓ Modeling Process
- ✓ Problems
- ✓ What types of models are out there?

Flow Processes

- ✓ a) Groundwater
- ✓ b) SOF
- ✓ c) HOF
- **d) SSF**
- e) Interception

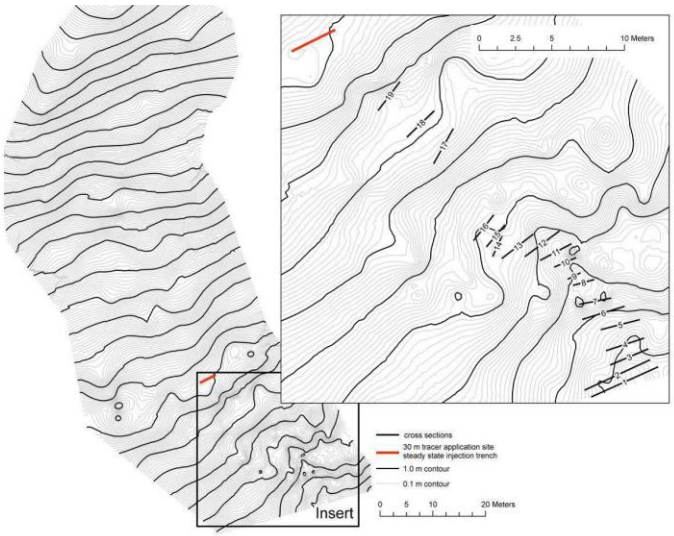
What does a model look like?

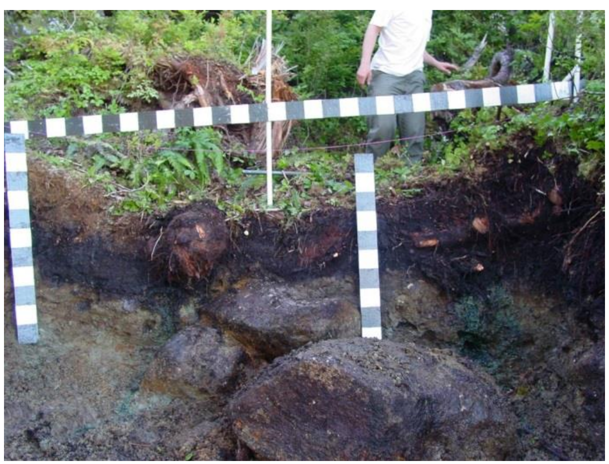
Step-by-step

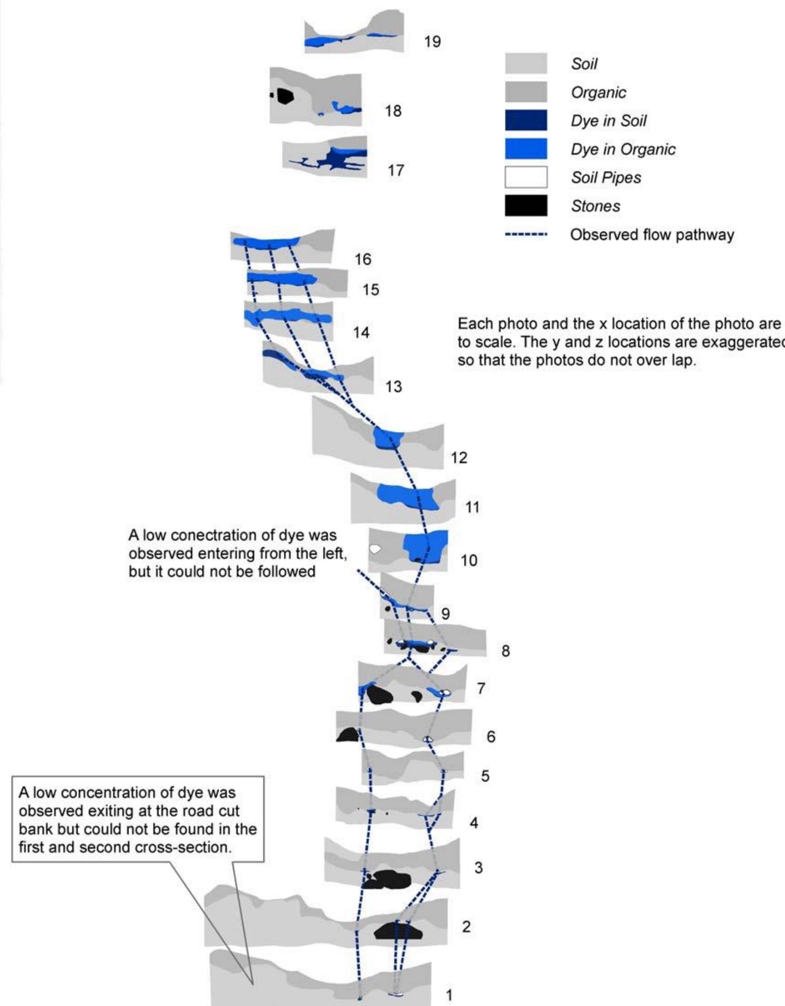
Example model

What have we learned?

Macropores





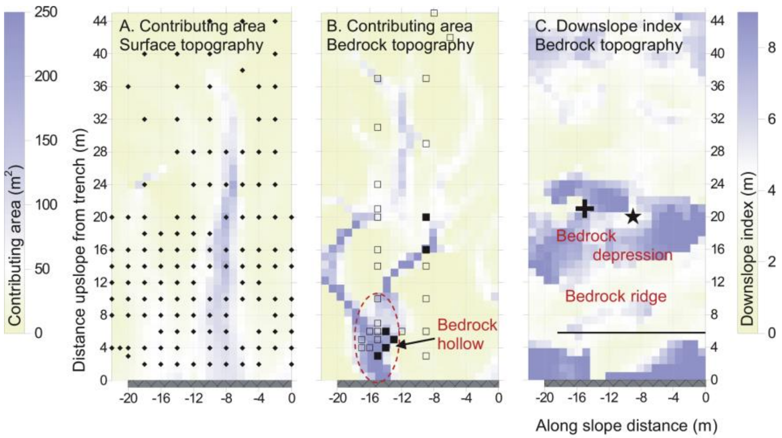


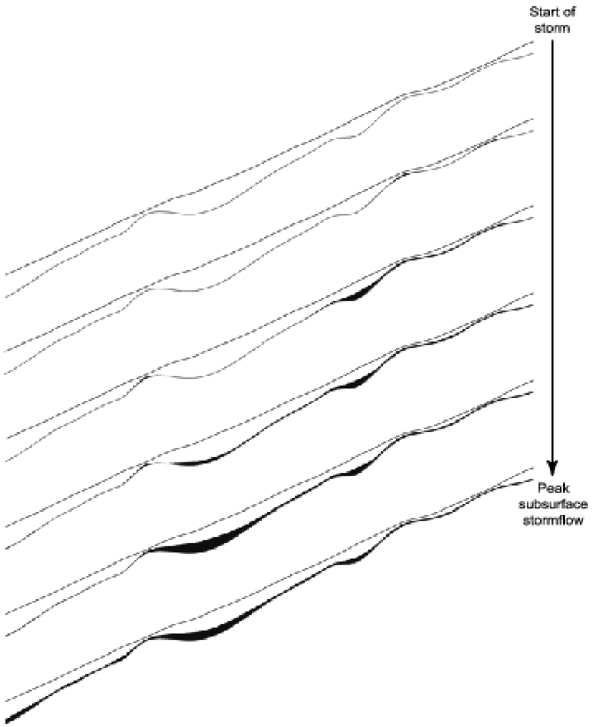
Anderson et al., 2009

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)

- ✓ Objectives
- ✓ What is a hydrological model ?
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- ✓ Problems
- ✓ What types of models are out there?

Flow Processes

- ✓ a) Groundwater
- ✓ b) SOF
- ✓ c) HOF
- **d) SSF**
- e) Interception

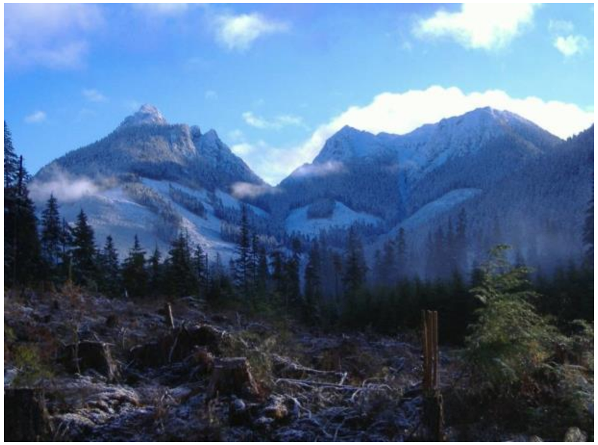
What does a model look like?

