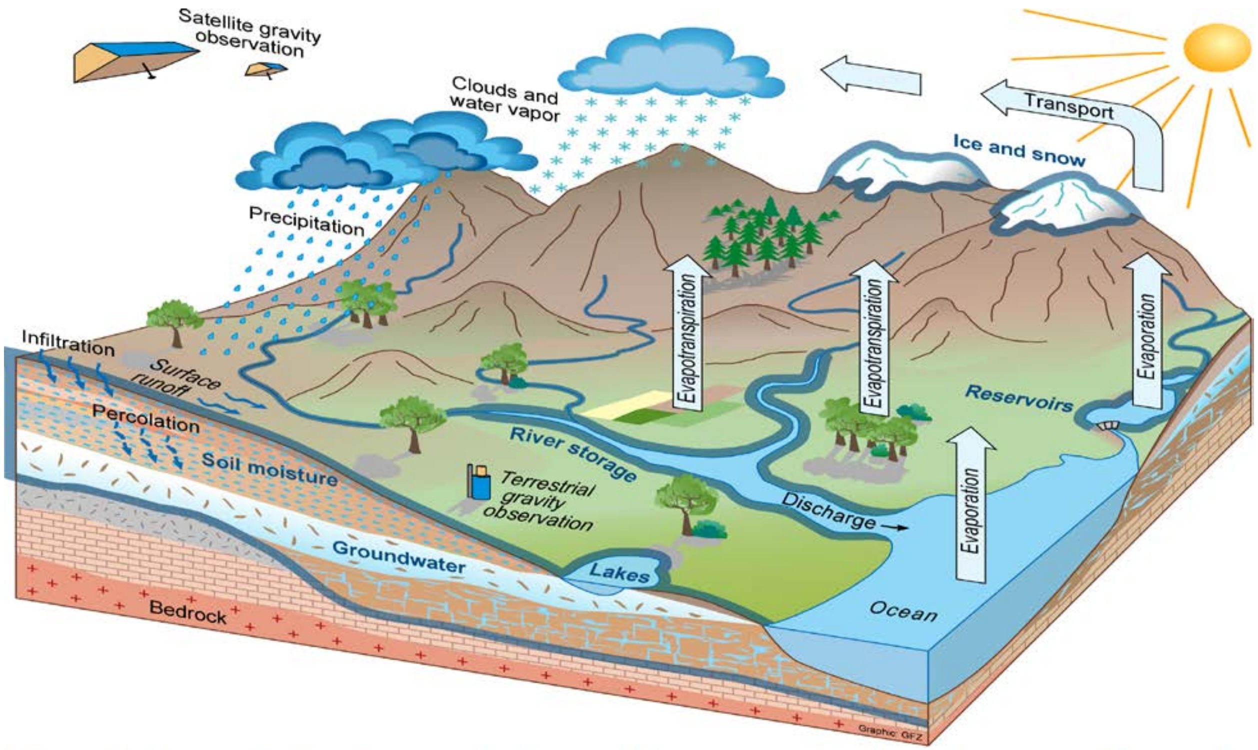
Modeling the hydrological cycle
- Lecture -

Andreas Güntner

The EGSIEM Autumn School
for Satellite Gravimetry Applications
11.-15. September 2017
Potsdam

The global water cycle

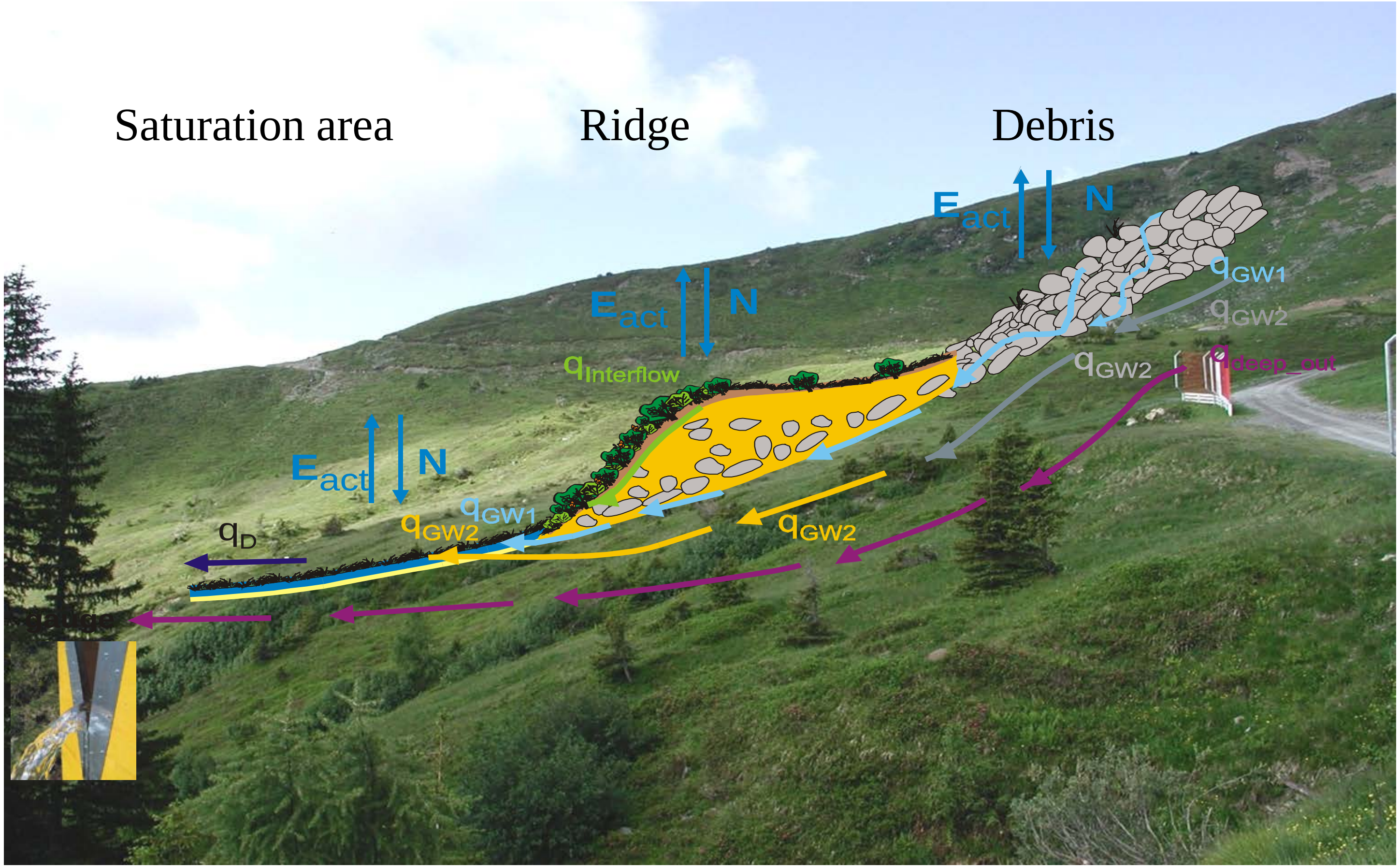


Continental water balance

$$P = AET + Q + \Delta S$$

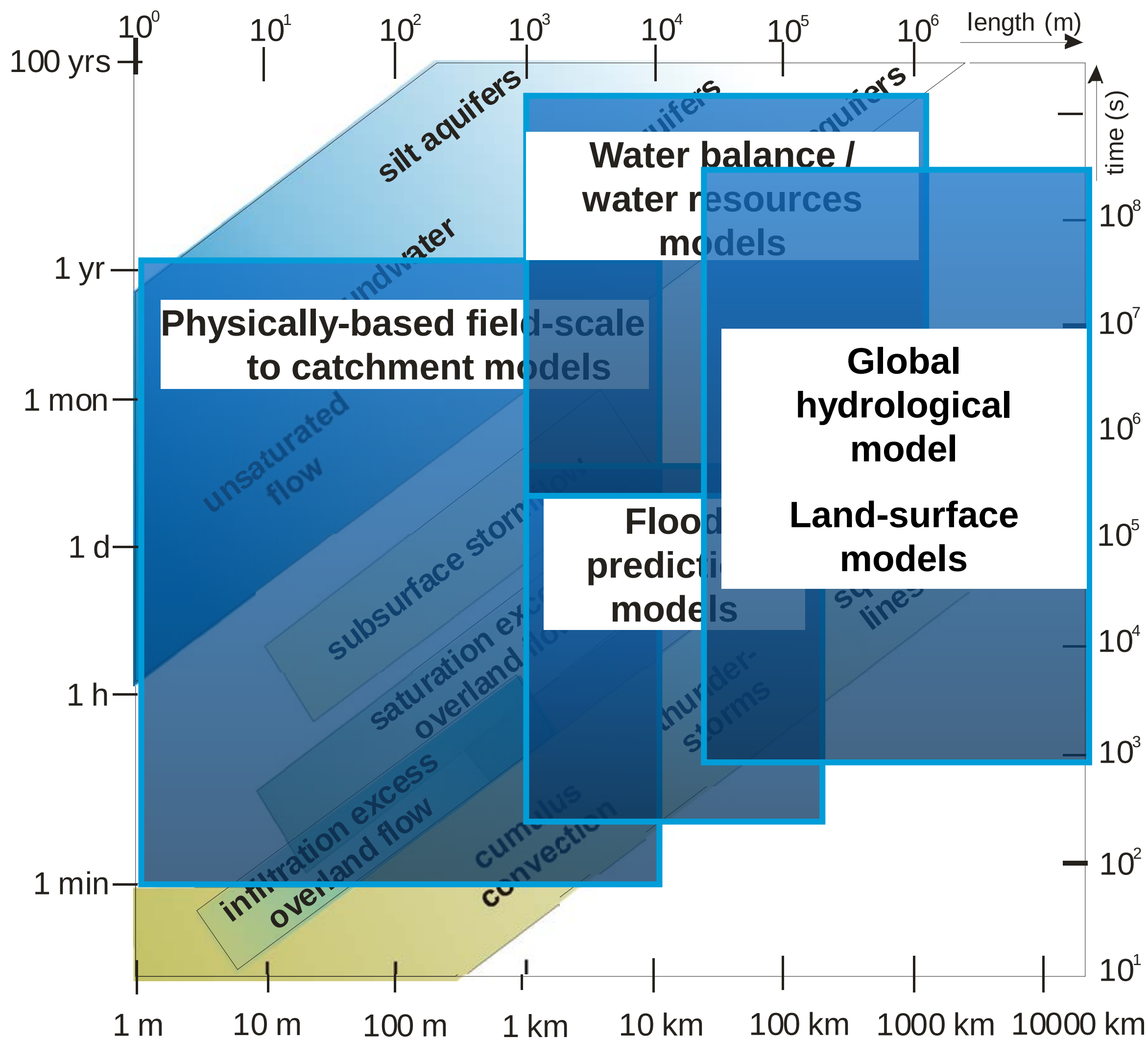
P: Precipitation
AET: Evapotranspiration
Q: Runoff
ΔS: Storage change

Hydrological processes



Löhnersbach, Salzburger Land, Austria

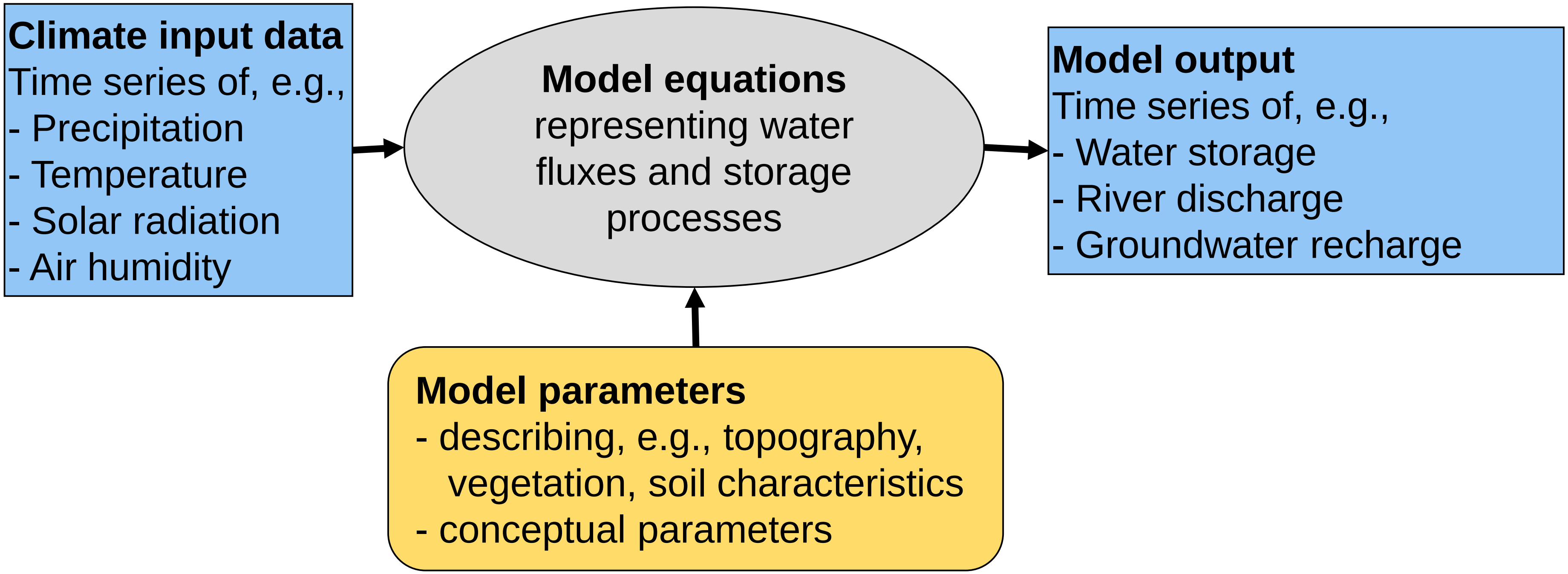
Spatial and temporal scales in hydrological modelling



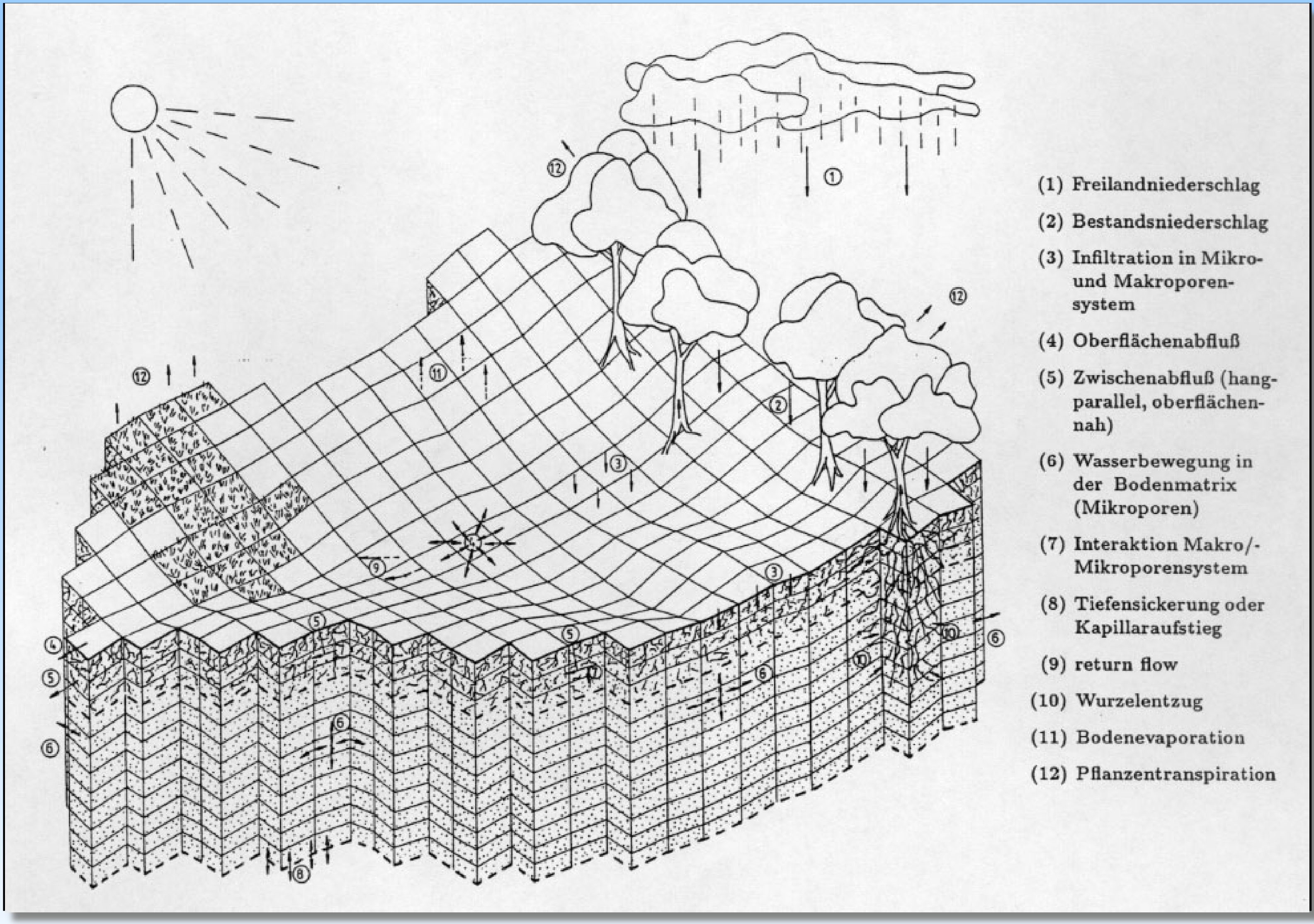
GFZ Helmholtz Centre Potsdam

EGSIEM European Gravity Service for Improved Emergency Management

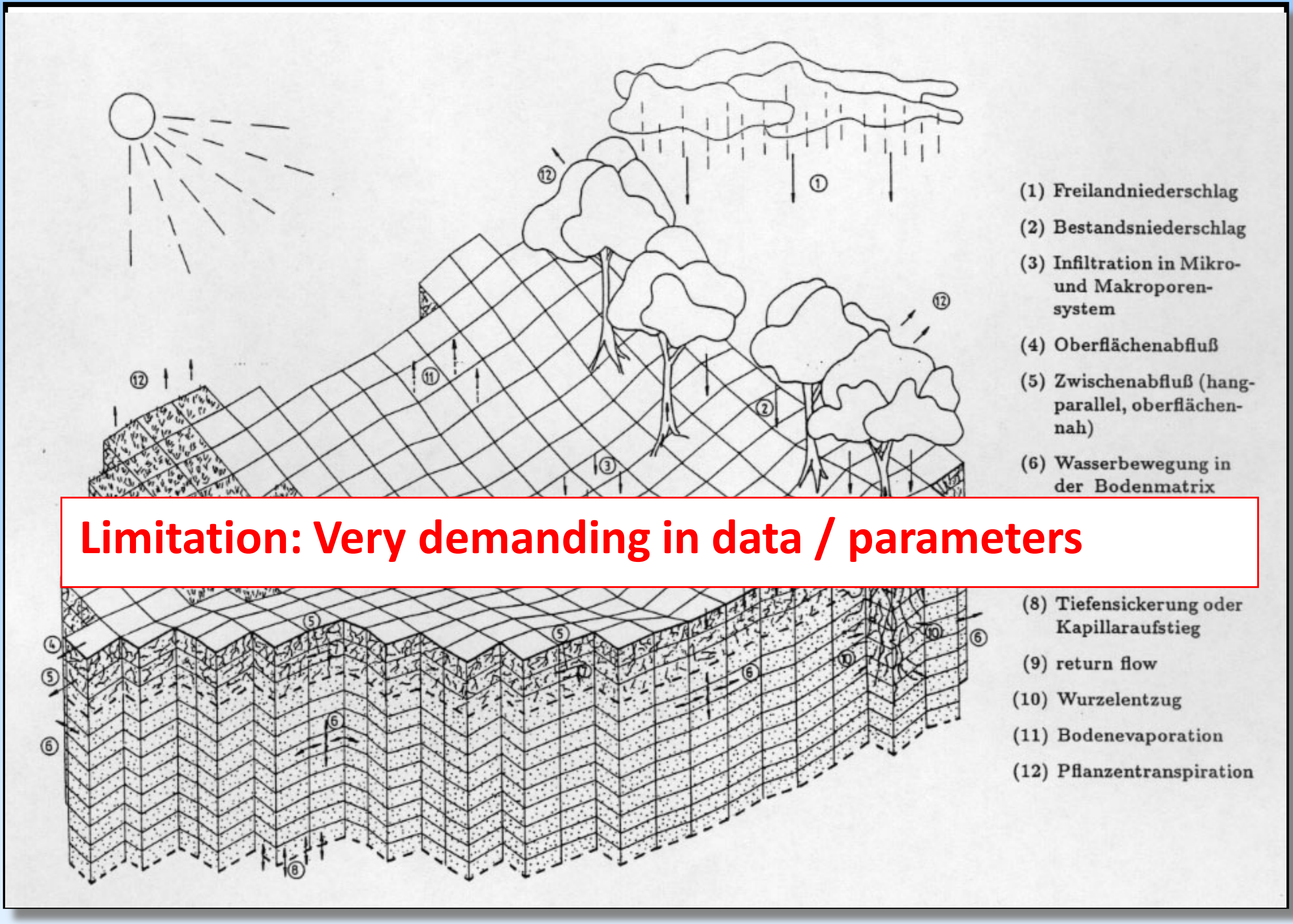
What is a hydrological model ?