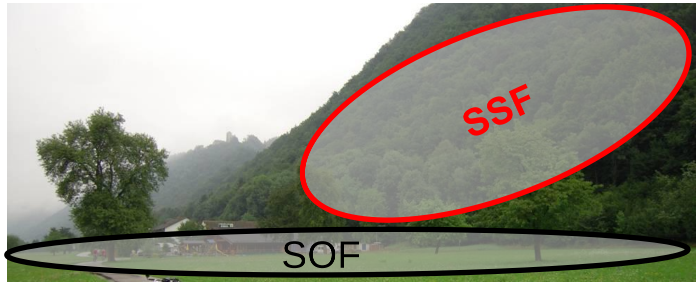
Step-by-step

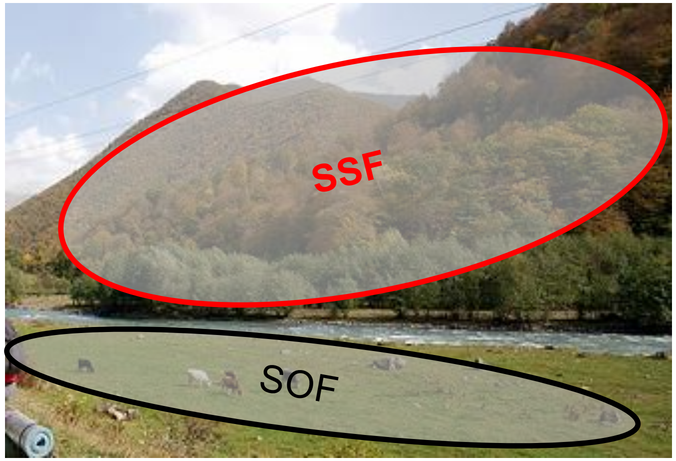
Example model

What have we learned?

Shallow subsurface flow





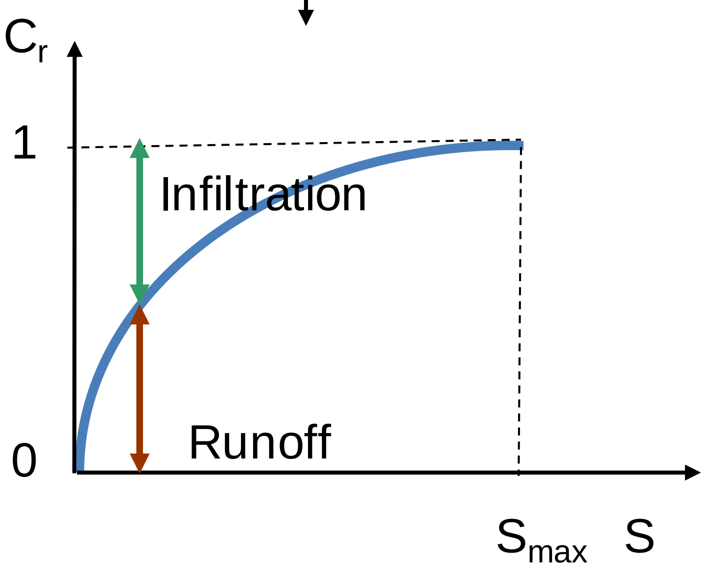


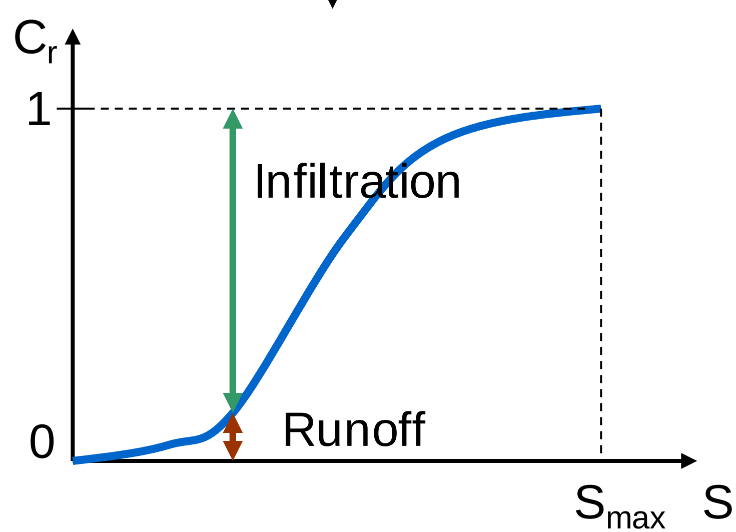
A powerful runoff generation concept

Probabilistic approach:

$$C_r = \left(\frac{S}{S_{\max}} \right)^{\beta}$$

$$C_r = \frac{1}{1 + e^{\left(\frac{-S/S_{\max} + 0.5}{\beta} \right)}}$$

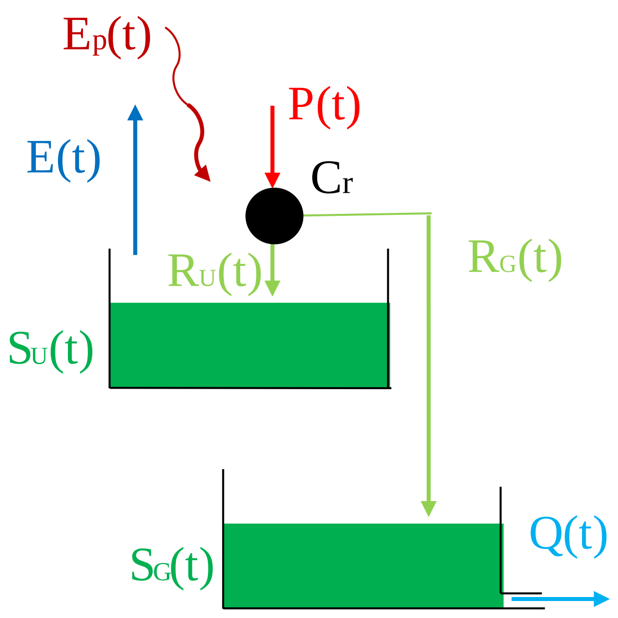




A powerful runoff generation concept

Probabilistic approach:

Distribution of field capacities to determine runoff coefficient *Cr* (i.e. proportion of rainfall that cannot be stored)