Detailed physically-based models



Detailed physically-based models



Limitation: Very demanding in data / parameters

For example:

Differential equation for unsaturated flow in a porous medium (Richards equation):

Soil water content

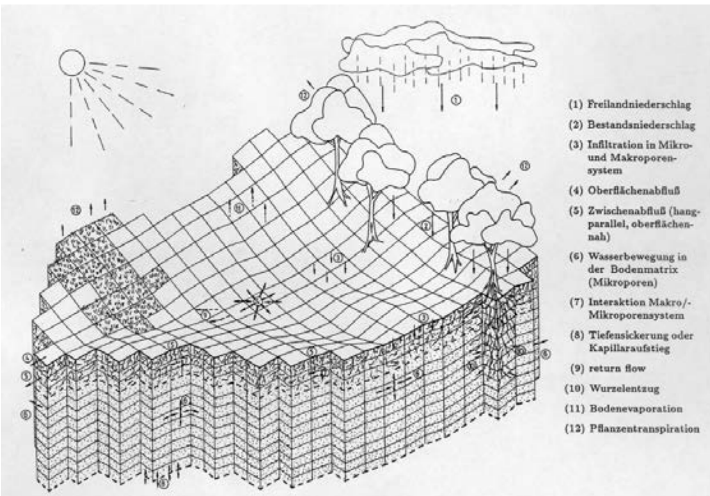
Hydraulic conductivity

$$\frac{\partial}{\partial x}\left(k_{xx}(\theta)\cdot\frac{\partial\psi}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_{yy}(\theta)\cdot\frac{\partial\psi}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_{zz}(\theta)\cdot\frac{\partial\psi}{\partial x}+1\right)=\frac{\partial\theta}{\partial t}-S$$

Gradient of soil water potential

Limitations of detailed physically-based models

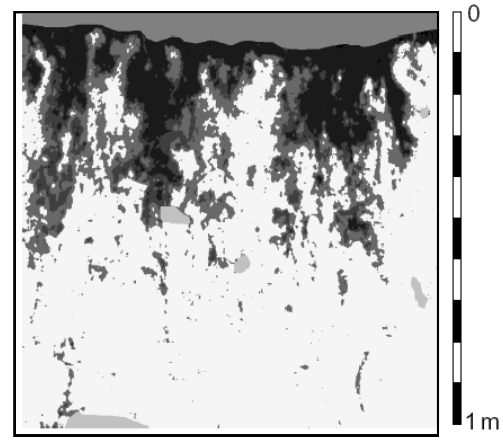
Example: Soil water fluxes



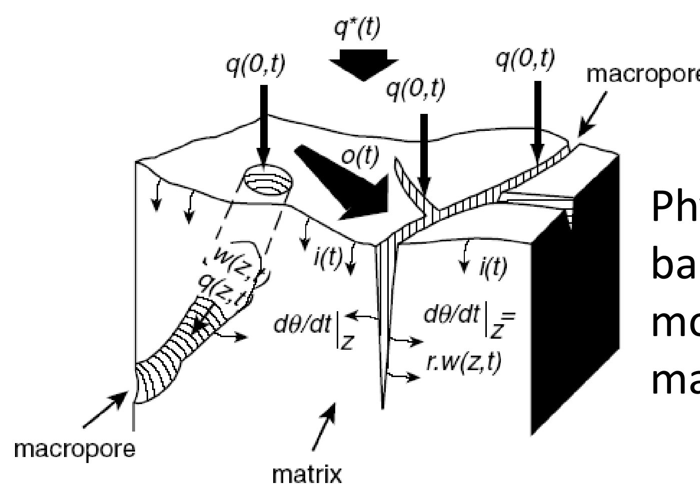
$$\frac{\partial}{\partial z}\left(k(\theta)\cdot\frac{\partial\psi}{\partial z}+1\right)=\frac{\partial\theta}{\partial t}-S$$

Richards equation assumes a **homogeneous porous medium**

$\neq$



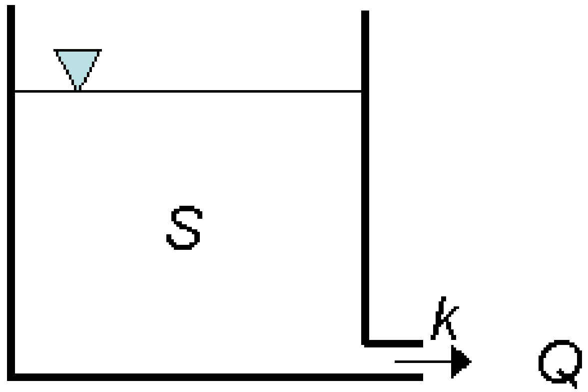
Real-world infiltration pattern in a soil



Physically-based model with macropores

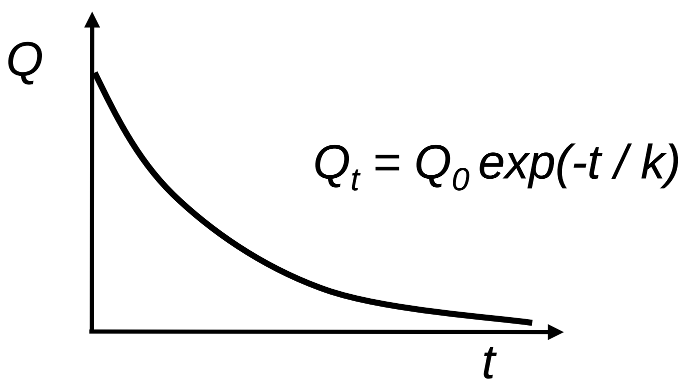
Conceptual models

Linear storage (bucket approach)



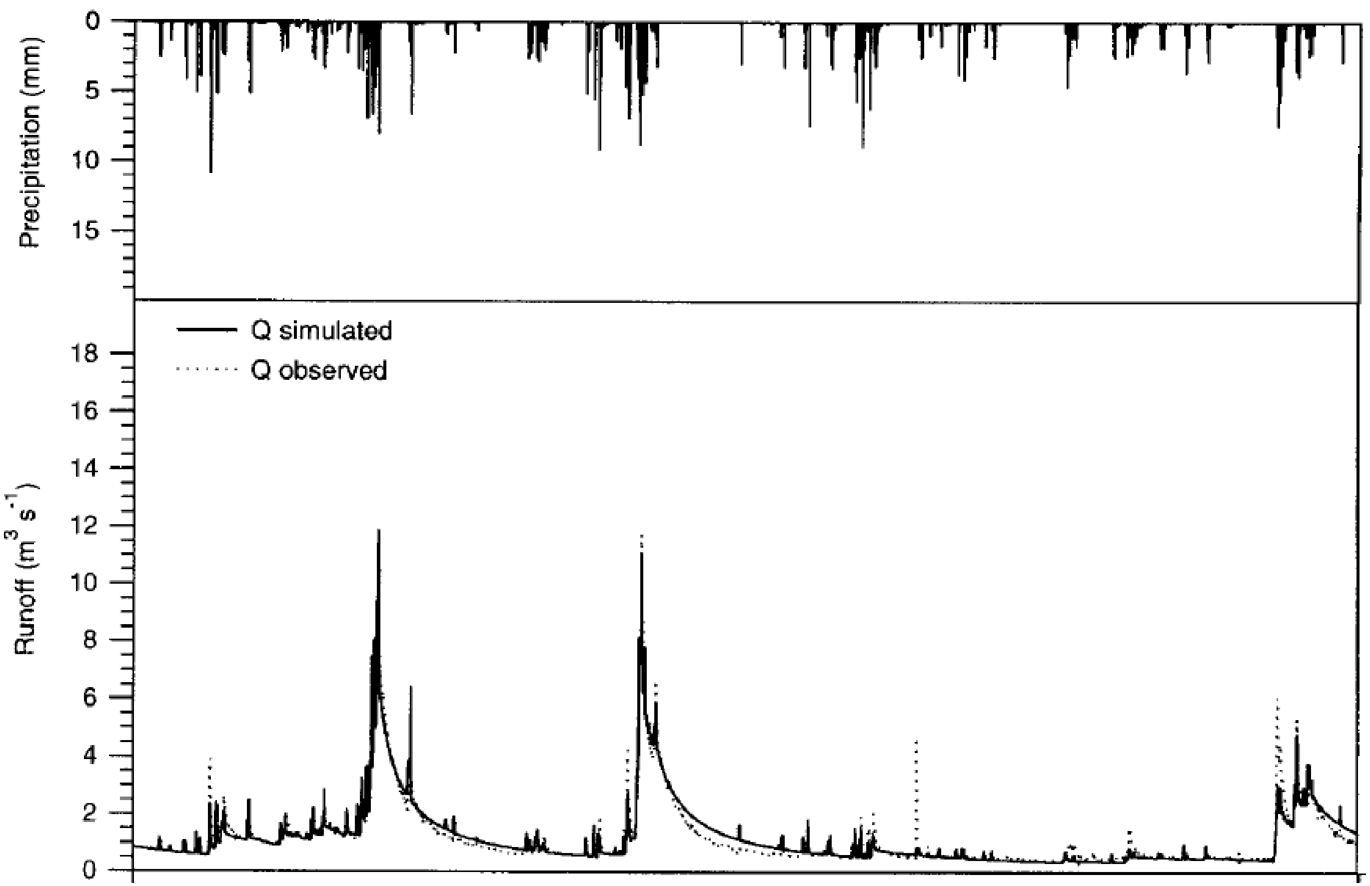
$$Q = k \cdot S$$

Q	Outflow (runoff)
k	Storage coefficient
S	Actual storage volume

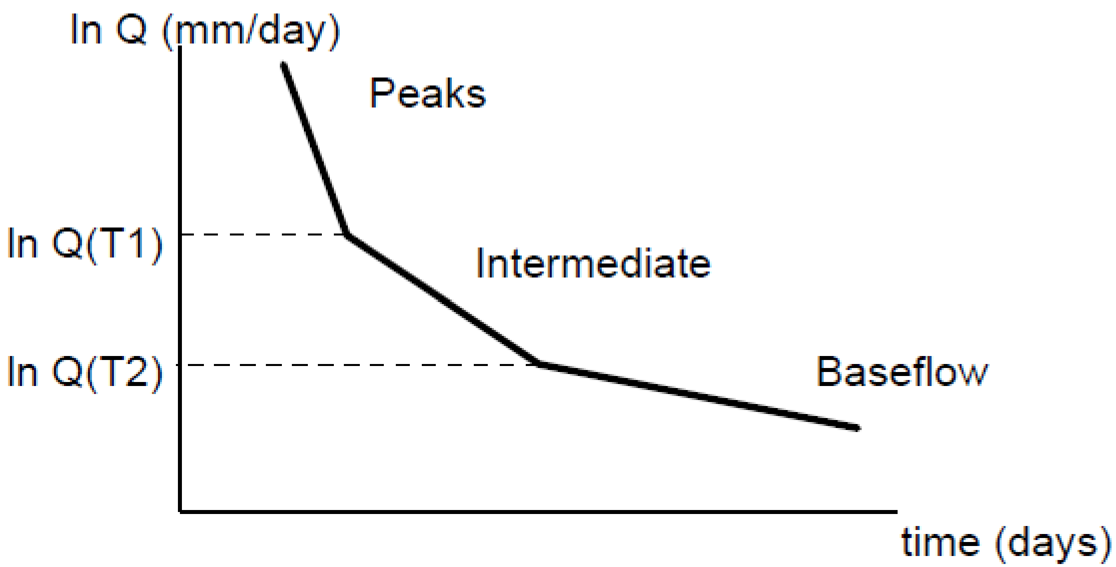


Conceptual models

Hydrograph

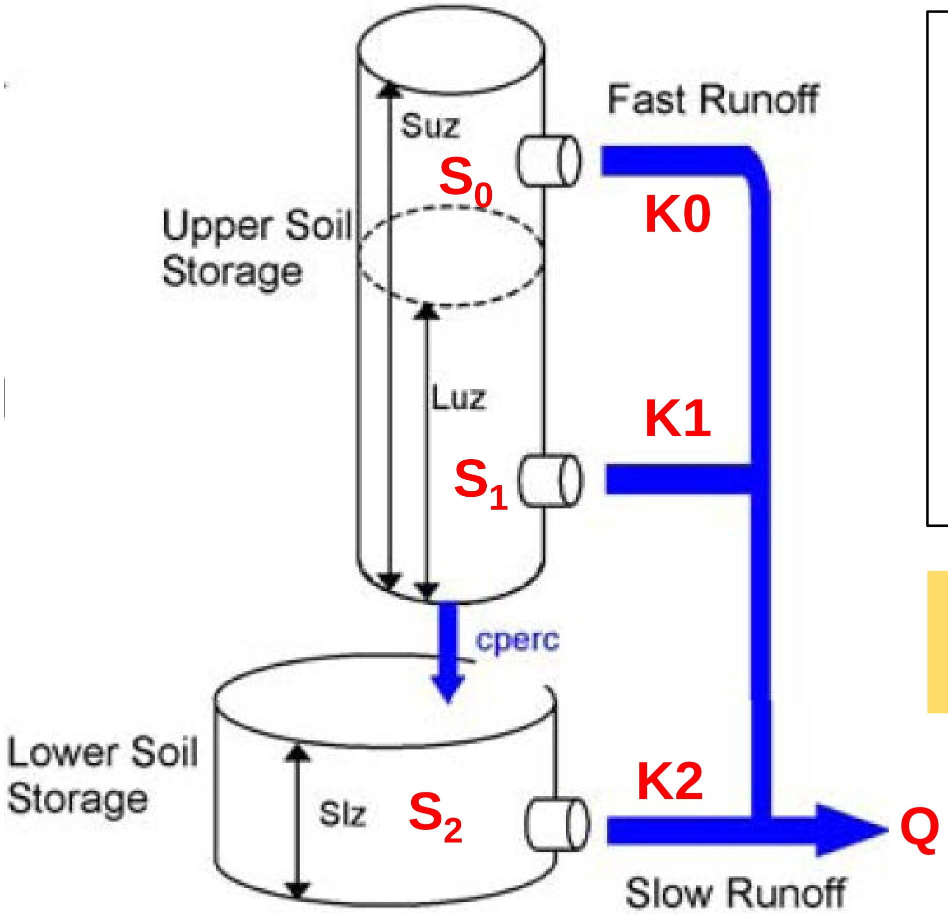


Hydrograph – Recession period



Conceptual models

Example: Soil and ground water fluxes



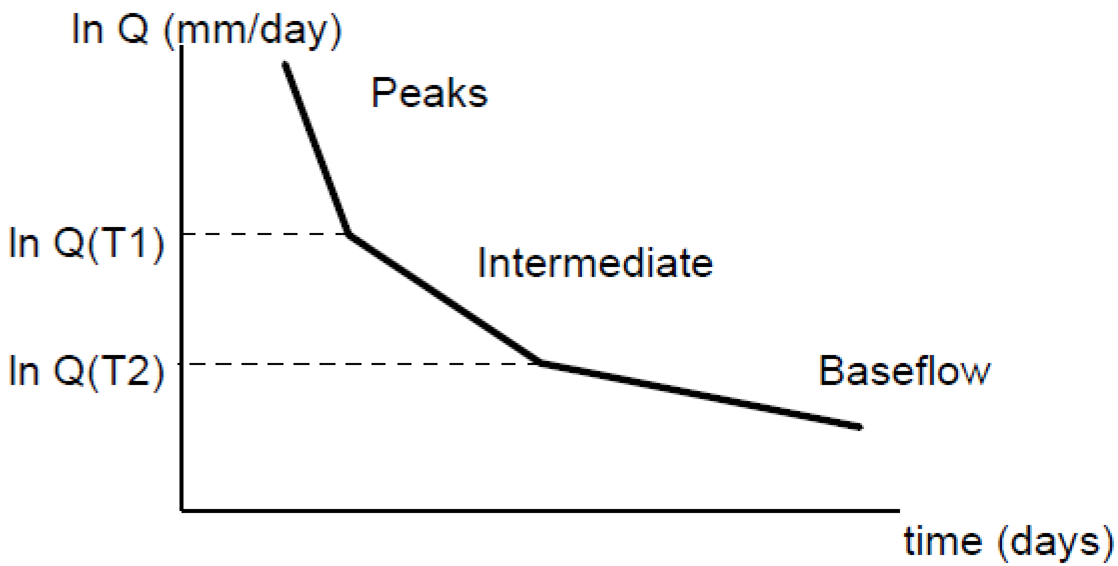
Linear storage approach used in many large-scale models

$$Q = k \cdot S$$

Q	Outflow (runoff)
K	Storage coefficient
S	Actual storage volume

K may be estimated/calibrated from observed discharge time series

Hydrograph – Recession period



- Slope of the recession:

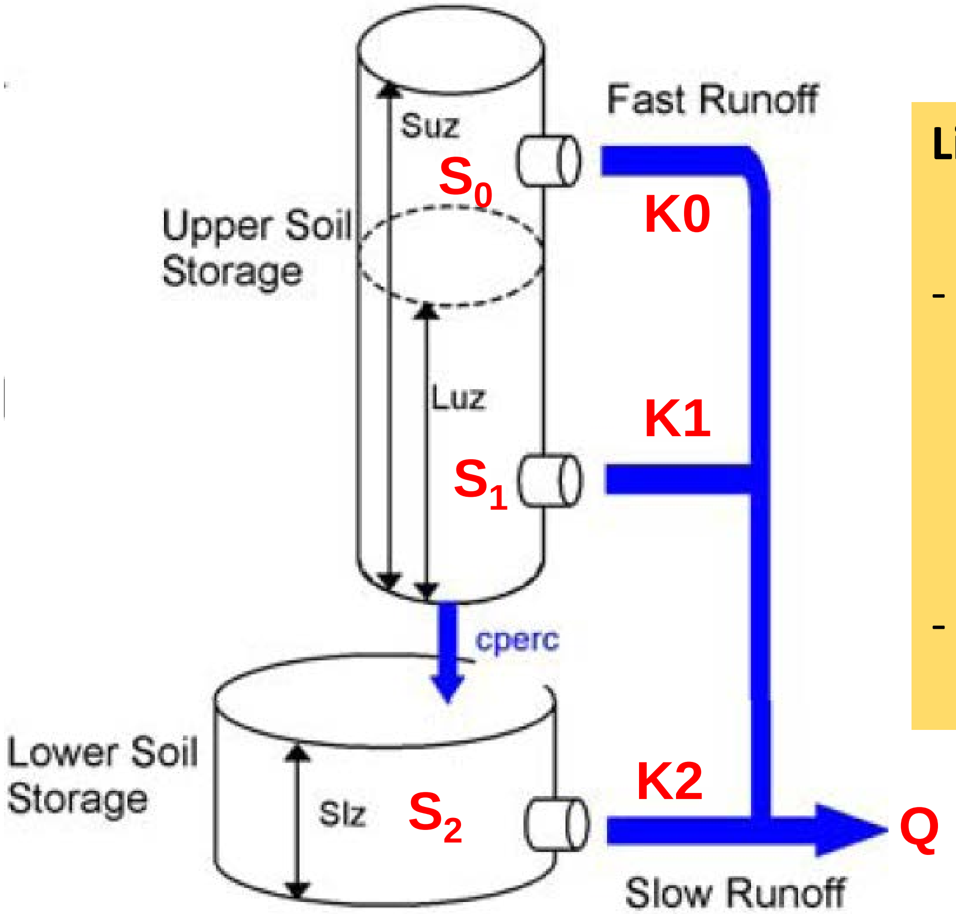
  Peaks: $K_0 + K_1 + K_2$

  Intermediate: $K_1 + K_2$

  Baseflow: K_2

Conceptual models

Example: Soil and ground water fluxes



Limitations:

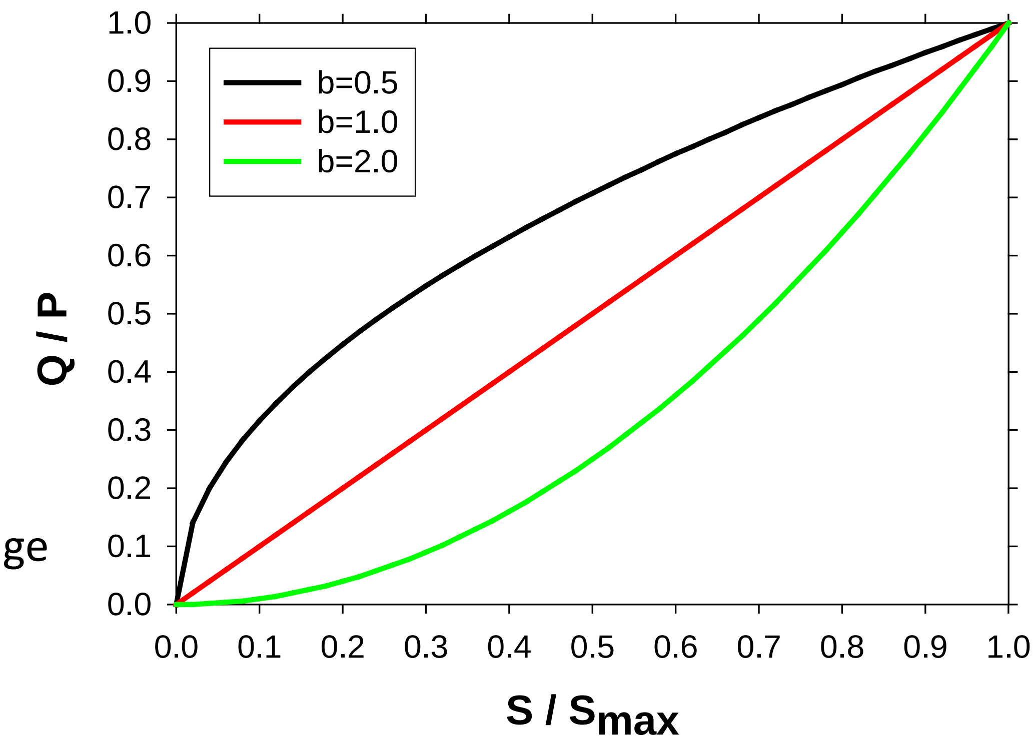
- Model can usually only be applied to situations for which it has been calibrated
  (poor for extremes, inter-annual variations, trends)
- Model cannot be transferred to other areas

Conceptual models

Runoff generation by a non-linear response function at the 0.5° scale

$$Q = P \cdot \left(\frac{S}{S_{max}} \right)^{\gamma}$$

Q	Runoff
P	Precipitation
S	Actual soil water content
S_{max}	Maximum soil water storage
γ	Calibration parameter

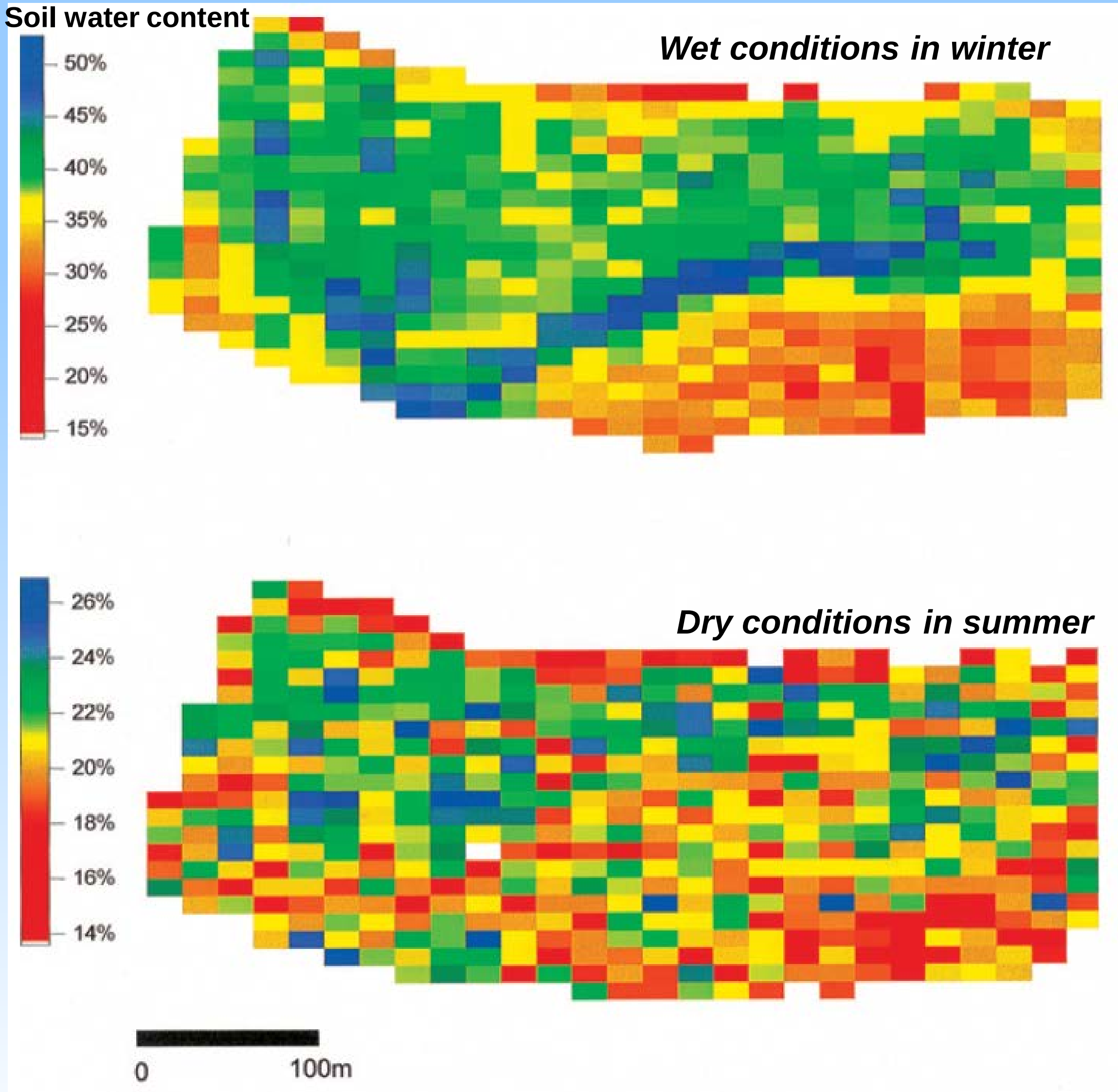


This equation is used, e.g., in the WaterGAP global hydrology model (WGHM) and the HBV model.

Water storage – spatial variability

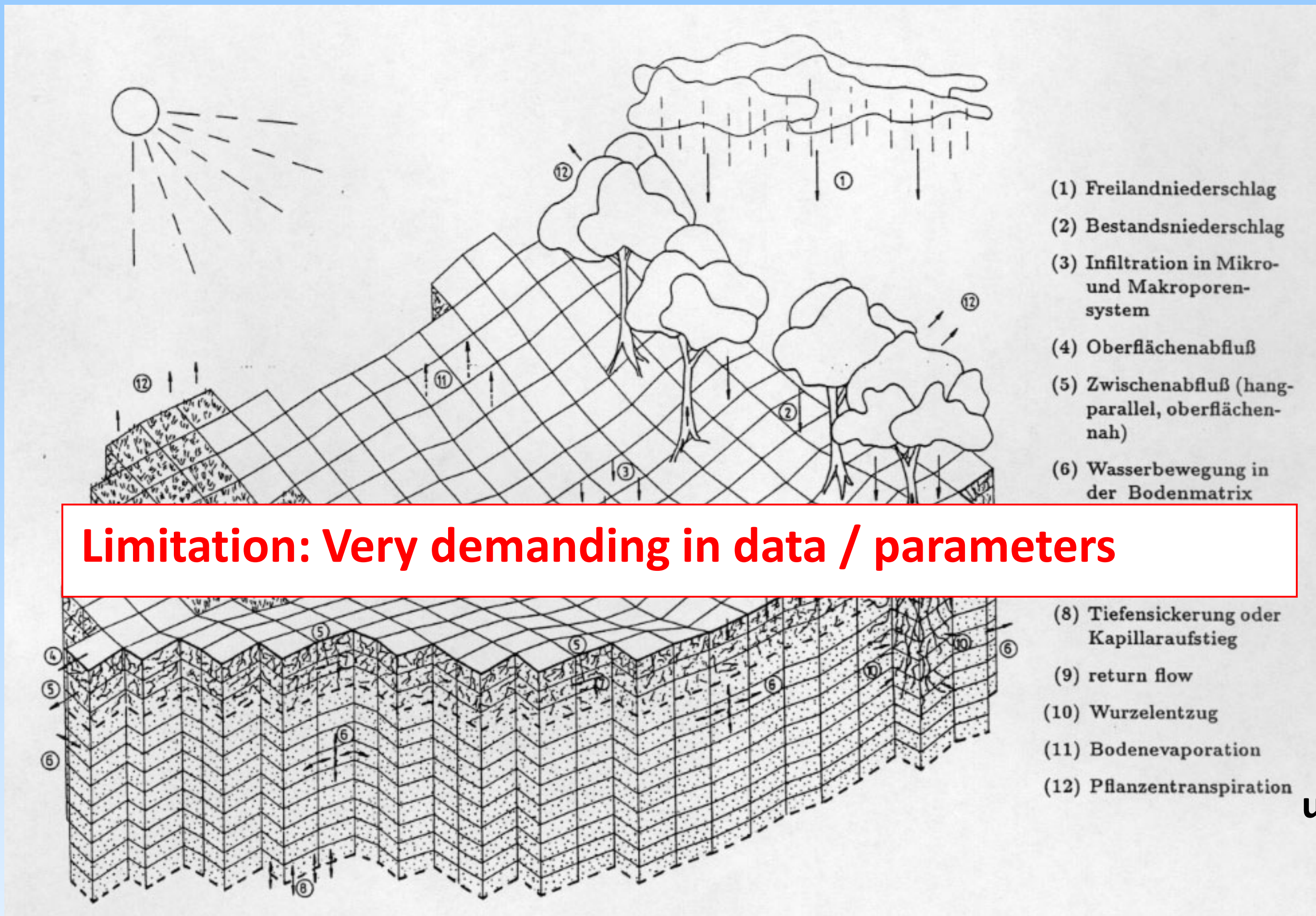
Tarrawarra catchment (Victoria, Australia) (Western & Grayson, 2001)

Water storage – spatial variability



Tarrawarra catchment (Victoria, Australia)
(Western & Grayson, 2001)

Representing spatial variability



Limitation: Very demanding in data / parameters

For example:

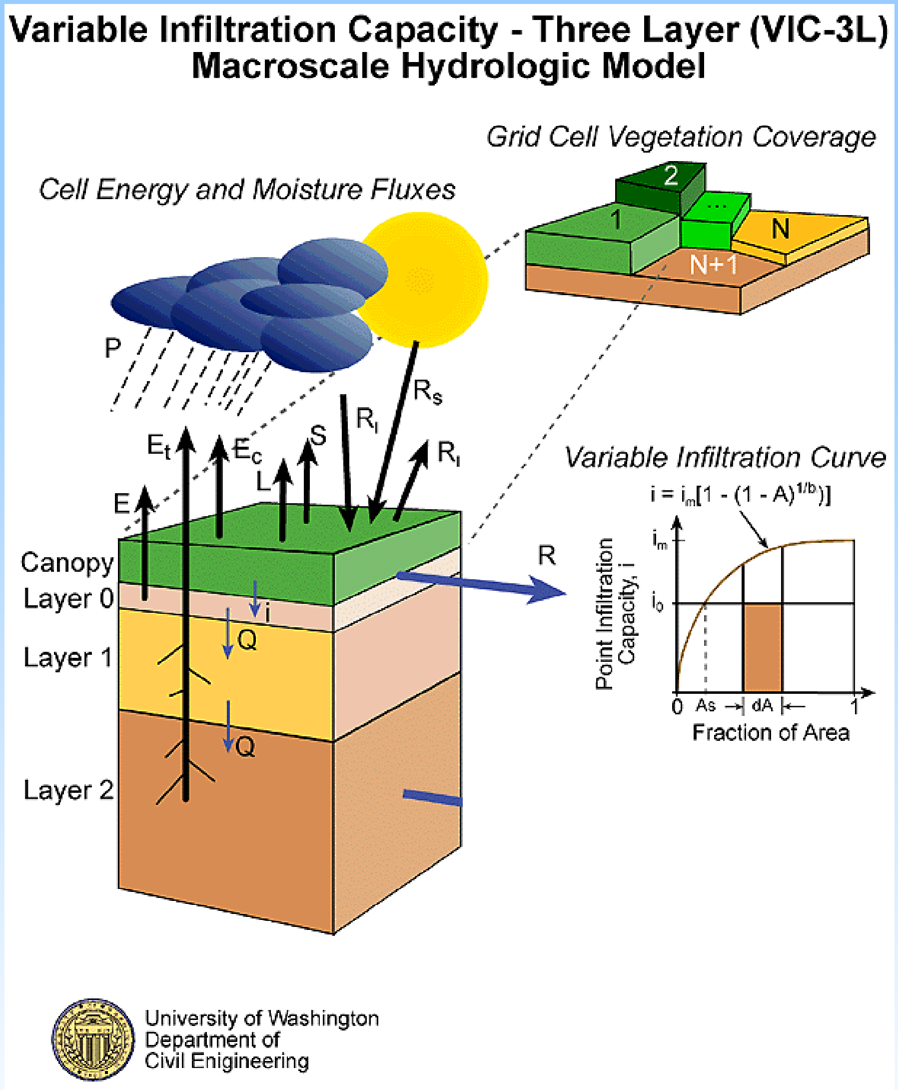
Differential equation for unsaturated flow in a porous medium

(Richards equation):

$$\frac{\partial}{\partial x}\left(k_{xx}(\theta)\cdot\frac{\partial\psi}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_{yy}(\theta)\cdot\frac{\partial\psi}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_{zz}(\theta)\cdot\frac{\partial\psi}{\partial x}+1\right)=\frac{\partial\theta}{\partial t}-S$$

Representing spatial variability

Variations of parameter values within a grid cell



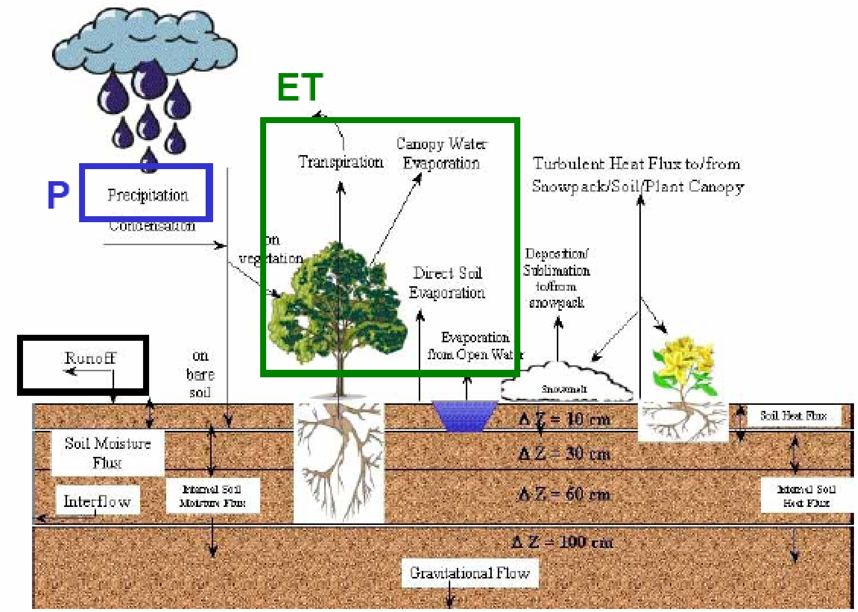
Mosaic approach

Distribution function

(Beispiel: VIC-Modell)

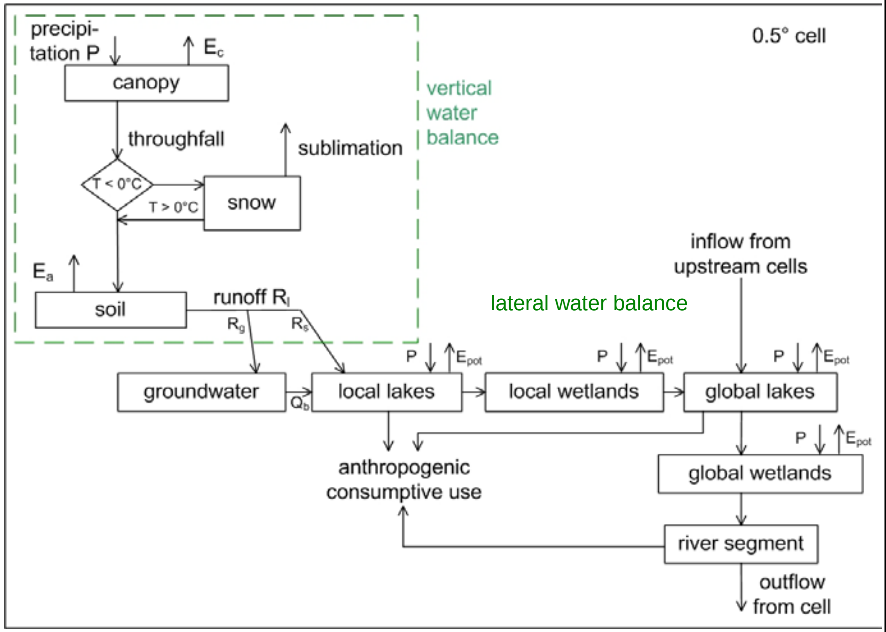
Large-scale models of continental hydrology

Land Surface Models



- Land surface description in climate models
- Water balance
- Energy balance
- (Carbon fluxes)
- Vertical water fluxes, several soil layers
- High temporal resolution (minutes-hours)