Water balance

$$\frac{dS_U}{dt} = R_U(t) - E(t)$$

$$\frac{dS_G}{dt} = R_G(t) - Q(t)$$

Water fluxes

$$R_U(t) = (1 - C_r)P(t)$$

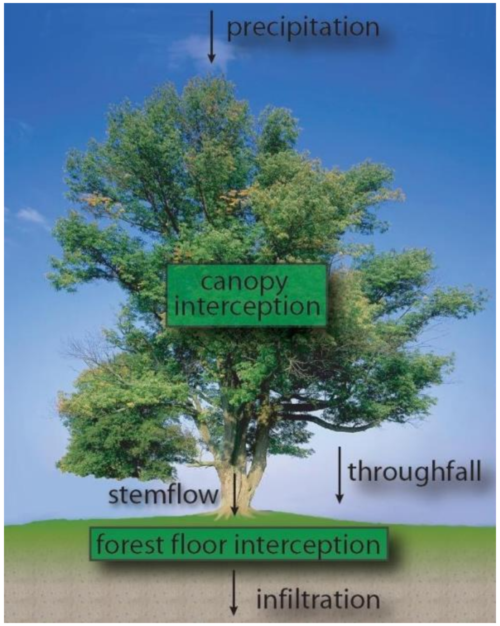
$$R_G(t) = C_r P(t)$$

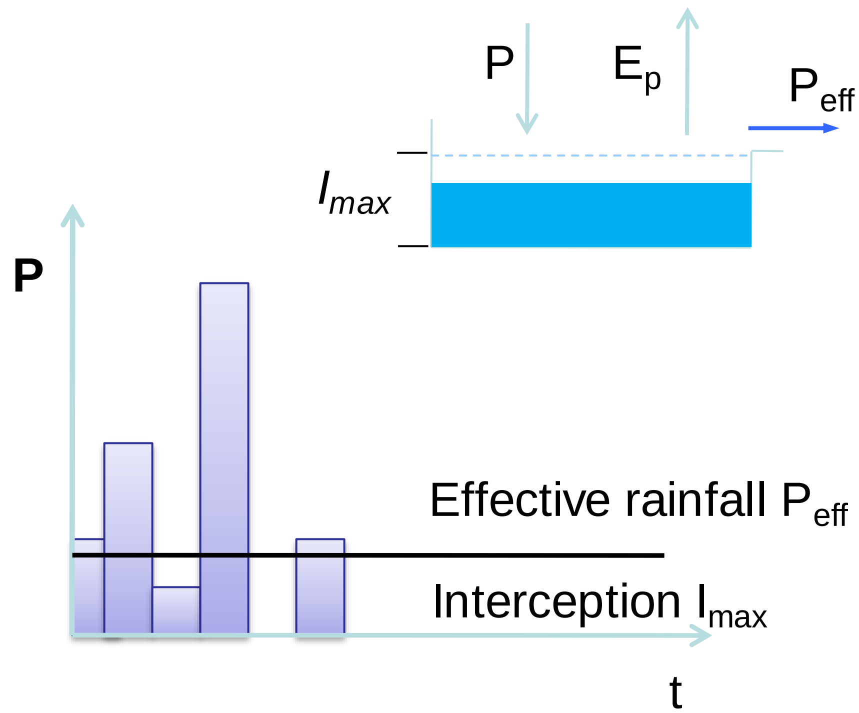
$$E(t) = f\left(E_p(t), S_U(t)\right)$$

$$Q(t) = \frac{S_G(t)}{k}$$

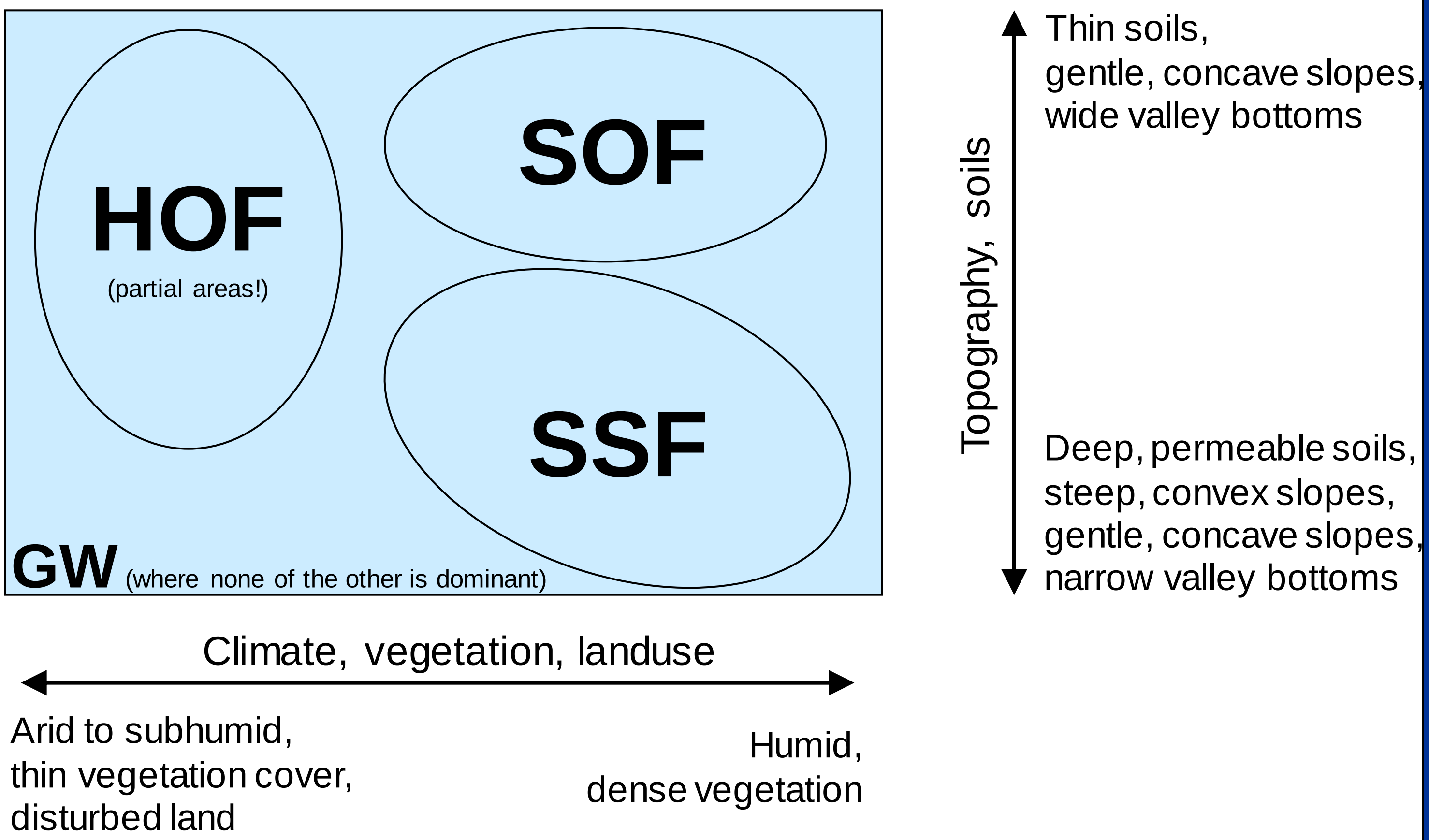
S_U: unsaturated storage, S_G: groundwater storage, R_U: recharge unsaturated zone, R_G: groundwater recharge, E_p: potential evaporation (energy input)

Interception store





Dominant Runoff processes



What is the basis of a conceptual model?

- Reservoirs
- Fluxes
- Transfer functions

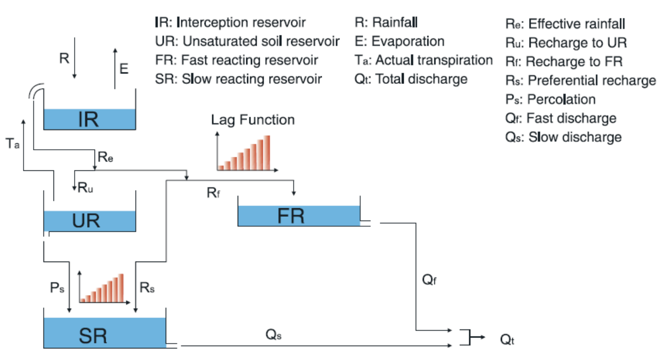
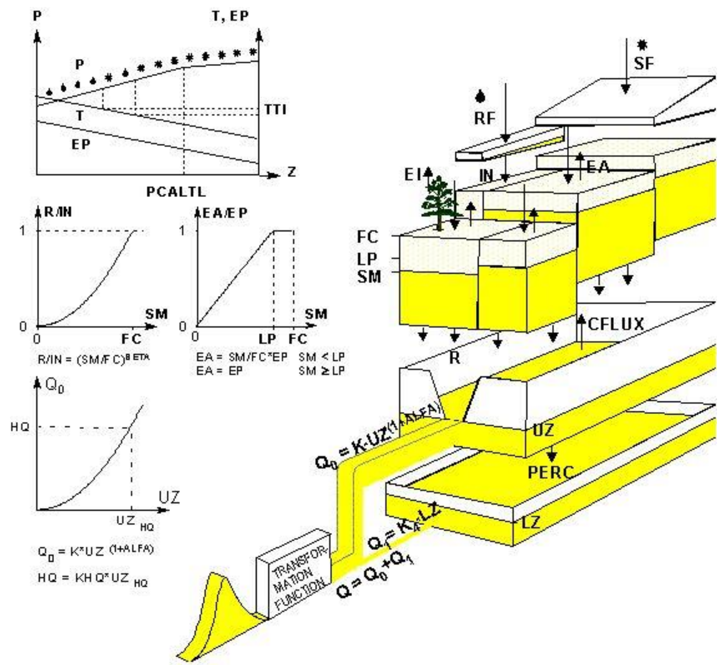


Figure 10. Structure schematization of the FLEX[B] model.