Global hydrological models



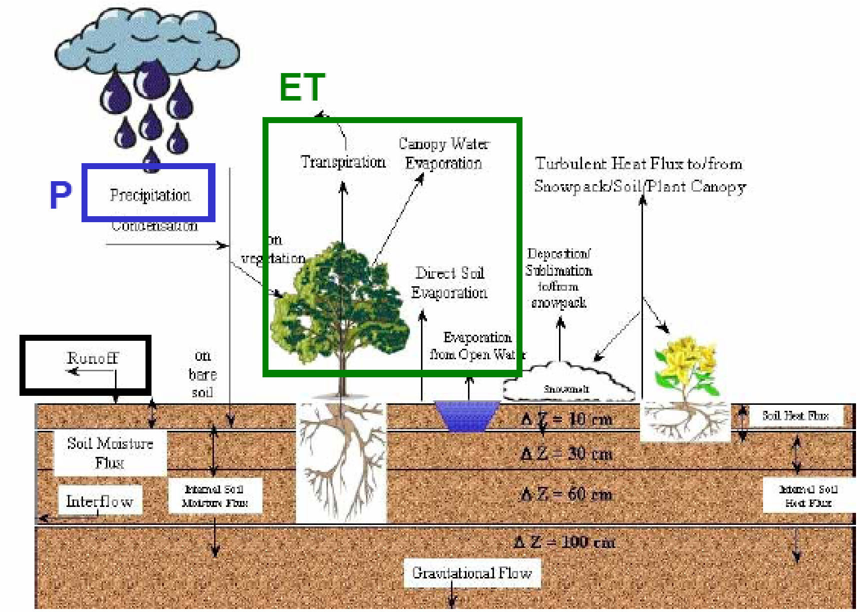
- Water balance for grid cells / river basins
- Lateral water fluxes
- Routing in river network
- (Water use / consumption)
- Daily – monthly temporal resolution
- Conceptual process representation

GFZ
Helmholtz Centre
Potsdam

EGSIEM
European Gravity Service for Improved Emergency Management

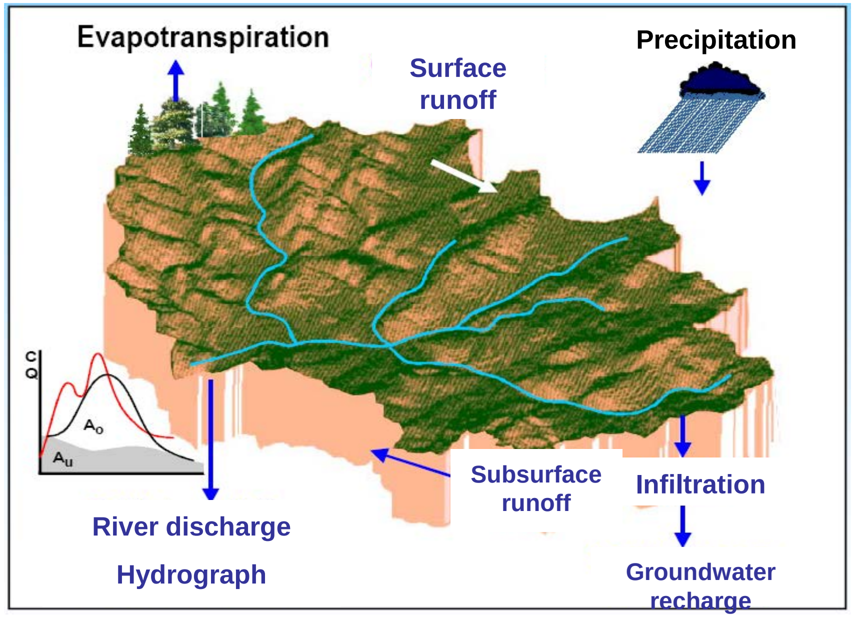
Large-scale models of continental hydrology

Land Surface Models



- Land surface description in climate models
- Water balance
- Energy balance
- (Carbon fluxes)
- Vertical water fluxes, several soil layers
- High temporal resolution (minutes-hours)

Global hydrological models



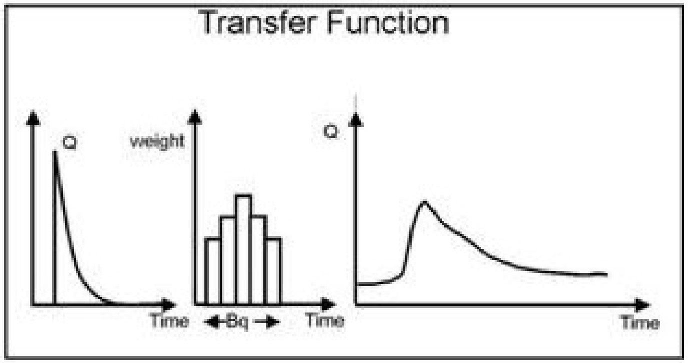
- Water balance for grid cells / river basins
- Lateral water fluxes
- Routing in river network
- (Water use / consumption)
- Daily – monthly temporal resolution
- Conceptual process representation

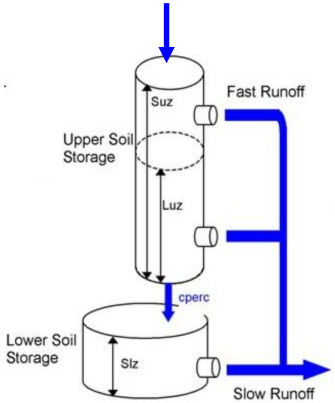
Types of hydrological models

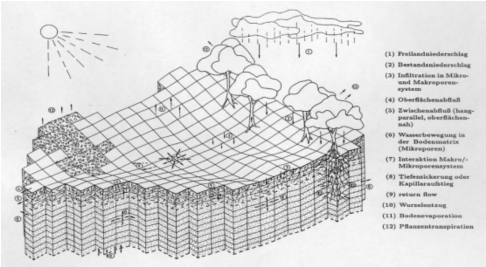
Deterministic Models

Degree of causality

Black-Box-Models | Conceptual Models | Physically- based Models

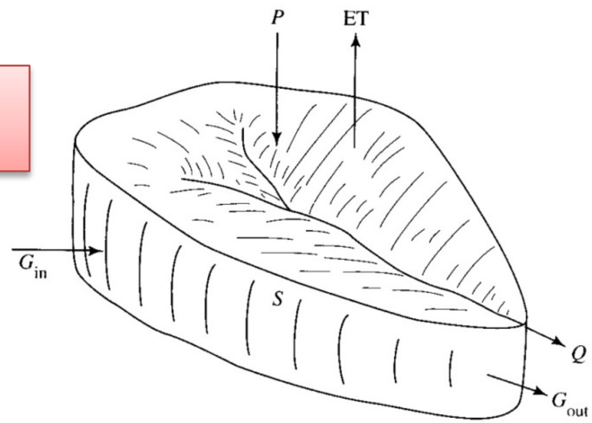




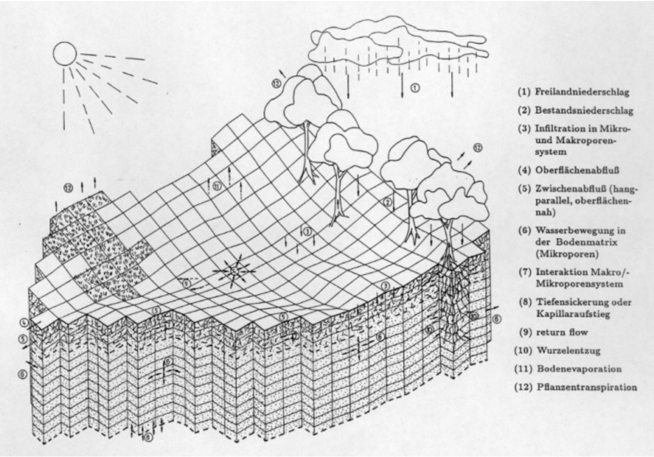


Spatial discretization

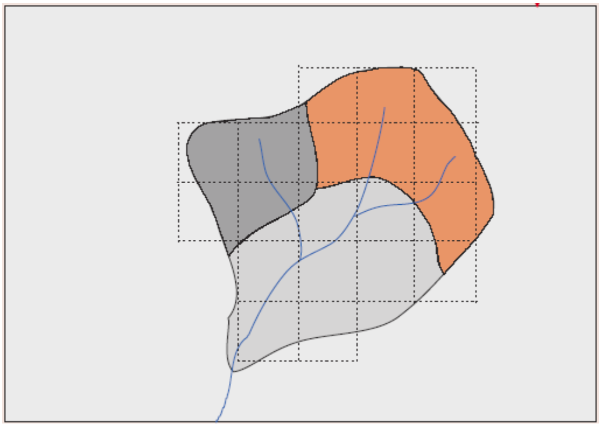
Lumped model



Spatially distributed model

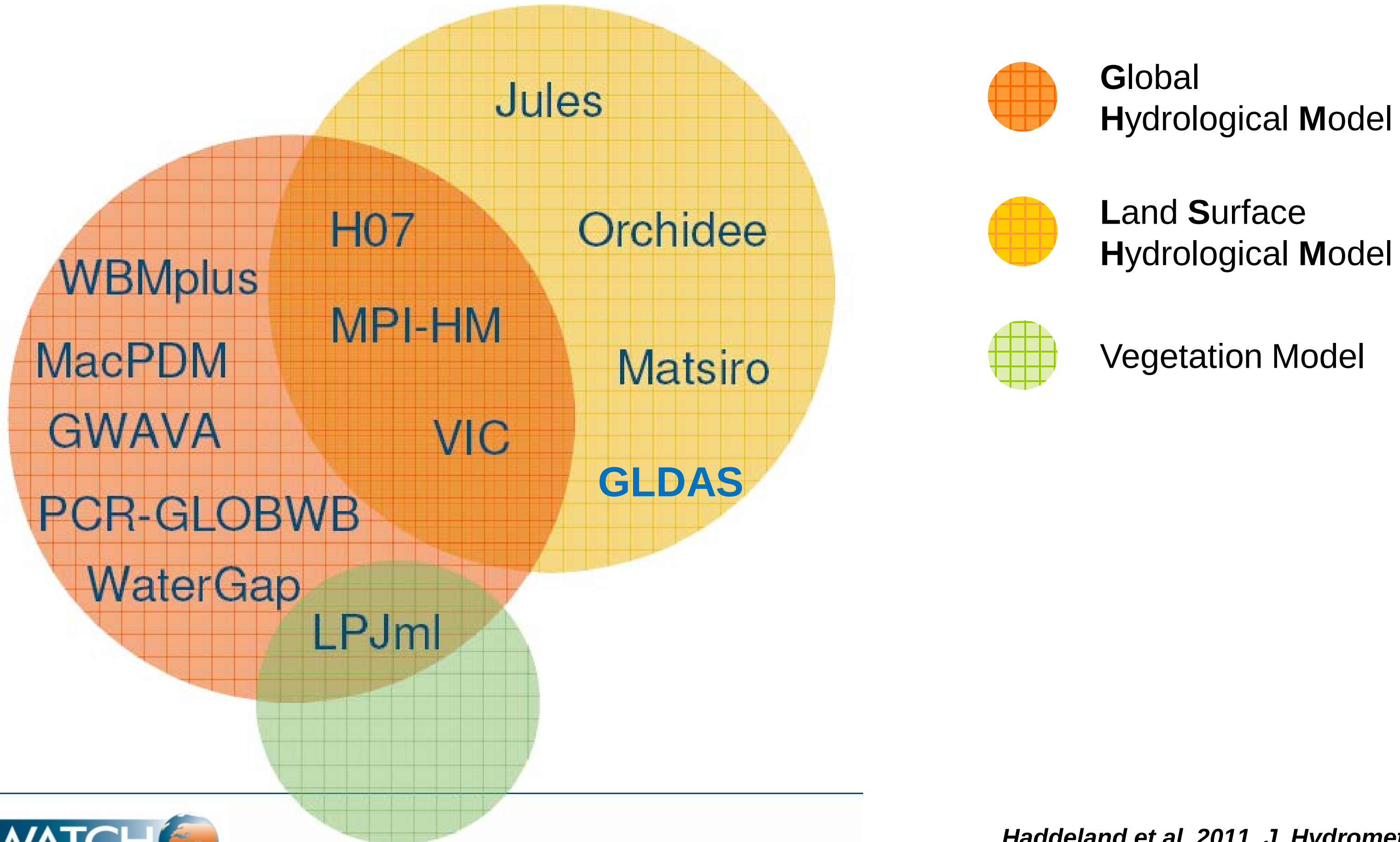


Semi-distributed model



Large-scale models of continental hydrology

WaterMIP (Water Model Intercomparison Project)



Haddeland et al. 2011, J. Hydrometeor.
Harding et al. 2011, J. Hydrometeor.

Large-scale models of continental hydrology

WaterMIP (Water Model Intercomparison Project)

Model name[1]	Model time step	Meteorological forcing variables[2]	Energy balance	Evapotranspiration scheme[3]	Runoff scheme[4]	Snow scheme	Reference(s)
GWAVA	Daily	P, T, W, Q, LWn, SW, SP	No	Penman-Monteith	Saturation excess / Beta function	Degree day	Meigh et al. (1999)
H08	6 h	R, S, T, W, Q, LW, SW, SP	Yes	Bulk formula	Saturation excess / Beta function	Energy balance	Hanasaki et al (2008a)
HTESSEL	1 h	R, S, T, W, Q, LW, SW, SP	Yes	Penman-Monteith	Infiltration excess / Darcy	Energy balance	Balsamo et al. (2009)
JULES	1 h	R, S, T, W, Q, LW, SW, SP	Yes	Penman-Monteith	Infiltration excess / Darcy	Energy balance	Cox et al. (1999), Essery et al. (2003)
LPJmL	Daily	P, T, LWn, SW	No	Priestley-Taylor	Saturation excess	Degree day	Bondeau et al. (2007), Rost et al. (2008)
MacPDM	Daily	P, T, W, Q, LWn, SW	No	Penman-Monteith	Saturation excess / Beta function	Degree day	Arnell (1999), Gosling and Arnell (2010)
MATSIRO	1 h	R, S, T, W, Q, LW, SW, SP	Yes	Bulk formula	Infiltration and saturation excess / Groundwater	Energy balance	Takata et al. (2003), Koirala (2010)
MPI-HM	Daily	P, T	No	Thornthwaite	Saturation excess / Beta function	Degree day	Hagemann and Gates (2003), Hagemann and Dümenil (1998)
Orchidee	15 min	R, S, T, W, Q, SW, LW, SP	Yes	Bulk formula	Saturation excess	Energy balance	De Rosnay and Polcher (1998)
VIC	Daily/ 3h	P, Tmax, Tmin, W, Q, LW, SW, SP	Snow season	Penman-Monteith	Saturation excess / Beta function	Energy balance	Liang et al. (1994)
WaterGAP	Daily	P, T, LWn, SW	No	Priestley-Taylor	Beta function	Degree day	Alcamo et al. (2003)

WATCH Water and Global Change

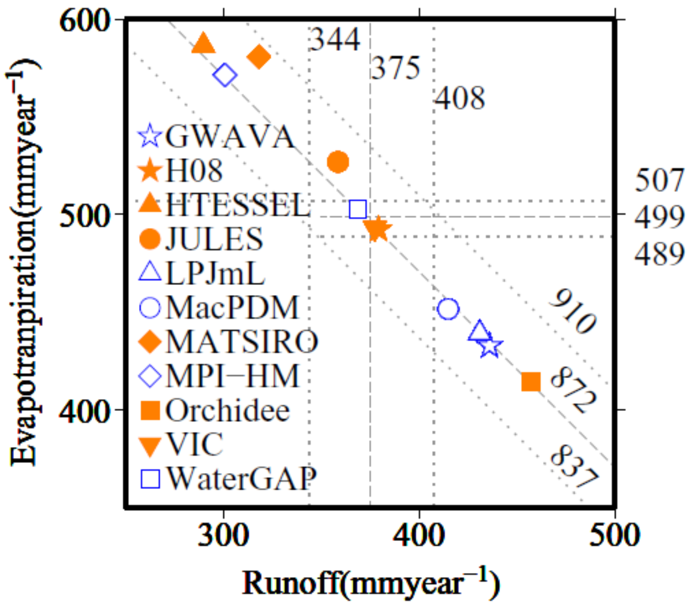
Haddeland et al. 2011, J. Hydrometeor.

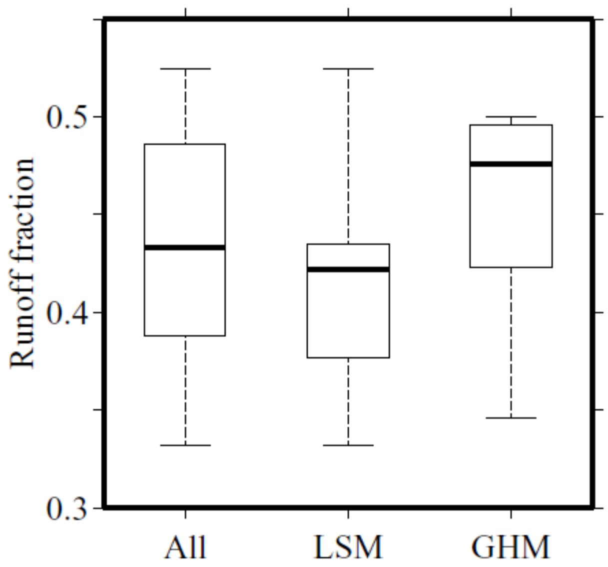
Column 3: R: Rainfall rate, S: Snowfall rate, P: Precipitation, T: Mean daily air temperature, Tmax: Maximum daily air temperature, Tmin: Minimum daily air temperature, W: Wind speed, Q: Specific humidity, LW: Longwave radiation flux (downward), LWn: Longwave radiation flux (net), SW: Shortwave radiation flux (downward), SP: Surface pressure

Large-scale models of continental hydrology

WaterMIP (Water Model Intercomparison Project)

Global simulation results (mean annual values 1985-1999)





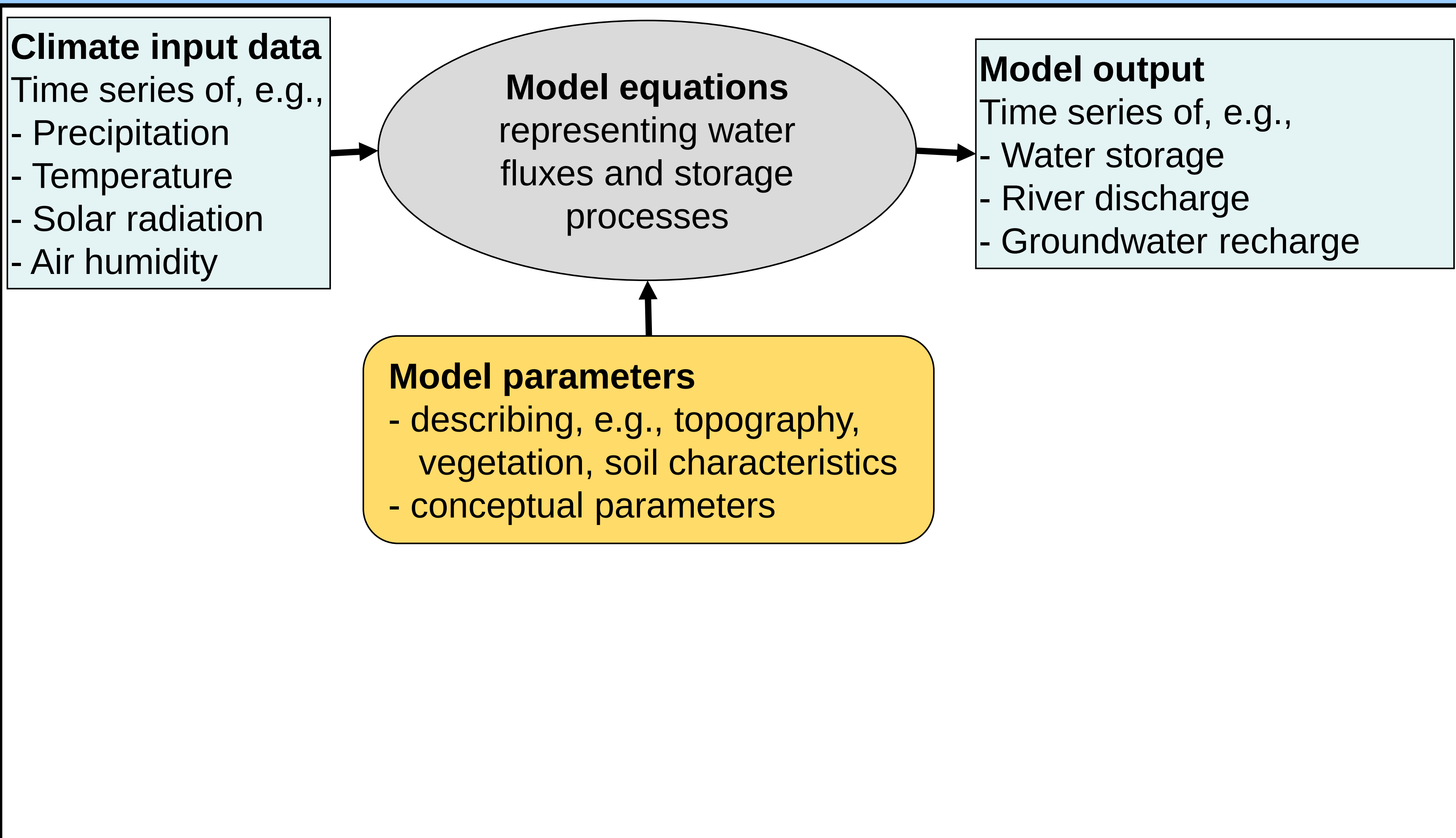
LSM: Land Surface Model

GHM: Global Hydrological Model

WATCH Water and Global Change

Haddeland, I., et al. (2011):
Multi-model estimate of the global terrestrial water balance: Setup and first results. J. Hydrometeor.

What is a hydrological model ?



Large-scale models of continental hydrology: parameters

Vegetation parameters (partly time-variable)

- Leaf area index
- Albedo
- Interception storage capacity
- Stomata resistence
- Aerodynamisc roughness
- Canopy hight
- Root depth
- …

Soil parameters

- Porosity
- Field capacity
- Hydraulic conductivity
- Soil depth
- Capillary head as function of water content
- Heat transport and storage
- …

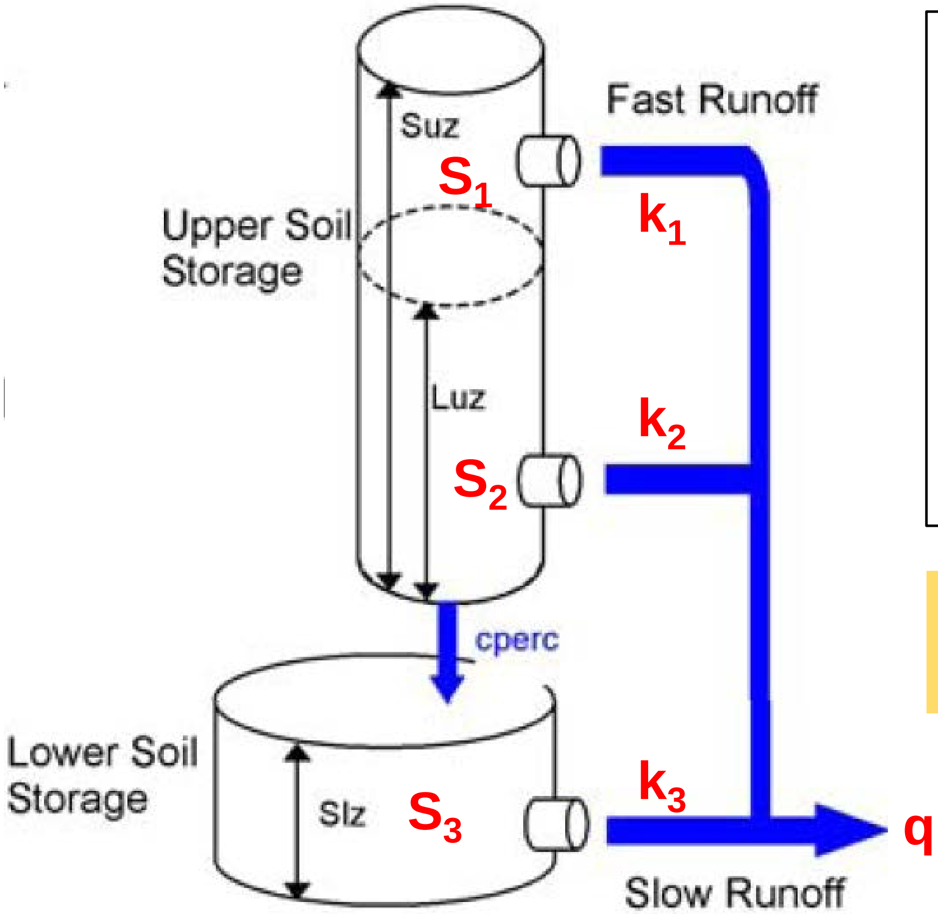
Snow parameters, e.g., density, water and energy storage and transport parameters

Other hydrological / hydraulic parameters

- Slope gradient
- River cross section geometry
- Lake /reservoir storage capacity …..

Conceptual models

Example: Soil and ground water fluxes



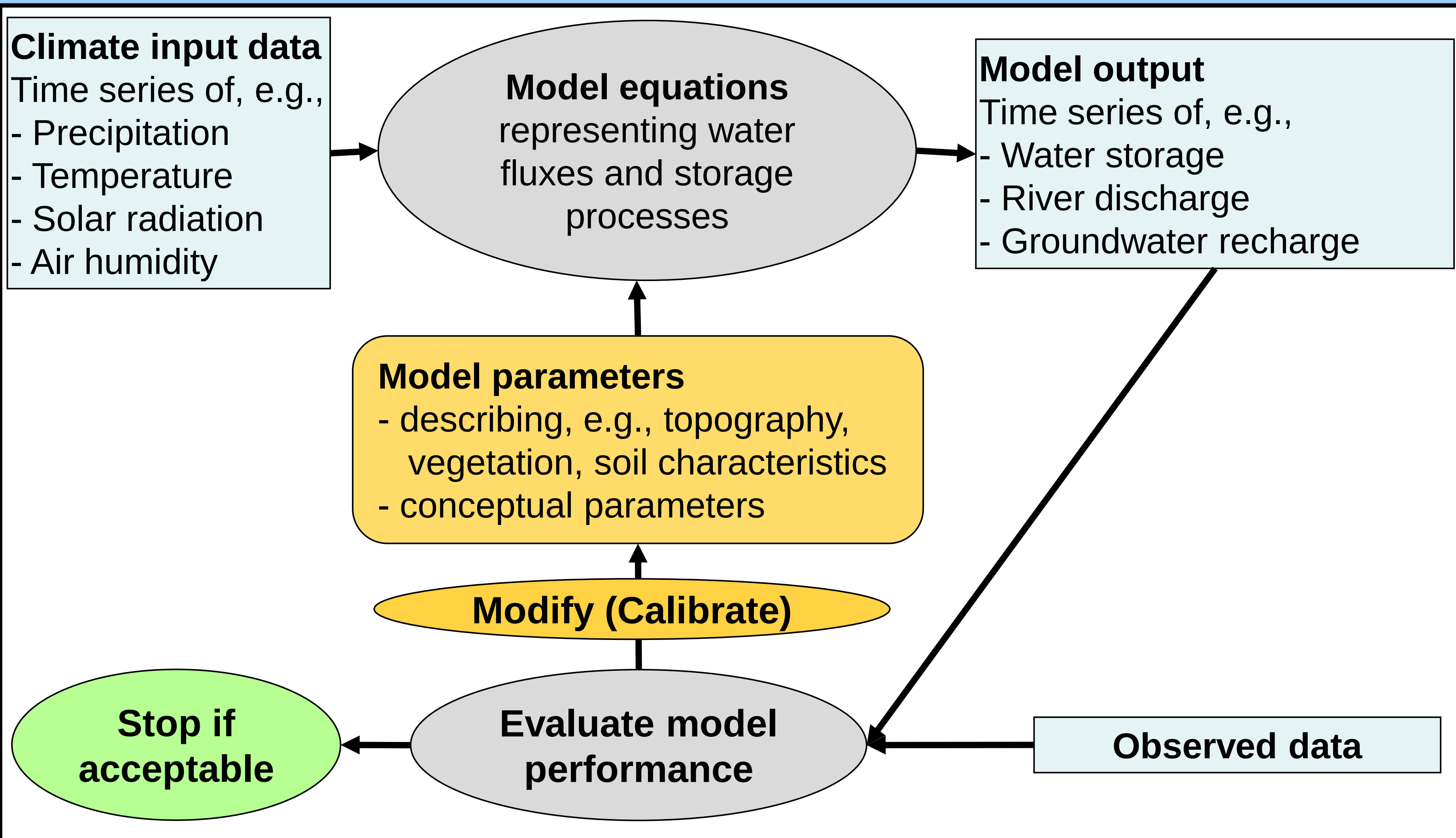
Linear storage approach used in many large-scale models

$$Q = k \cdot S$$

Q	Outflow (runoff)
k	Storage coefficient
S	Actual storage volume

k may be estimated/calibrated from observed discharge time series

Calibration of hydrological models



Calibration of hydrological models

Water balance of a river basin :

Traditional calibration variable (→ Q)

$$P = E + Q + \Delta S$$

Model input (→ P)

Simulated in the model based on meteorological input data (→ E)

P: Precipitation

E: Evapotranspiration

Q: Runoff (**measured time series of river discharge**)

ΔS: Water storage change

Calibration of hydrological models

Water balance of a river basin :

Traditional calibration variable

$$P = E + Q + \Delta S$$

Model input

Simulated in the model based on meteorological input data

P: Precipitation

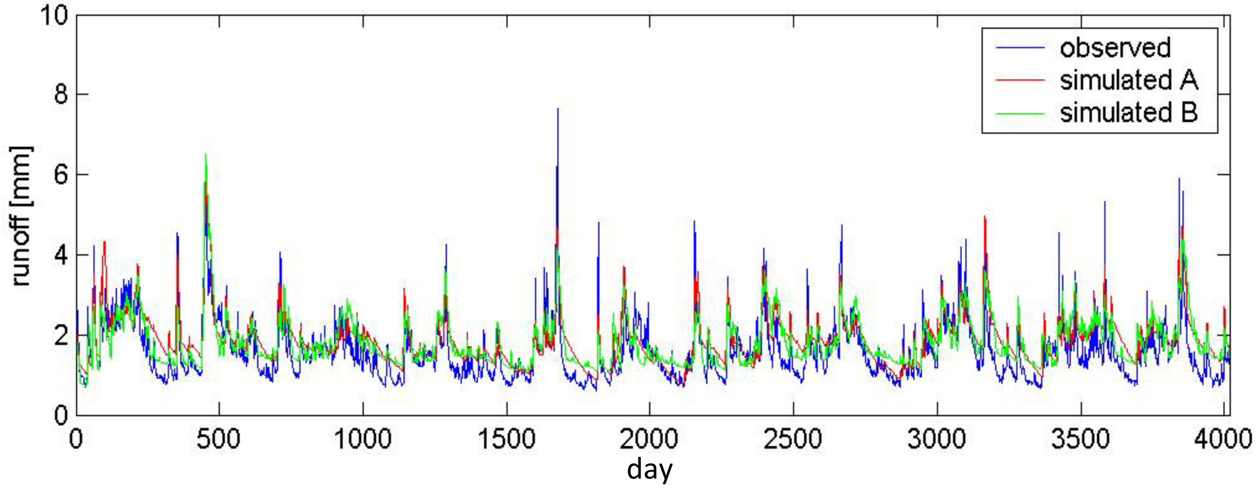
E: Evapotranspiration

Q: Runoff (**measured time series of river discharge**)

ΔS: Water storage change

Calibration of hydrological models

River discharge at Hainburg, Austria (Danube river, basin area 104 000 km²)

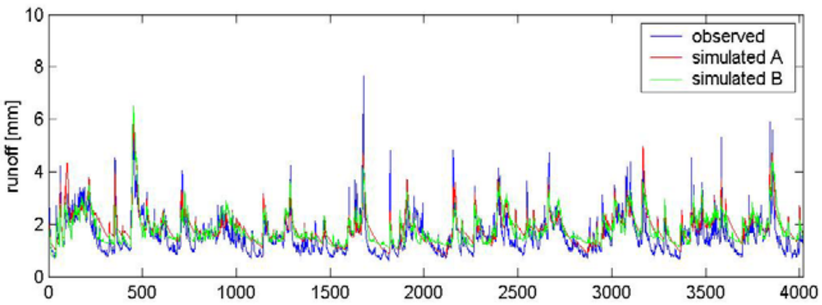


Calibration of hydrological models – Performance criteria

$$RMSE = \sqrt{\frac{1}{n}\sum_{t=1}^{n}(O_t - P_t)^2}$$

$$Nash-Sutcliffe\ efficiency = 1 - \frac{\frac{1}{n}\sum_{t=1}^{n}(O_t - P_t)^2}{\frac{1}{n}\sum_{t=1}^{n}(O_t - \overline{O})^2}$$

$$logEff = 1 - \frac{\frac{1}{n}\sum_{t=1}^{n}(\log O_t - \log P_t)^2}{\frac{1}{n}\sum_{t=1}^{n}(\log O_t - \overline{\log O})^2}$$



Efficiency values [-∞;1]

1: optimal fit

0: model is not better than the mean of the observations

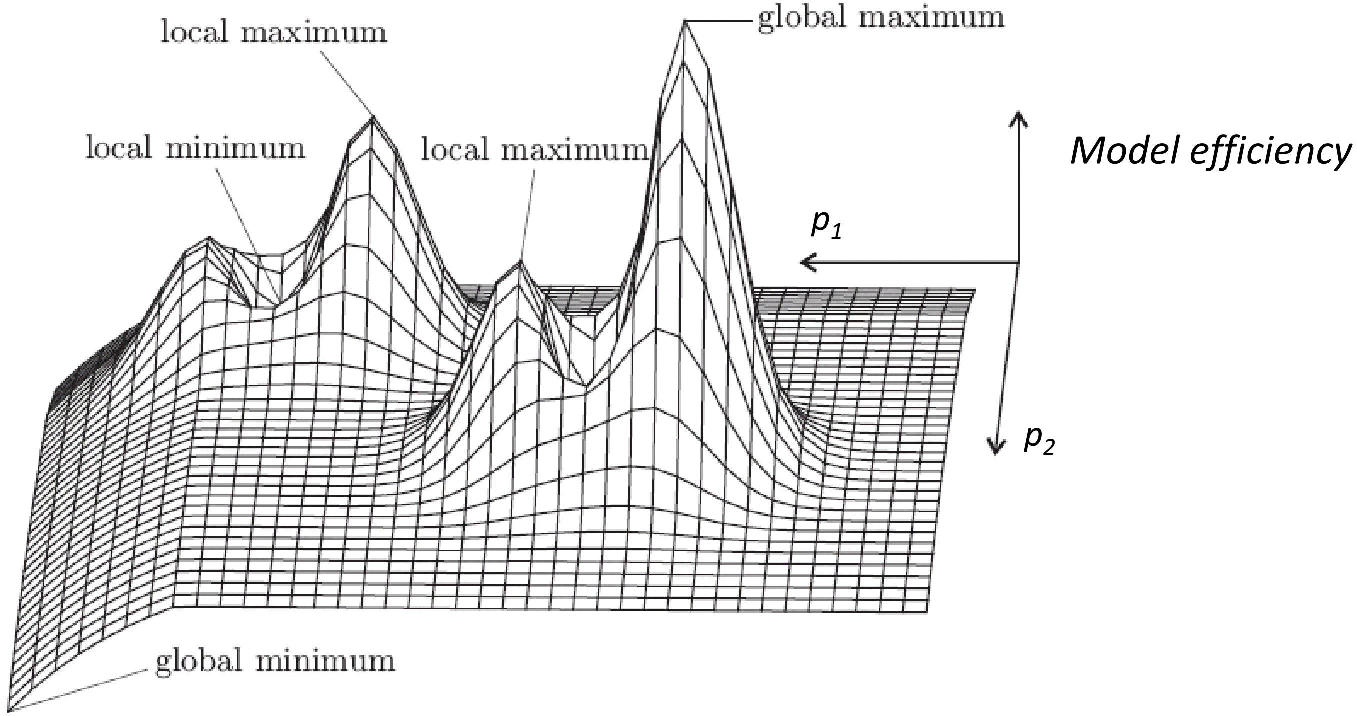
P_t simulated discharge at time t

O_t observed discharge at time t

n number of observations (time steps)