P = Precipitation
T = Temperature
SF = Snow
RF = Rain
Z = Elevation
PCALTL = Threshold for altitude correction
TTI = Threshold temperature interval
IN = Infiltration
EP = Potential evapotranspiration
EA = Actual evapotranspiration
EI = Evaporation from interception
SM = Soil moisture storage
FC = Maximum soil moisture storage
LP = Limit for potential evapotranspiration

BETA = Soil parameter
R = Recharge
CFLUX = Capillary transport
UZ = Storage in upper response box
LZ = Storage in lower response box
PERC = Percolation
K, K_4 = Recession parameters
ALFA = Recession parameter
Q_0, Q_1 = Runoff components
HQ = High flow parameter
KHQ = Recession at HQ
HQ_{UZ} = UZ level at HQ

Conceptual model

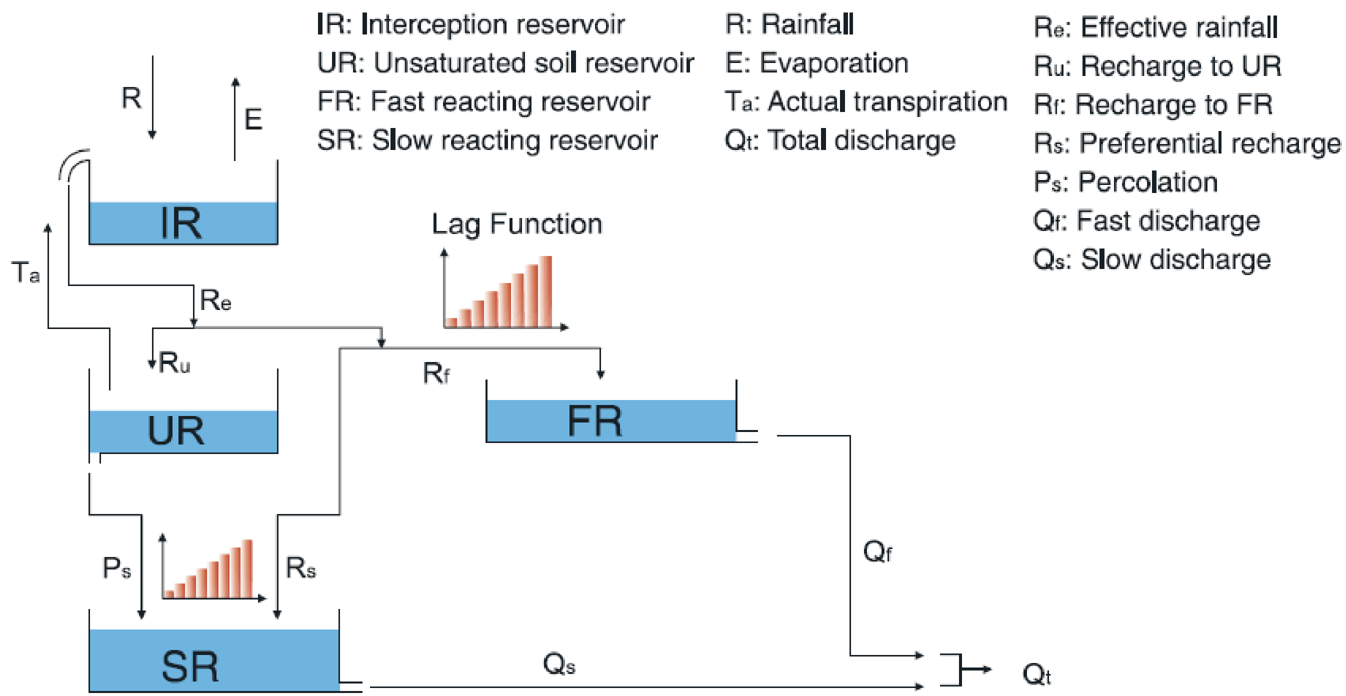
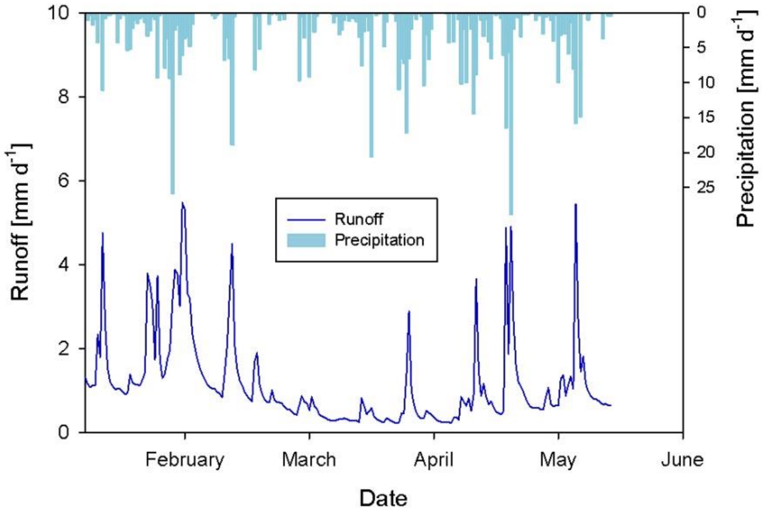


Figure 10. Structure schematization of the FLEX^{B} model.

What is the thought process behind a model?

???



What is the thought process behind a model?

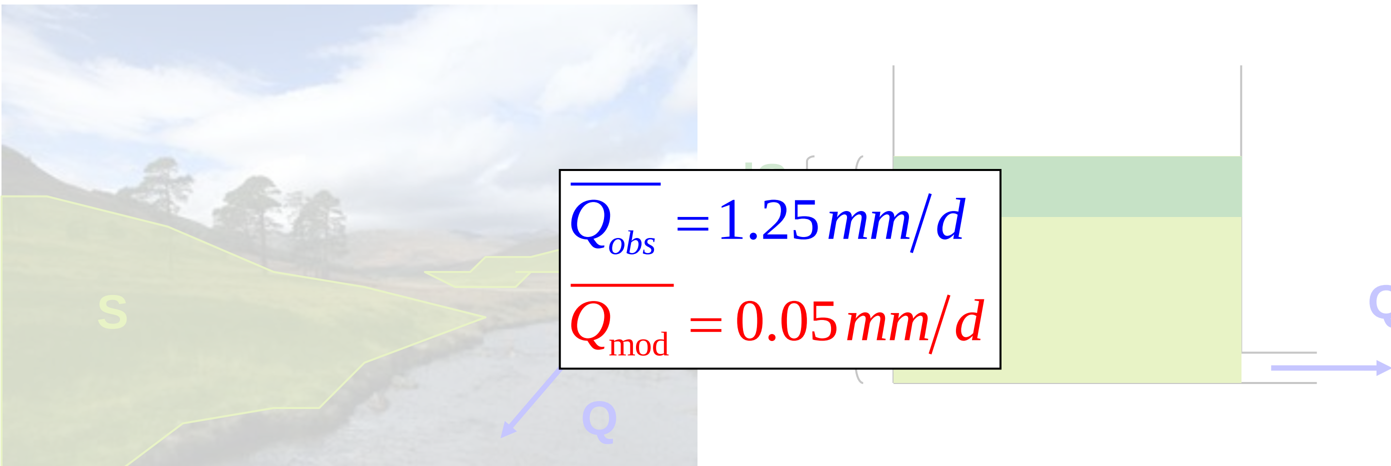
$$Q(t) = S(t) \cdot k$$

Mass balance or Continuity Equation

$$\frac{dS}{dT} = -Q(t)$$

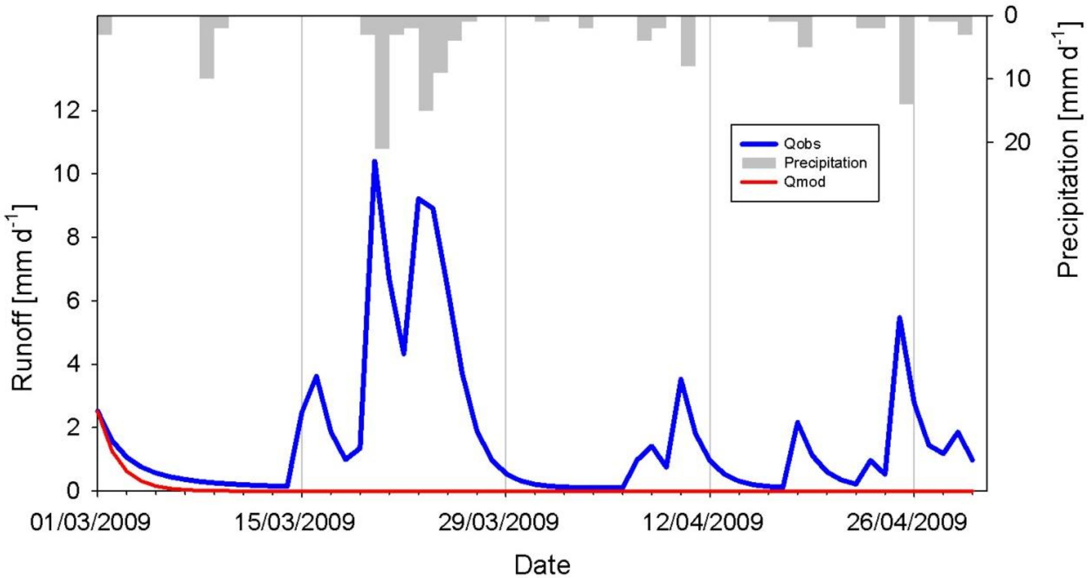
$$Q(t) = Q_0 \cdot e^{(-k \cdot t)}$$

What is the thought process behind a model?

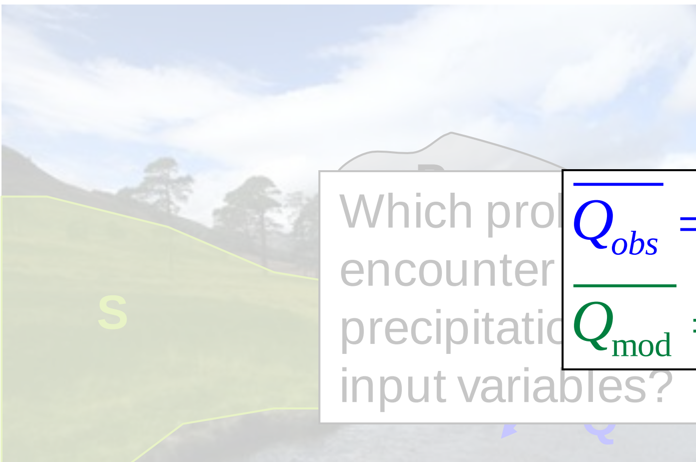


$$\overline{Q_{obs}} = 1.25\,mm/d$$

$$\overline{Q_{\mathrm{mod}}} = 0.05\,mm/d$$



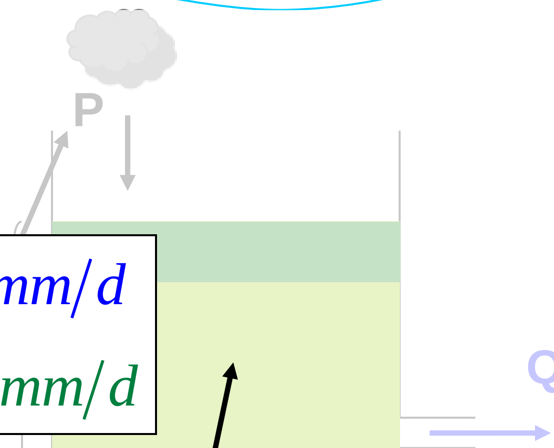
What is the thought process behind a model?

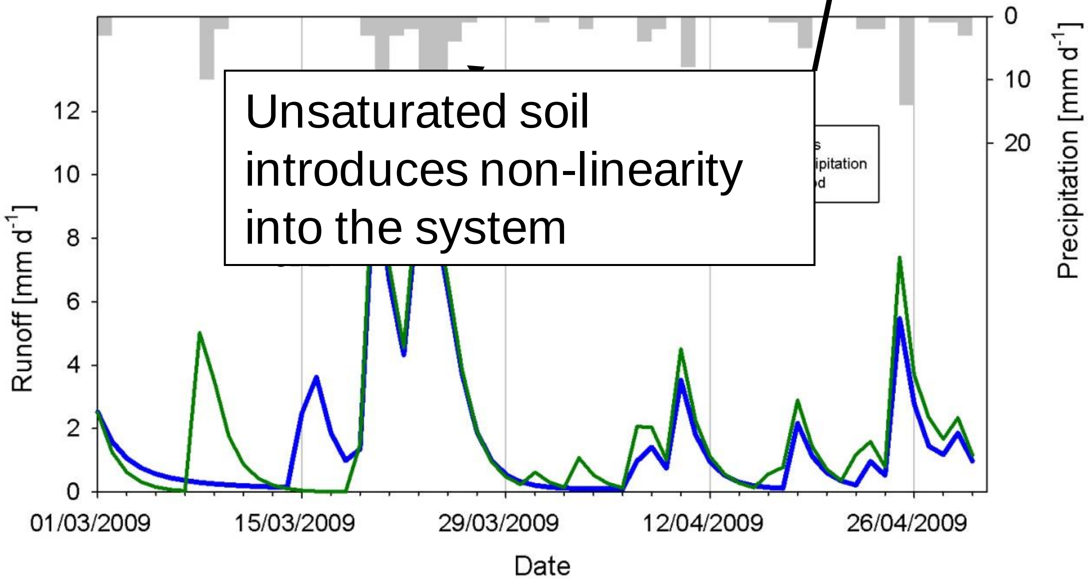


Which pro
encounter
precipitatio
input variables?

$$\overline{Q_{obs}} = 1.25\,mm/d$$

$$\overline{Q_{\text{mod}}} = 1.43\,mm/d$$





Unsaturated soil introduces non-linearity into the system

✓ Objectives

✓ What is a hydrological model ?

✓ Why do we care?

✓ Modeling Process

✓ Problems

✓ What types of models are out there?

✓ Flow Processes

✓ a) Groundwater

✓ b) SOF

✓ c) HOF

✓ d) SSF

✓ e) Interception

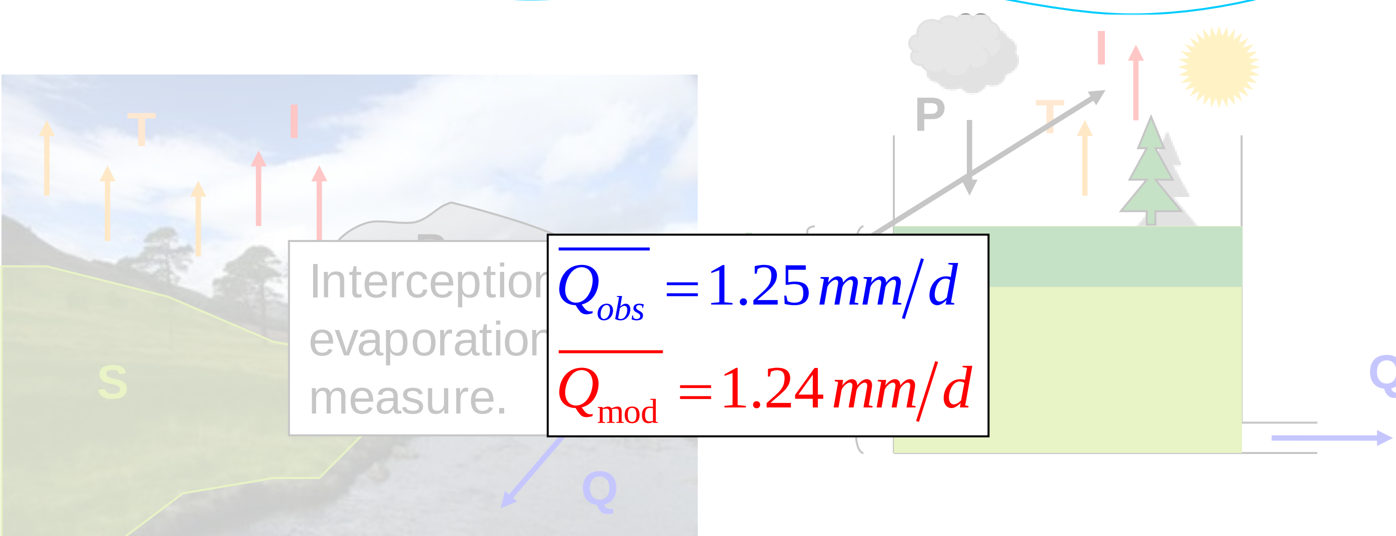
✓ What does a model look like?