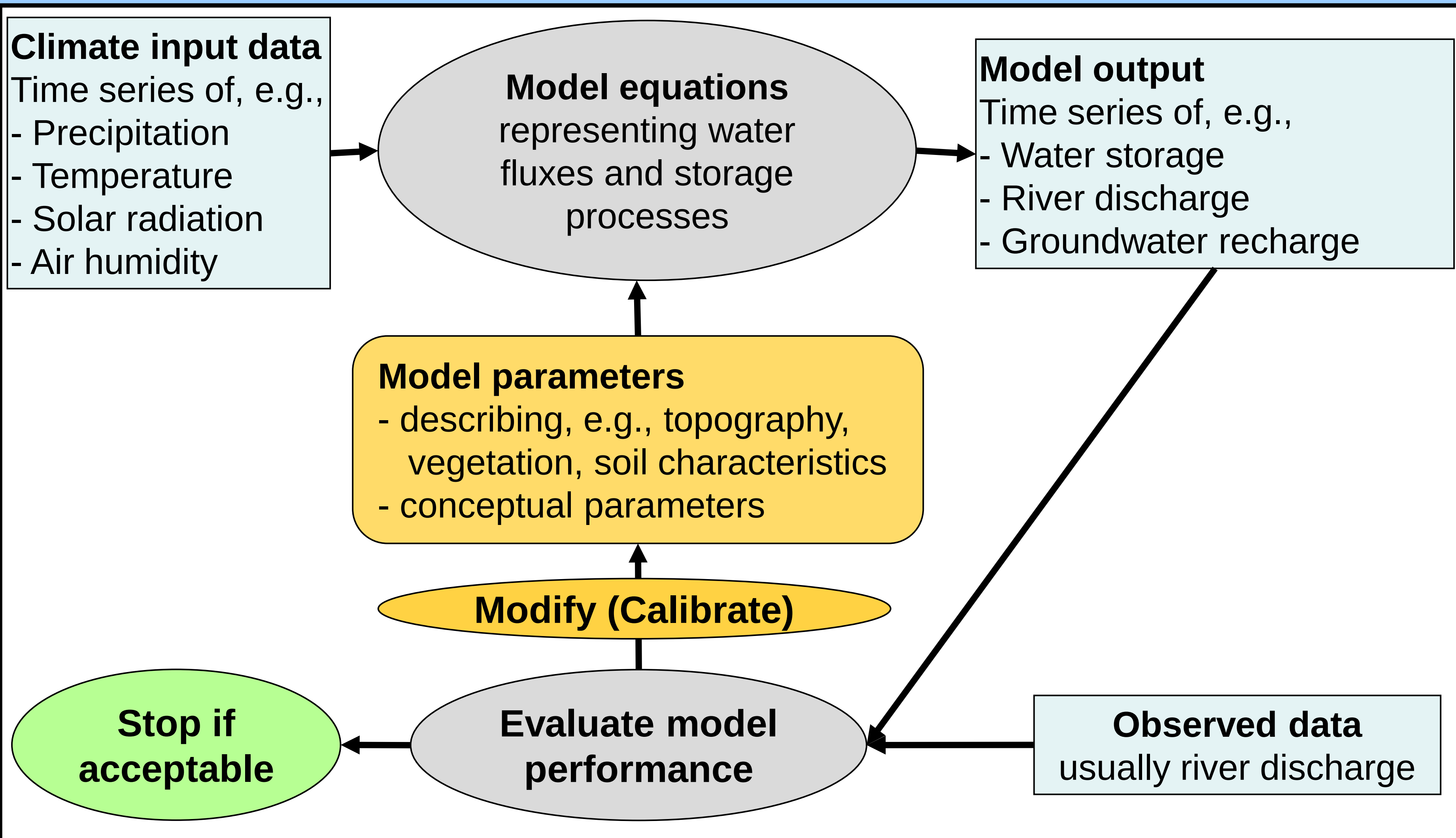
Calibration of hydrological models

Response surface of performance criterion



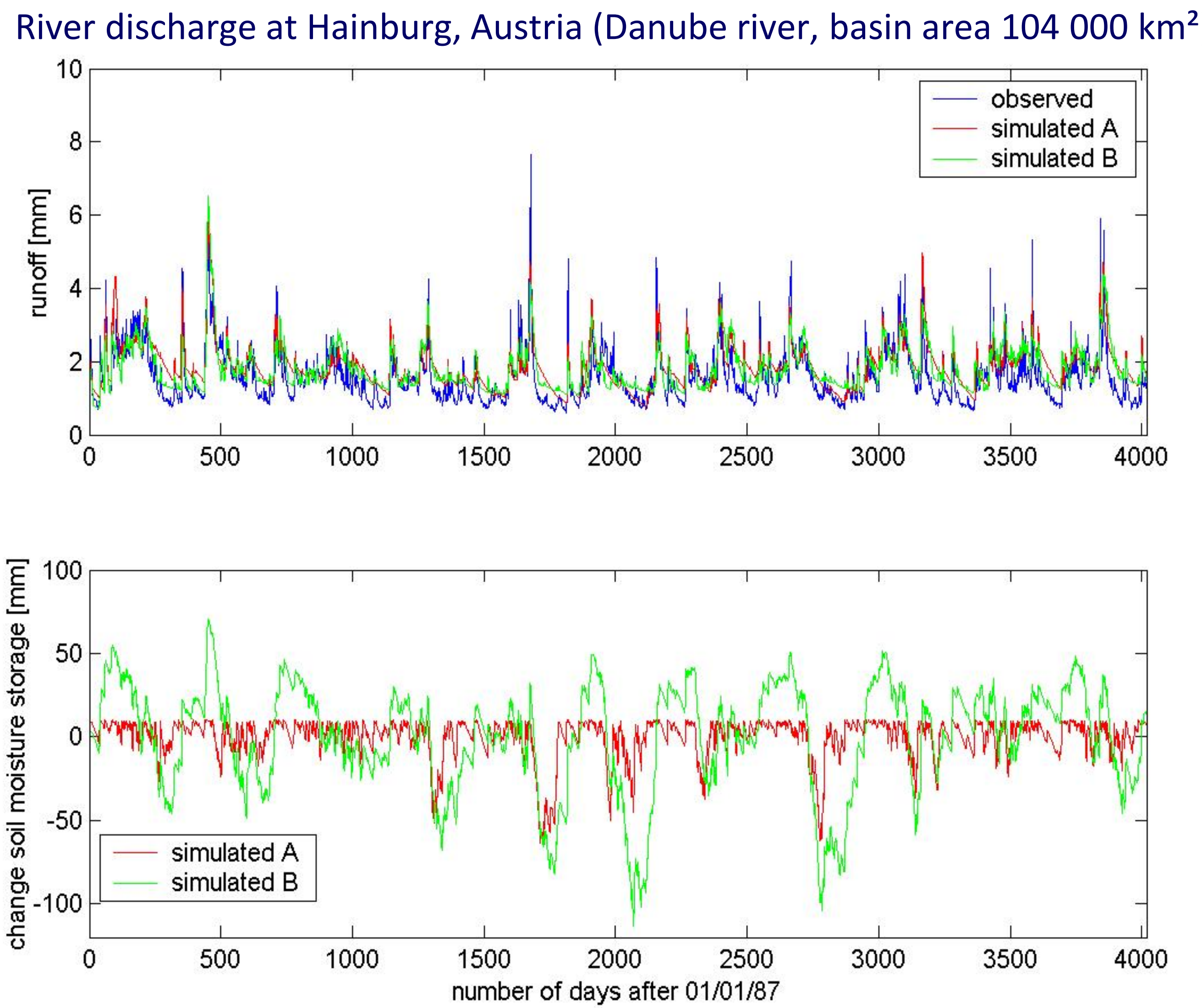
Powerful automatic global calibration algorithms are available(e.g., Shuffled complex evolution algorithm, Dynamically dimensioned search algorithm). But careful selection of performance criteria and expert-based evaluation is necessary.

Calibration of hydrological models



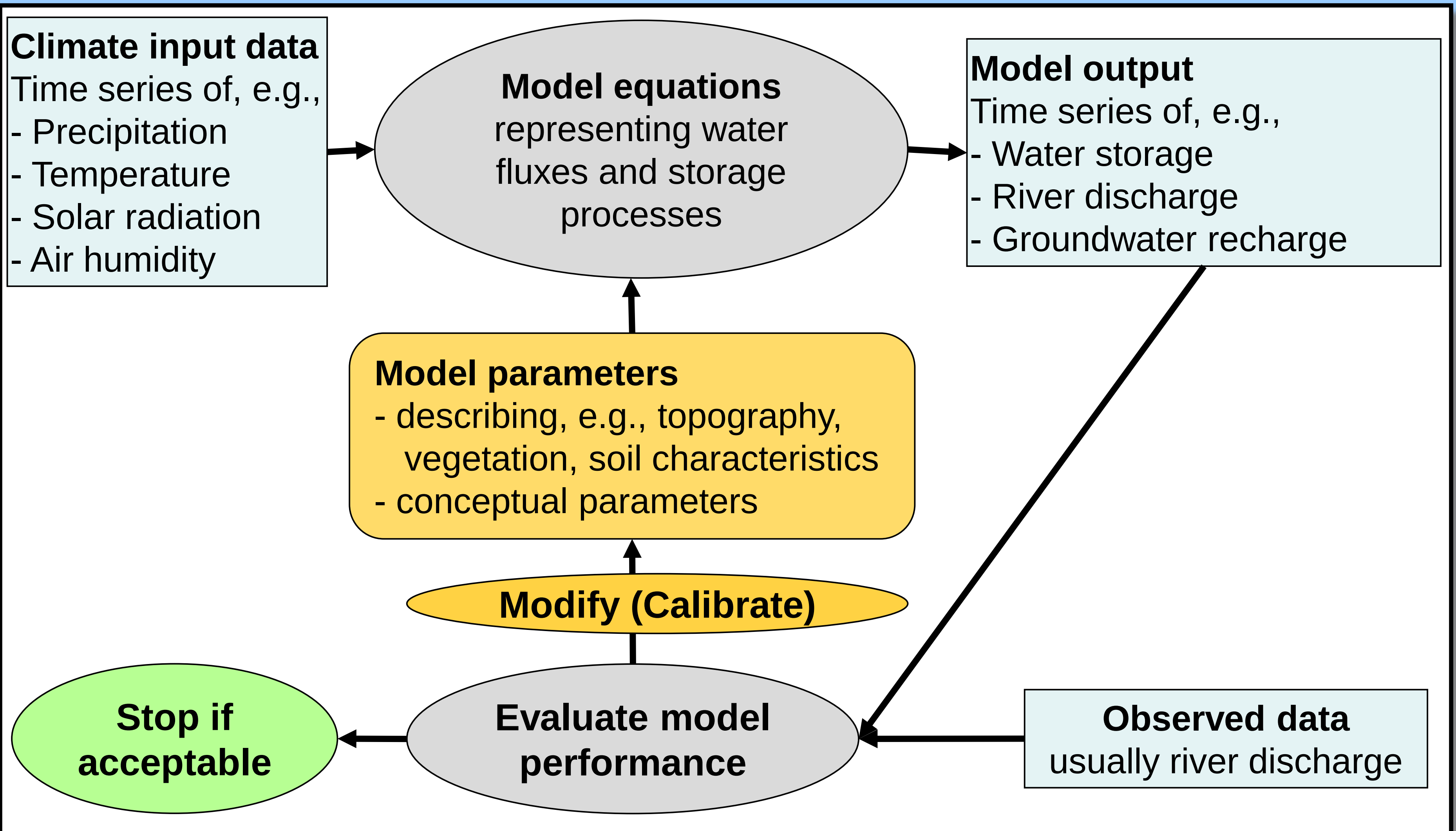
Calibration of hydrological models

Simulated basin-average soil moisture for the two model versions

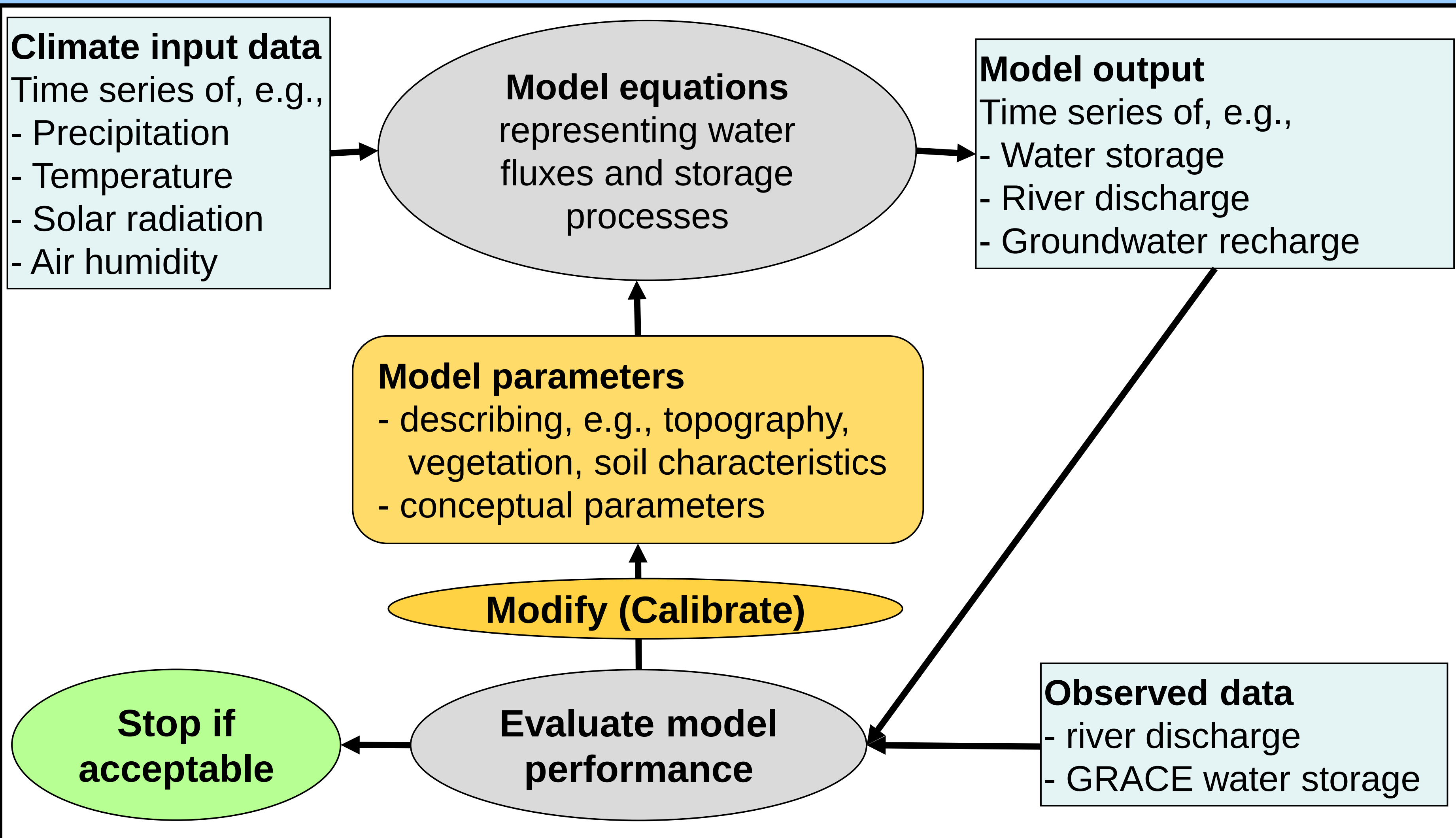


(Data from Merz & Blöschl, TU Wien)

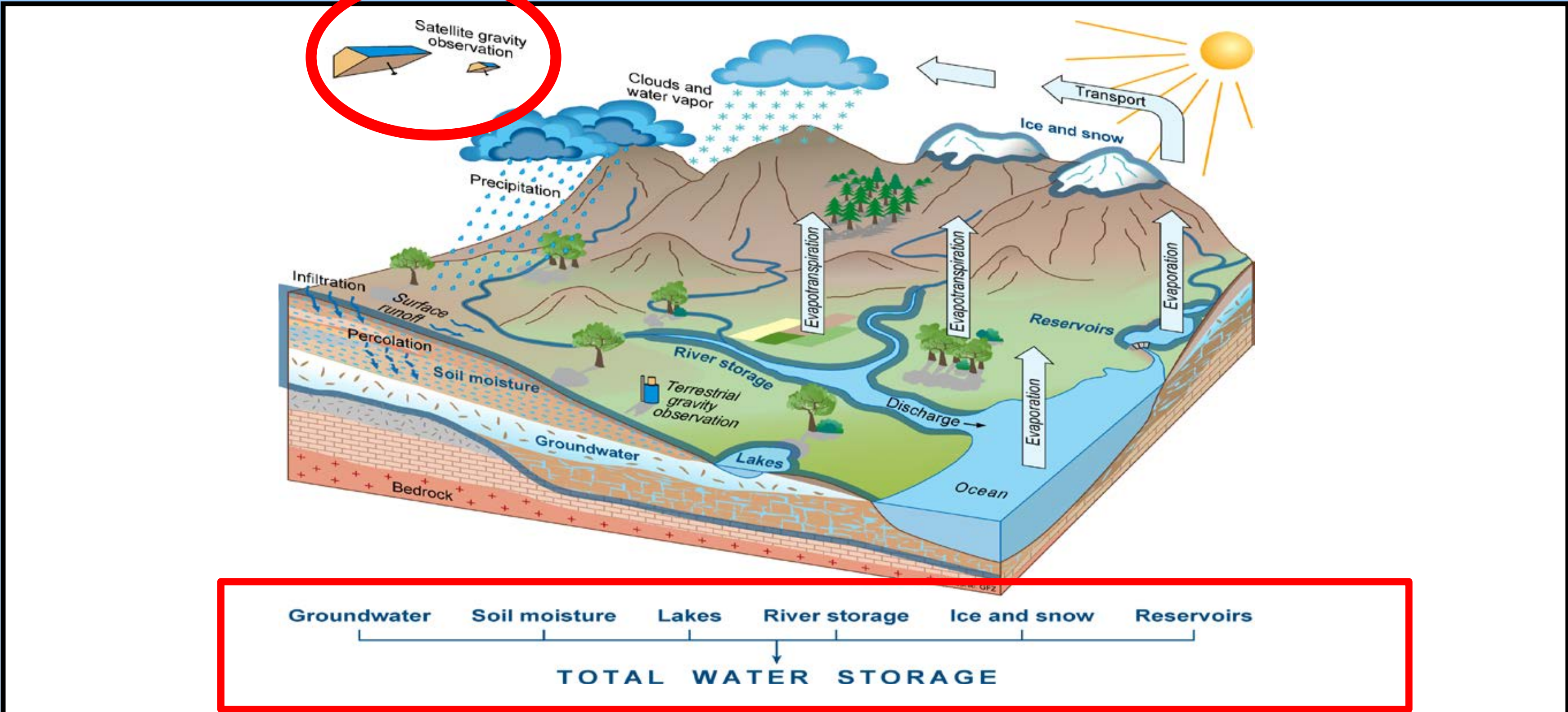
Calibration of hydrological models



Multi-criterial calibration of hydrological models



The global water cycle



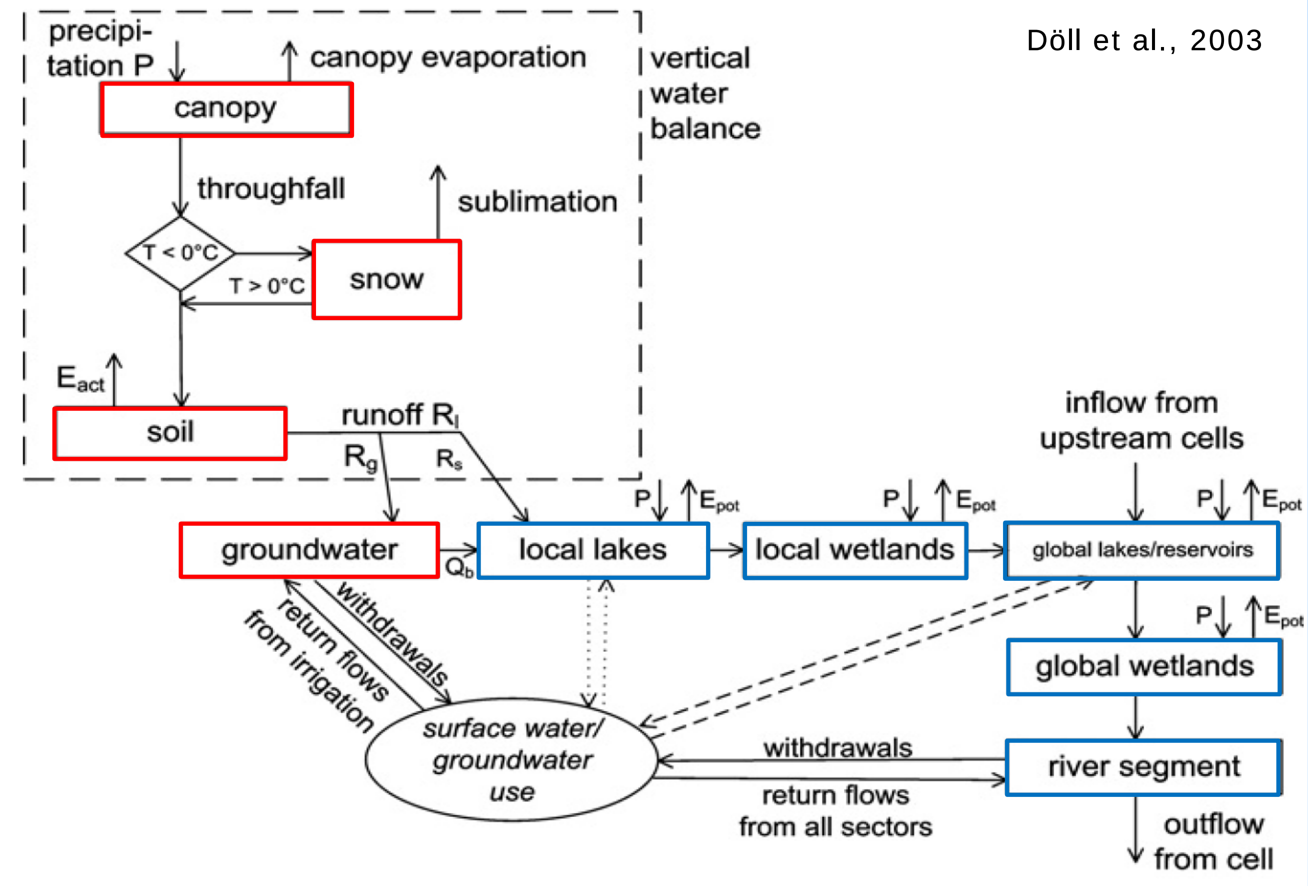
Continental water balance

$$P = AET + Q + \Delta S$$

P: Precipitation
AET: Evapotranspiration
Q: Runoff
ΔS: Storage change

Structure of large-scale hydrological models

WaterGAP global hydrology model (WGHM) (0.5° resolution)



Total continental water storage change

$\Delta S = \Delta S_{canopy} + \Delta S_{snow} + \Delta S_{soil} + \Delta S_{gw} + \Delta S_{lakes} + \Delta S_{wetl} + \Delta S_{river}$

Large-scale models of continental hydrology

1) WaterGAP Global Hydrology model (WGHM)

Total continental water storage change ΔS :

$$\Delta S = \Delta S_{canopy} + \Delta S_{snow} + \Delta S_{soil} + \Delta S_{groundwater} + \Delta S_{rivers} + \Delta S_{lakes/reservoirs} + \Delta S_{wetlands}$$