Step-by-step

Example model

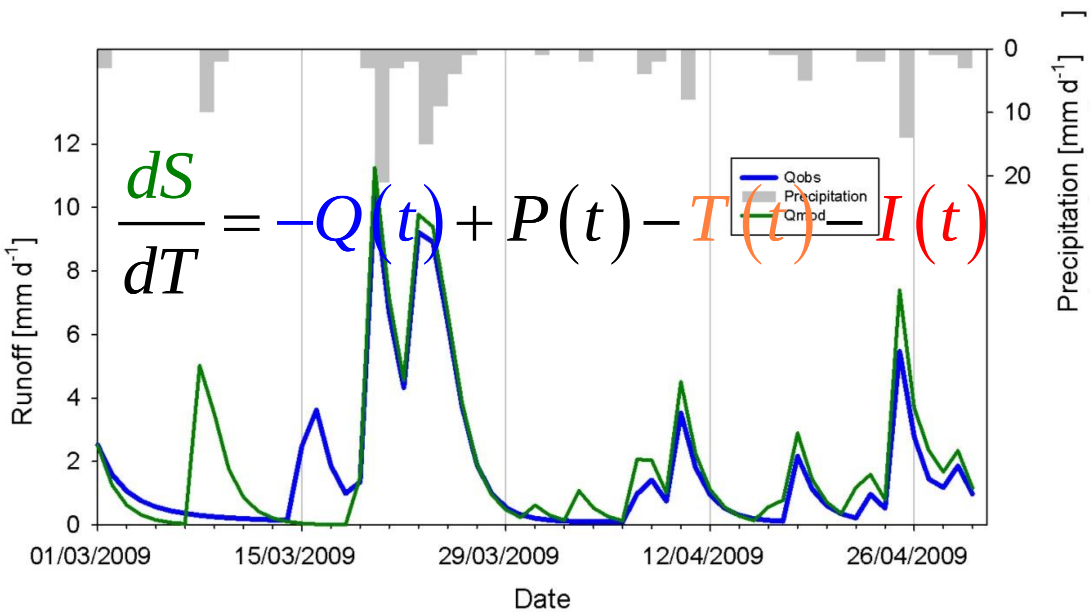
What have we learned?

What is the thought process behind a model?



$$\overline{Q_{obs}} = 1.25\,mm/d$$

$$\overline{Q_{mod}} = 1.24\,mm/d$$



$$\frac{dS}{dT} = -Q(t) + P(t) - T(t) - I(t)$$

- ✓ Objectives
- ✓ What is a hydrological model ?
- ✓ Why do we care?
- ✓ Modeling Process
- ✓ Problems
- ✓ What types of models are out there?
- ✓ Flow Processes
- ✓ a) Groundwater
- ✓ b) SOF
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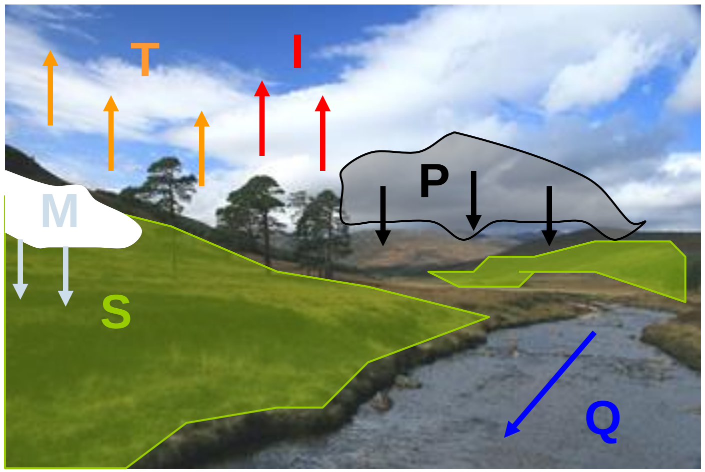
- ✓ d) SSF
- ✓ e) Interception
- ✓ What does a model look like?

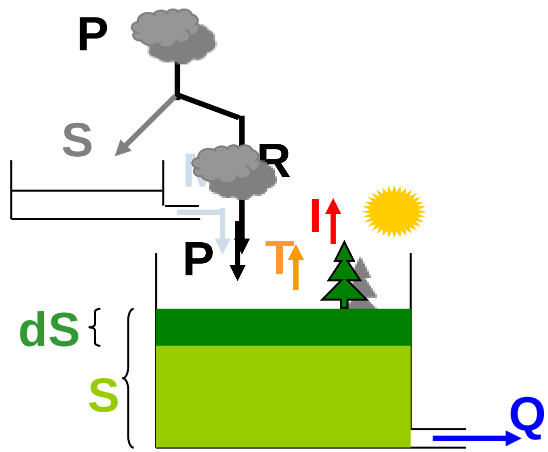
Step-by-step

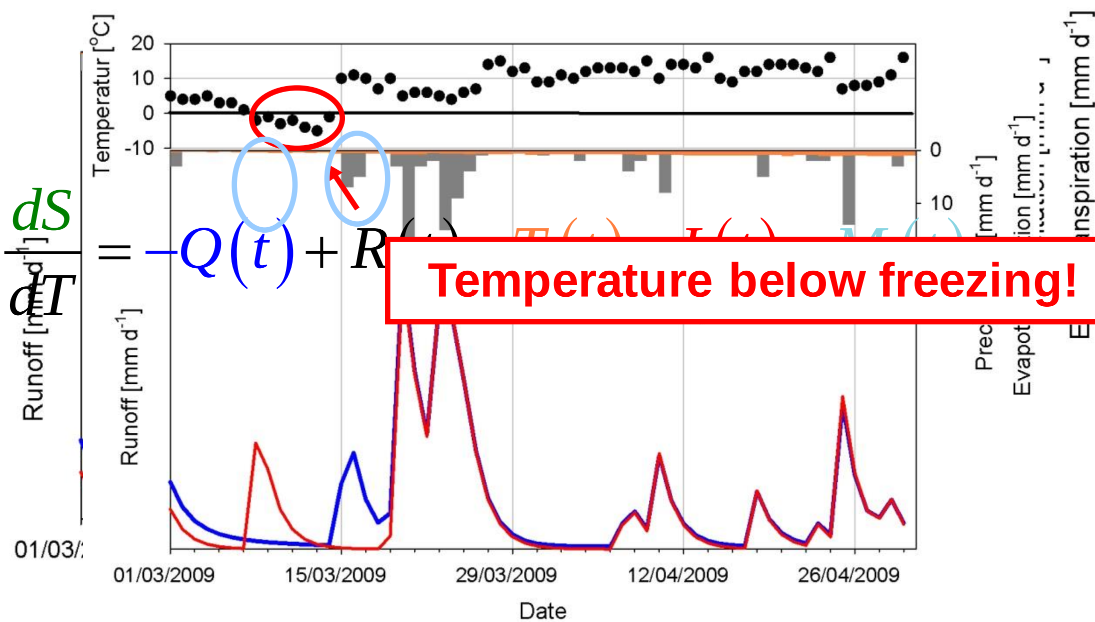
Example model

What have we learned?

What is the thought process behind a model?







- ✓ Objectives
- ✓ What is a hydrological model ?
- ✓ Why do we care?
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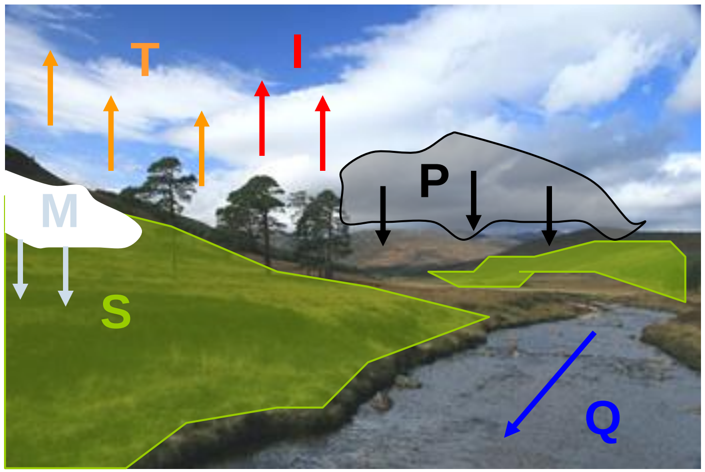
- ✓ Flow Processes
- ✓ a) Groundwater
- ✓ b) SOF
- ✓ c) HOF
- ✓ d) SSF
- ✓ e) Interception
- ✓ What does a model look like?

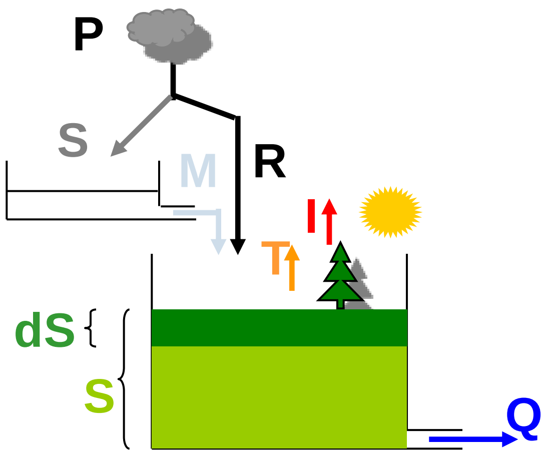
Step-by-step

Example model

What have we learned?

What is needed for a conceptual model?