Soil depth = root zone

2) Land Dynamics (LaD) World

$$\Delta S = \Delta S_{snow} + \Delta S_{soil} + \Delta S_{groundwater}$$

Soil depth = root zone

3) Global Land Data Assimilation System (GLDAS)

$$\Delta S = \Delta S_{canopy} + \Delta S_{snow} + \Delta S_{soil}$$

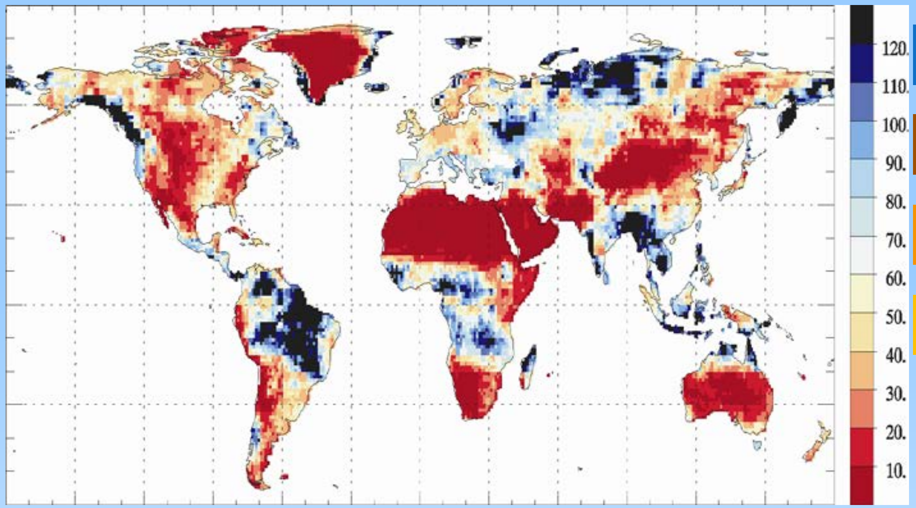
Soil depth	GLDAS-CLM	= 3.43m
	GLDAS-Mosaic	= 3.50m
	GLDAS-Noah	= 2.00m
	GLDAS-VIC	= 1.90m

Large-scale models of continental hydrology

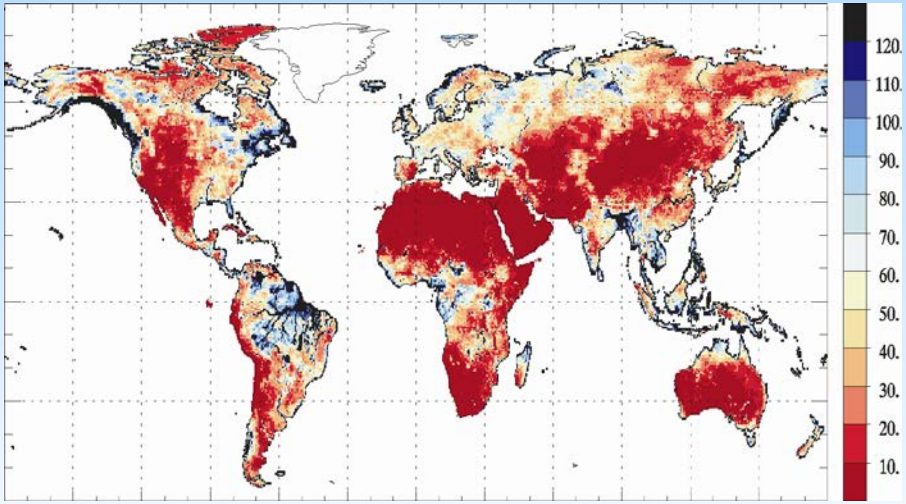
Variations of continental water storage

RMS variability of monthly values around annual mean for 2004
(in mm w.eq.)

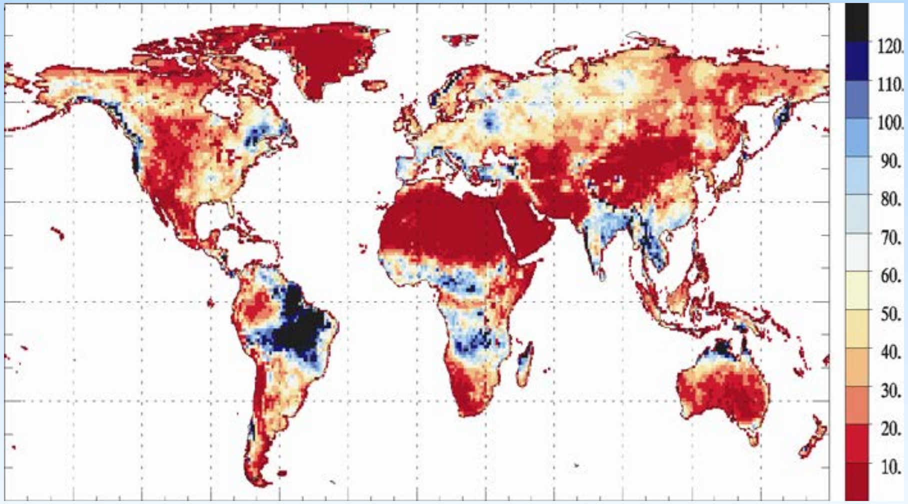
LaD



WGHM



GLDAS-Noah



Multi-criterial calibration of hydrological models

Water balance of a river basin :

Traditional calibration variable

$$P = E + Q + \Delta S$$

Additional calibration variable

P: Precipitation

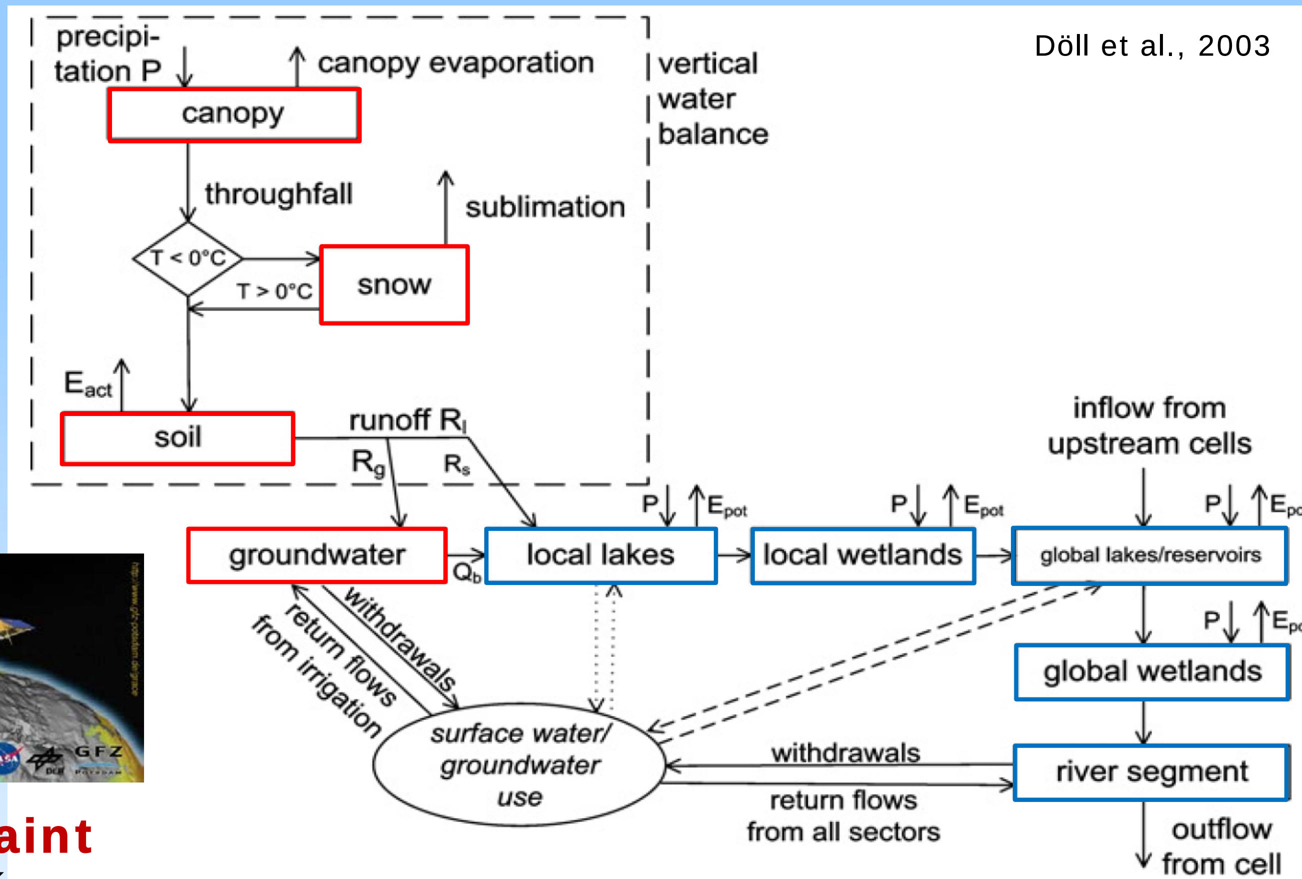
E: Evapotranspiration

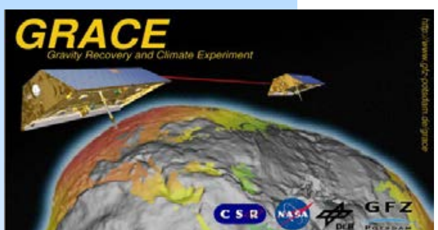
Q: Runoff (**measured time series of river discharge**)

ΔS: Water storage change (**basin-average values from GRACE**)

Multi-criterial calibration of hydrological models

WaterGAP global hydrology model (WGHM) (0.5° resolution)





Constraint

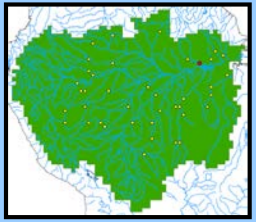
Total continental water storage change

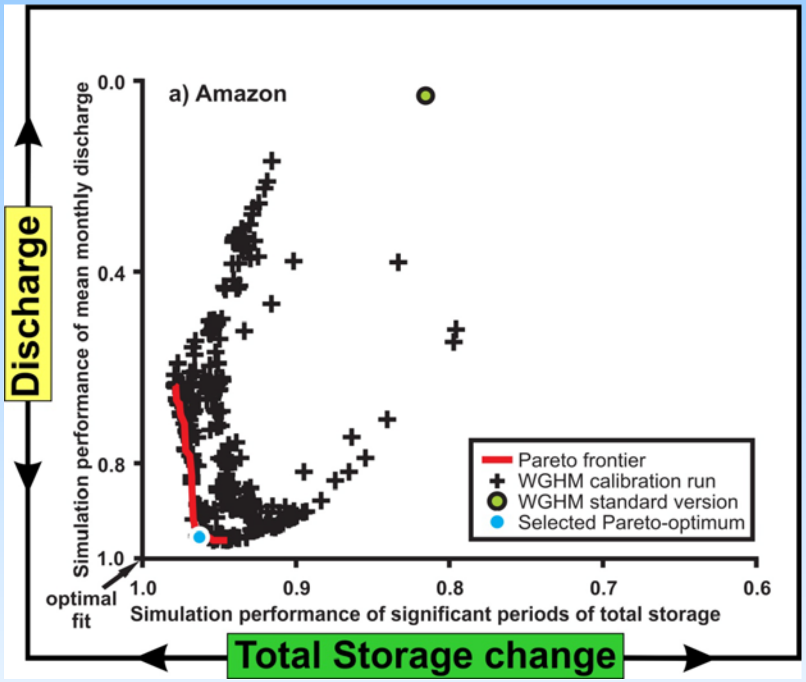
$$\Delta S = \Delta S_{canopy} + \Delta S_{snow} + \Delta S_{soil} + \Delta S_{gw} + \Delta S_{lakes} + \Delta S_{wetl} + \Delta S_{river}$$

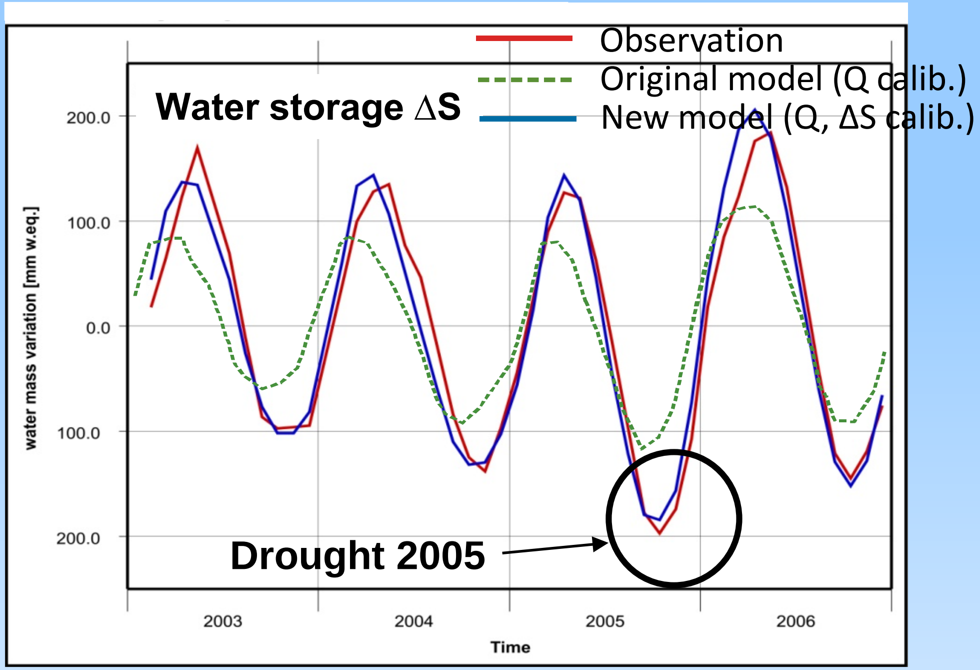
Multi-criterial calibration of hydrological models

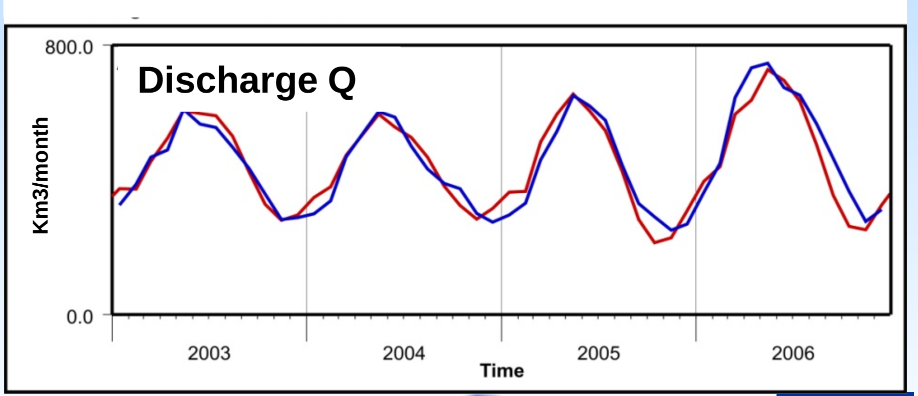
WaterGAP global hydrology model (WGHM) (0.5° resolution)

Example: Amazon basin









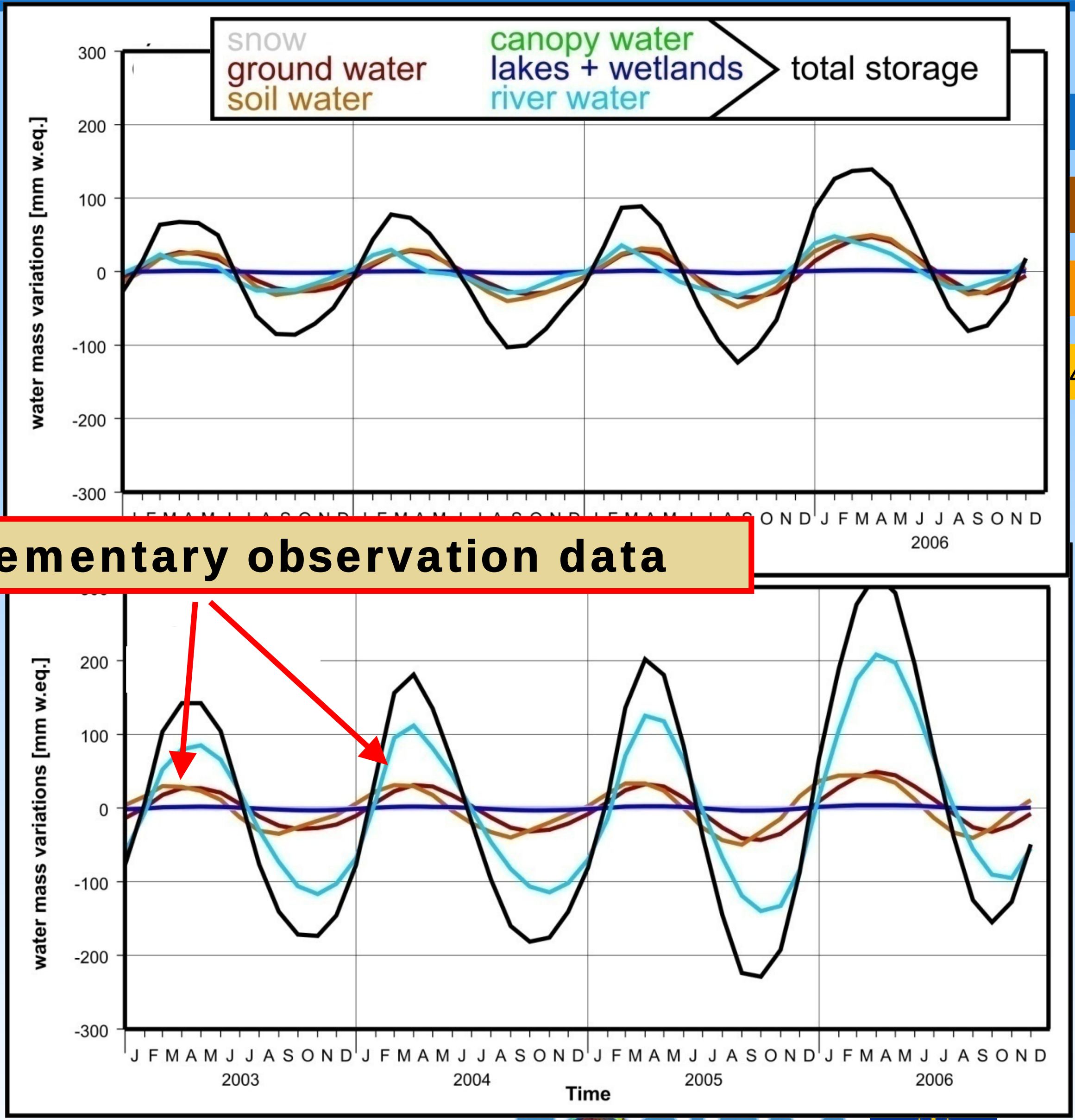
Werth et al. (2009), EPSL

Multi-criterial calibration of hydrological models

Example: Amazon basin

Original model

Calibrated model



Evaluate by complementary observation data

Werth & Güntner (2010), HESS

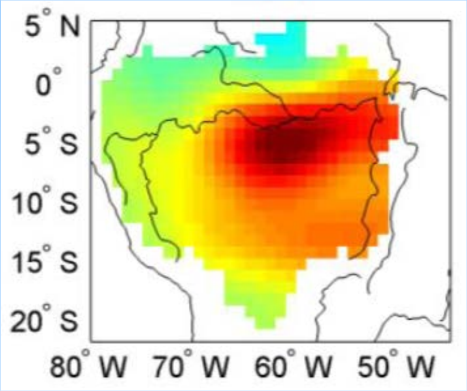
GFZ Helmholtz Centre Potsdam

EGSIEM European Gravity Service for Improved Emergency Management

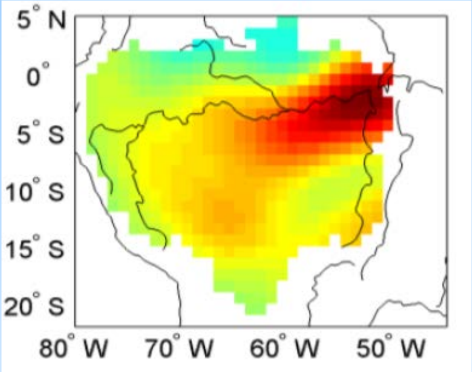
Multi-criterial calibration of hydrological models