Input data:

Precipitation

Temperature

Soil characteristics

Land cover,…

Calibration data:

Stream flow

Groundwater level

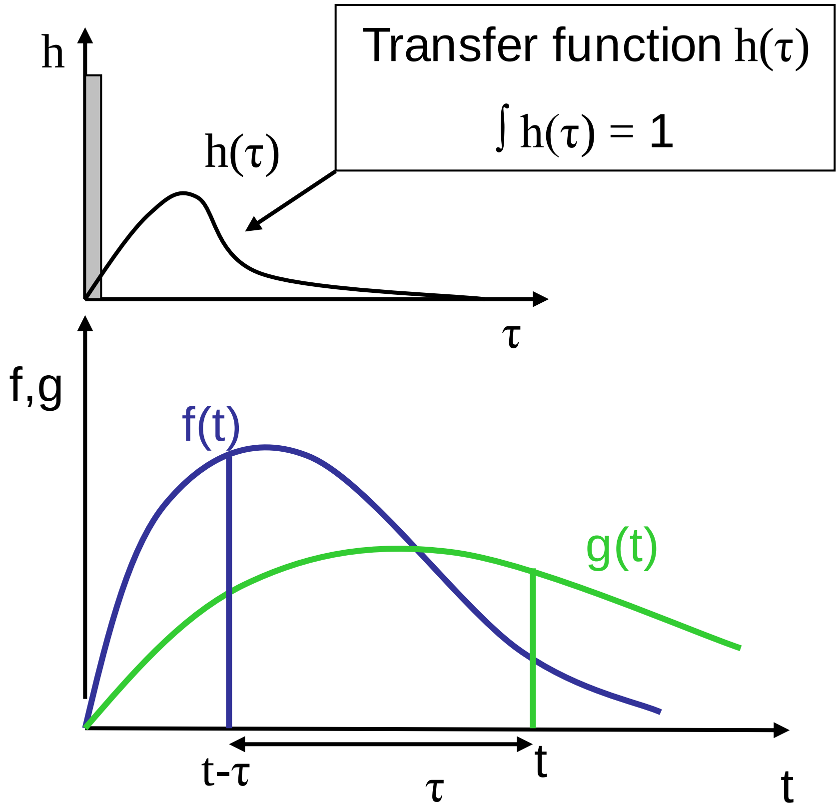
Snow cover,…

Model:

Mathematical expressions which formulate the relations between input, system states and output.

Transfer functions

- Transfer functions used to **<u>offset</u>** **<u>fluxes</u>**, estimate residence times, assess damping of a tracer signal
- The concept of convolution is frequently applied in conceptual models



Convolution integral

$$g\left(t\right)=f*h=\int_{0}^{t}f(t-\tau)h(\tau)d\tau$$

- ✓ Objectives
- ✓ What is a hydrological model ?
- ✓ Why do we care?
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- ✓ Problems
- ✓ What types of models are out there?
- ✓ Flow Processes
- ✓ a) Groundwater
- ✓ b) SOF
- ✓ c) HOF
- ✓ d) SSF
- ✓ e) Interception
- ✓ What does a model look like?

<u>Step-by-step</u>

Example model

What have we learned?

Examples of transfer functions

- **FLEX model**
  transfer functions to add a lag to the processes

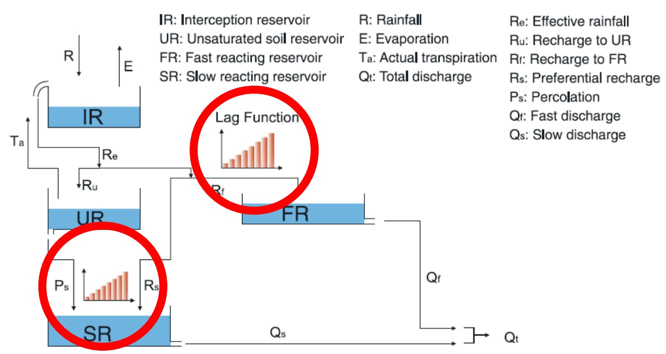
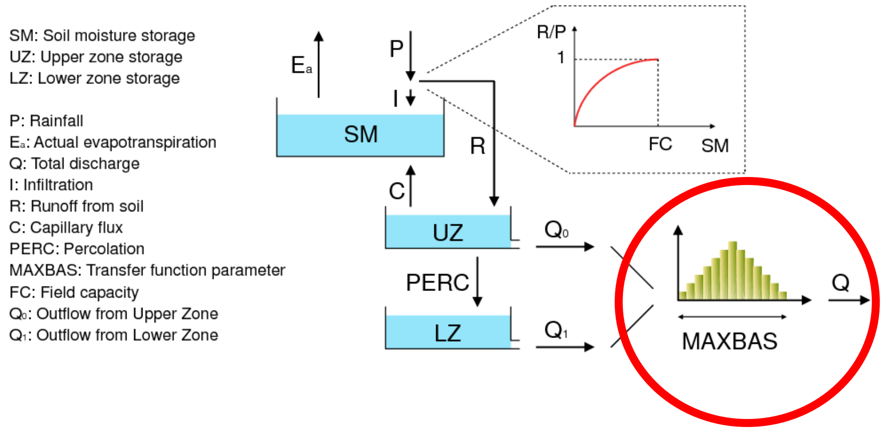


Figure 10. Structure schematization of the FLEX[B] model.

- **HBV model**
  triangular transfer function to simulate lag caused by stream routing



- ✓ Objectives
- ✓ What is a hydrological model ?
- ✓ Why do we care?
- ✓ Modeling Process
- ✓ Problems
- ✓ What types of models are out there?
- ✓ Flow Processes
- ✓ a) Groundwater
- ✓ b) SOF
- ✓ c) HOF
- ✓ d) SSF
- ✓ e) Interception
- ✓ What does a model look like?
- **Step-by-step**
- Example model
- What have we learned?

Step-by-step model set-up

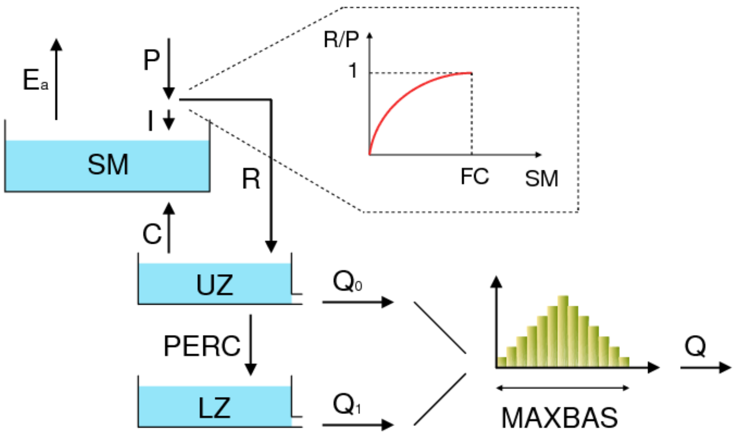
1. Perceptual model

- Think about the system:

  a) where is the water stored

  b) where does it go from the storages?
- Help yourself with some drawings
- Re-use existing concepts, i.e. reservoirs, transfer functions, probability distributions
- Make up new ones when they do not work:

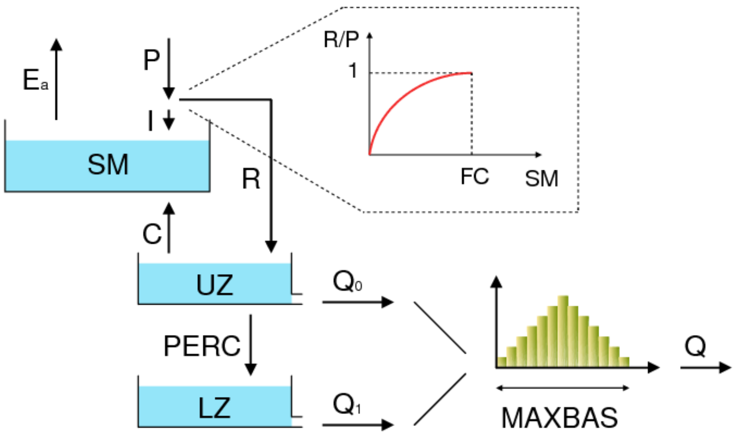
Be creative!!



Step-by-step model set-up

2. Conceptual model

- What do you need to specify to run the model?
- Choose equations for the fluxes
- Set-up water balance for each model component ($^{dS}/_{dt}$=I-O)
- Identify model parameters and corresponding units
- Identify model state variables
- Prepare forcing (e.g. P and Ep) and reference (e.g. Q_{obs}) data



$Q_m=f(S_i,\theta,F)$

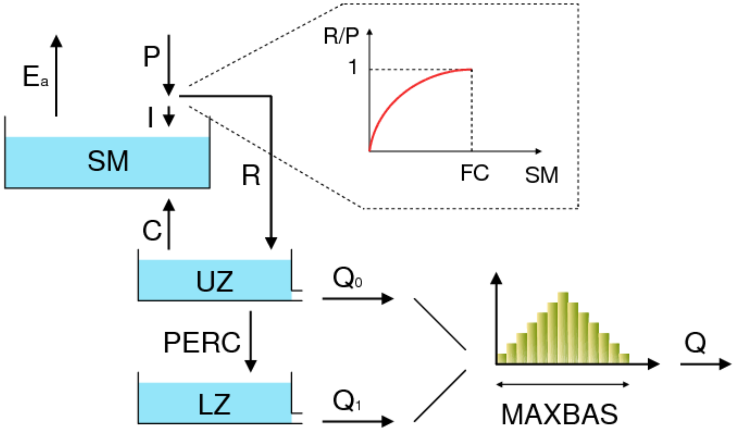
Step-by-step model set-up

3. Procedural model

- Read forcing data
- Specify model parameters
- Read initial conditions
- Allocate and initialize variables
- Run a loop

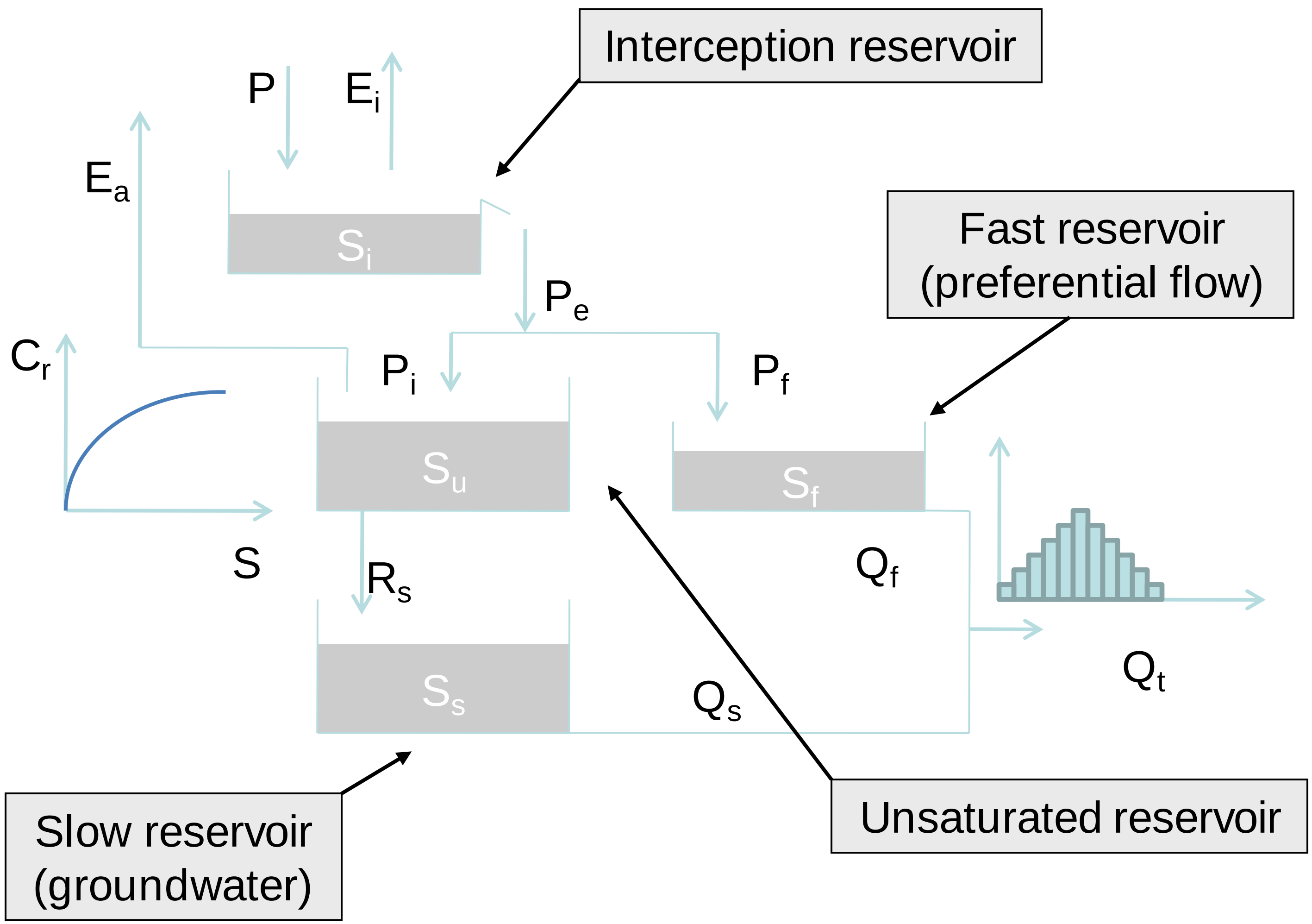
  a) calculate fluxes

  b) update states
- Calculate model output



$$Q_m=f(S_i,\theta,F)$$

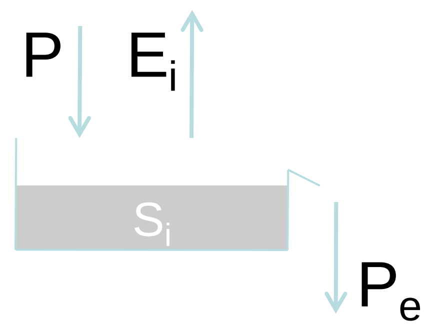
Example model structure



Example model

<u>Interception reservoir</u>

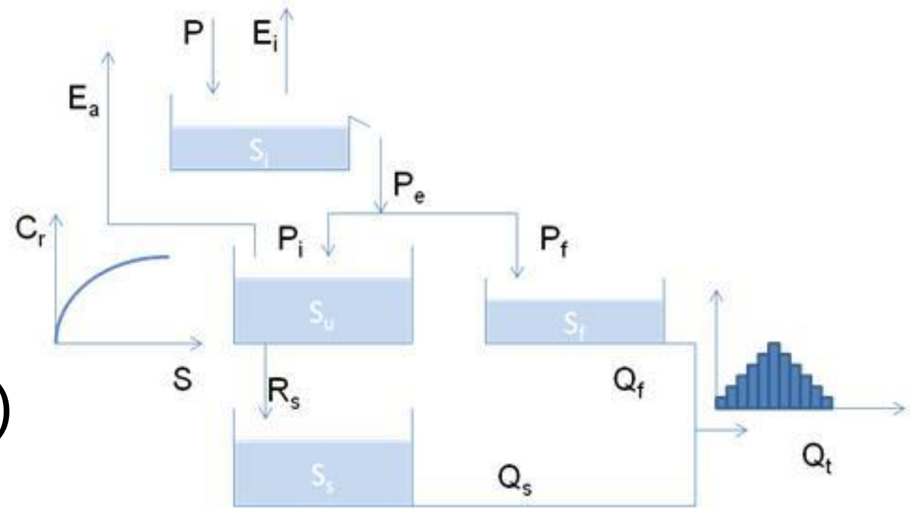
- $S_i = S_i + P\Delta t$
- $P_e\Delta t = \max(S_i - I_{max}, 0)$
- $S_i = S_i - P_e\Delta t$
- $E_i\Delta t = \min(E_p\Delta t,\ S_i)$
- $S_i = S_i - E_i\Delta t$



$$\Delta S_i = (P - E_i - P_e)\ \Delta t$$

Example model

- $C_r=(S_u/S_{umax})^{\beta}$
- $P_f=C_r*P_e$
- $P_i=(1-C_r)*P_e$
- $E_a=C_e*E_p$
- $R_s=P_{max}(S_u/S_{umax})$
- $Q_f=S_f*K_f$
- $Q_s=S_s*K_s$



What have we learned?

• A Hydrological Model is a simplified and **abstract representation** of the movement of water in the hydrological cycle.

• Hydrological models are necessary for **flood prediction**, **water supply** management and **water quality** issues.

• Hydrological models can be distinguished in what **degree of complexity** they represent reality: empirical, conceptual, physical and stochastic models, all of which can be lumped or distributed.

• The input – output relationships in conceptual models are based on **storages** which are connected by **fluxes** and **transfer functions**.

• Data necessary to set-up and run a simple conceptual model: times-series of **precipitation**, **temperature** and observed **stream flow**.


Thank you!