Evaluation of spatio-temporal patterns of total water storage

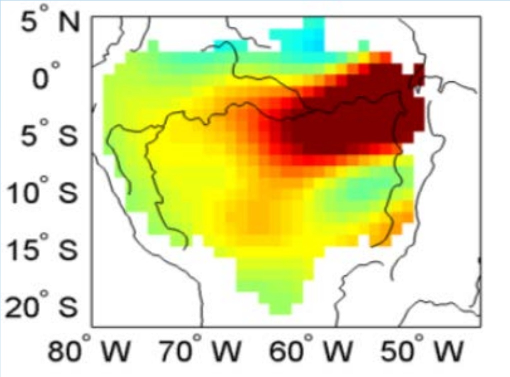
GRACE
(GRGS solution)

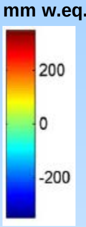


Original WGHM
(River flow velocity 1.0 m/s)



WGHM after multi-criterial calibration with GRACE and discharge time series
(River flow velocity 0.3 m/s)



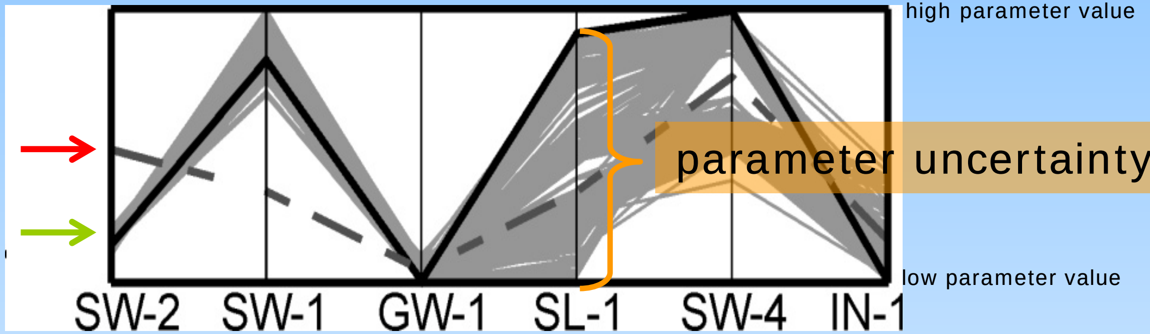


	Original WGHM	WGHM after multi-criterial calibration
Spatial correlation of 1st EOF between GRACE and WGHM	**0.82**	**0.69**

de Linage et al. (2009), AGU

Multi-criterial calibration of hydrological models

Example Amazon basin: Calibration results – parameter values



original

calibrated

River flow velocity

HBV gamma
(runoff coefficient)

Baseflow coefficient

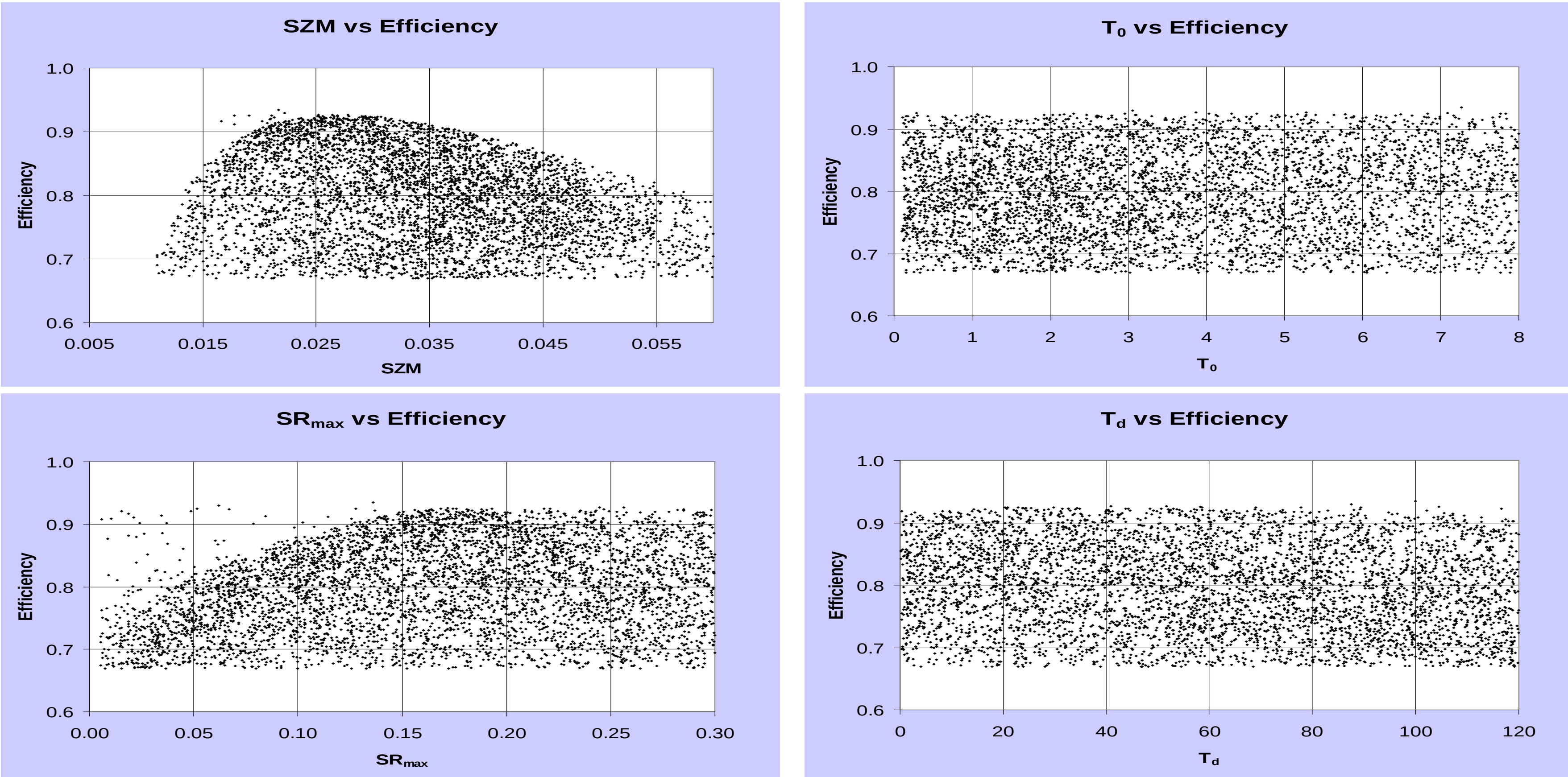
Root depth

Wetland depth

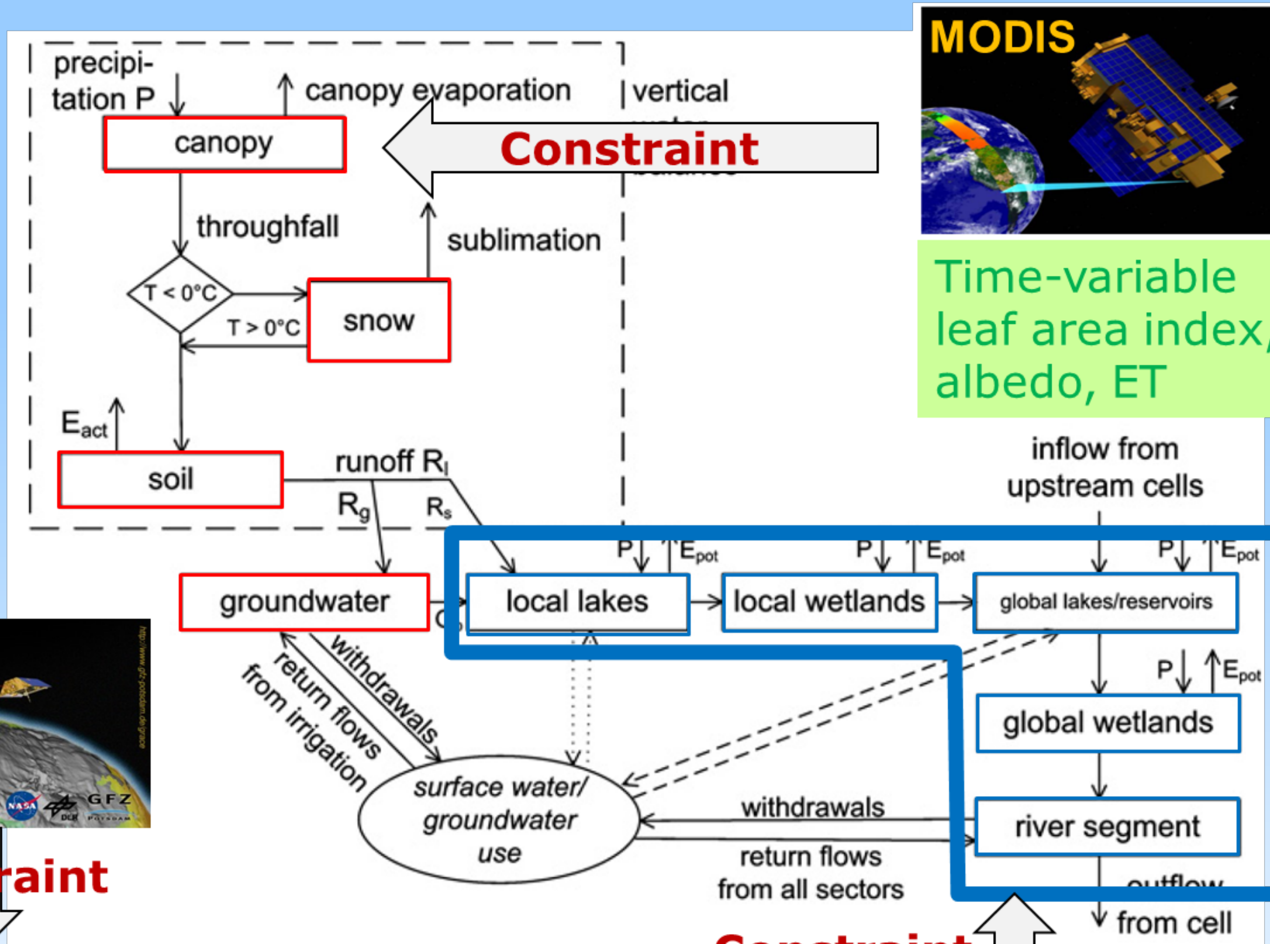
Interception
storage capacity

Calibration of hydrological models

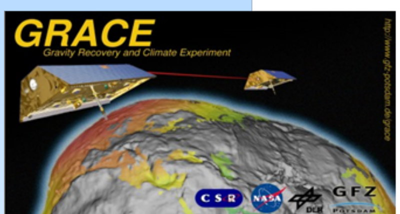
Parameter uncertainty – parameter equifinality



Multi-criterial calibration of hydrological models



Time-variable leaf area index, albedo, ET



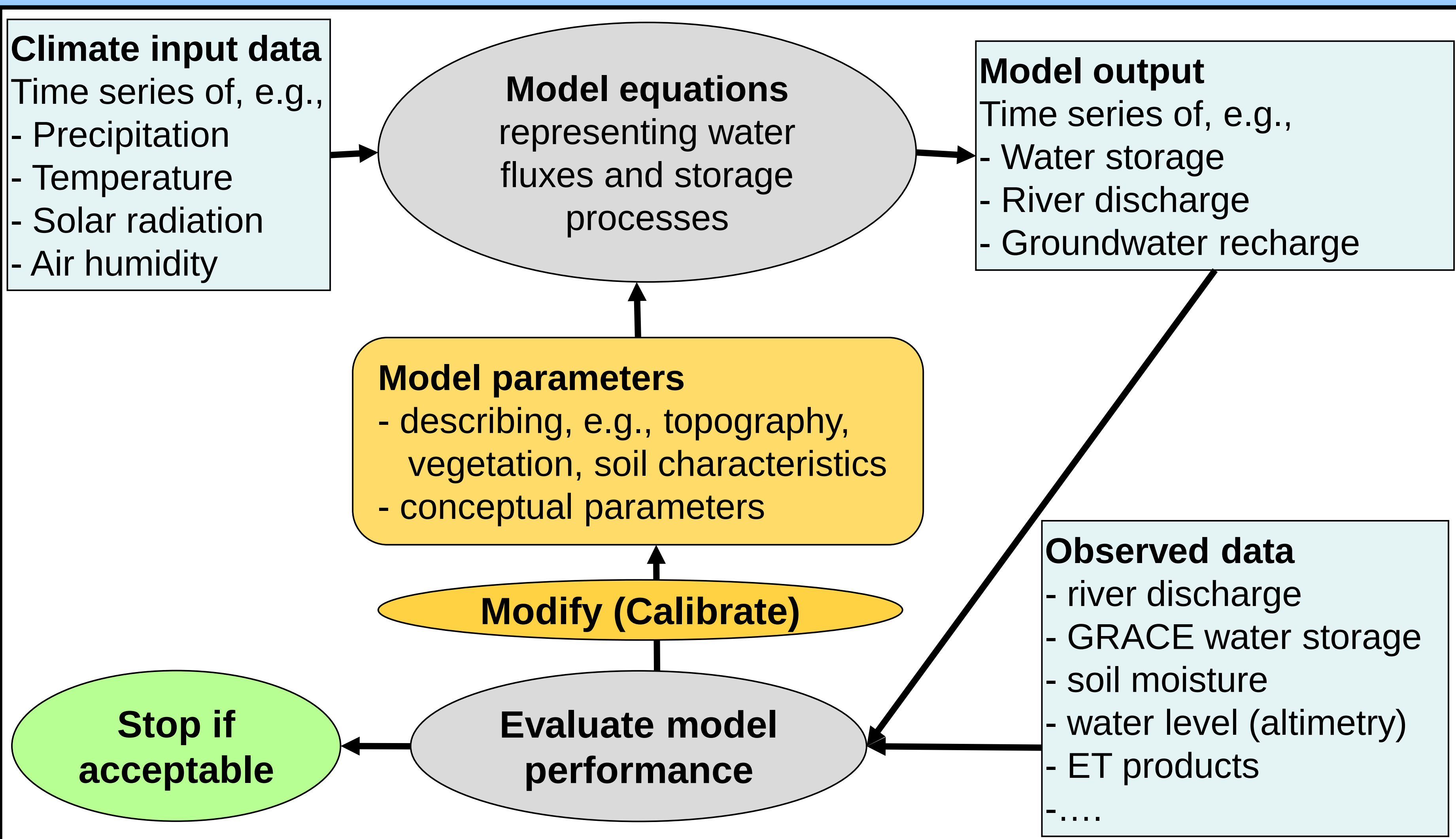
Constraint

ΔS (total)

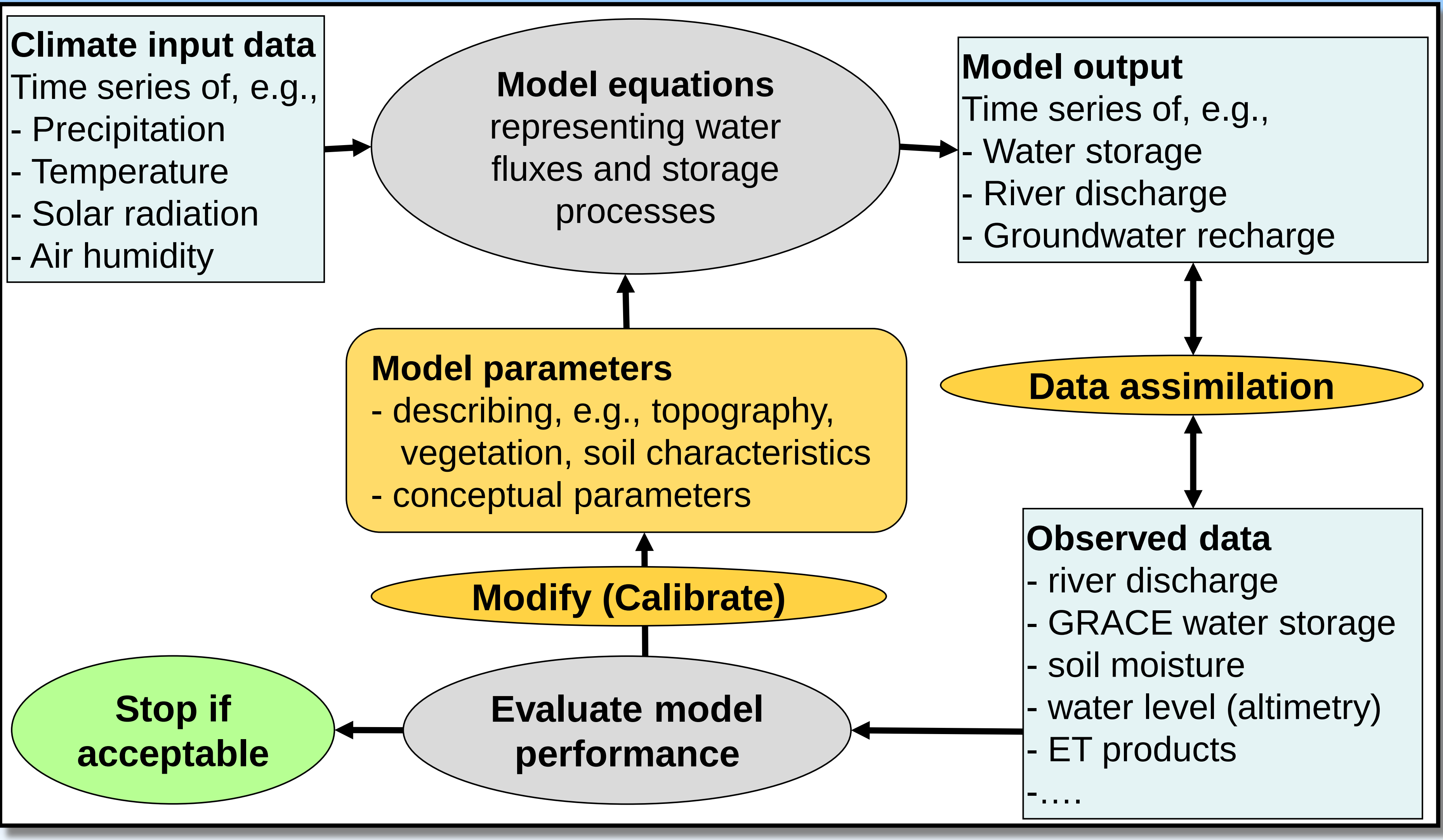
Constraint

Surface water storage from multiple satellite products (optical, radar, altimetry)

Multi-criterial calibration of hydrological models



Multi-criterial calibration of hydrological models



Lessons learned

- Models are a simplified representation of reality and are set up for a particular purpose (→ check adequacy for your particular application!)
- Large-scale hydrological models usually need calibration (parameters are conceptual and/or not measurable at the model scale)
- Large uncertainties / differences in simulation results of global hydrological models → try to use multi-model ensembles
- Reduce parameter uncertainty / equifinality and improve internal process representation (the model should do the right thing for the right reason) by → multi-criterial model calibration

Literature:

General introduction to hydrological modelling:

Beven, Keith J. (2012): Rainfall-Runoff Modelling: The Primer. Wiley-Blackwell.

Multi-criterial calibration with GRACE data:

Werth, S. & Güntner, A. (2010): Calibration analysis for water storage variability of the global hydrological model WGHM. Hydrology and Earth System Sciences, 14, 59–78.

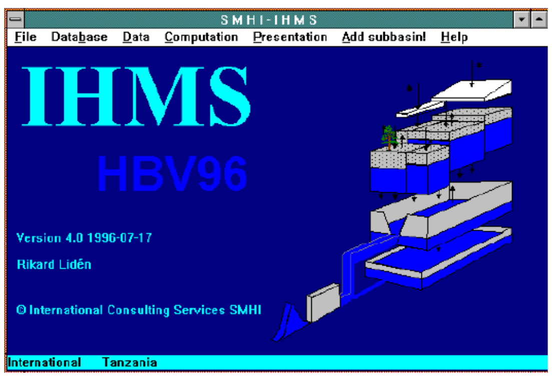
Modeling the hydrological cycle
- Practical -

Andreas Güntner

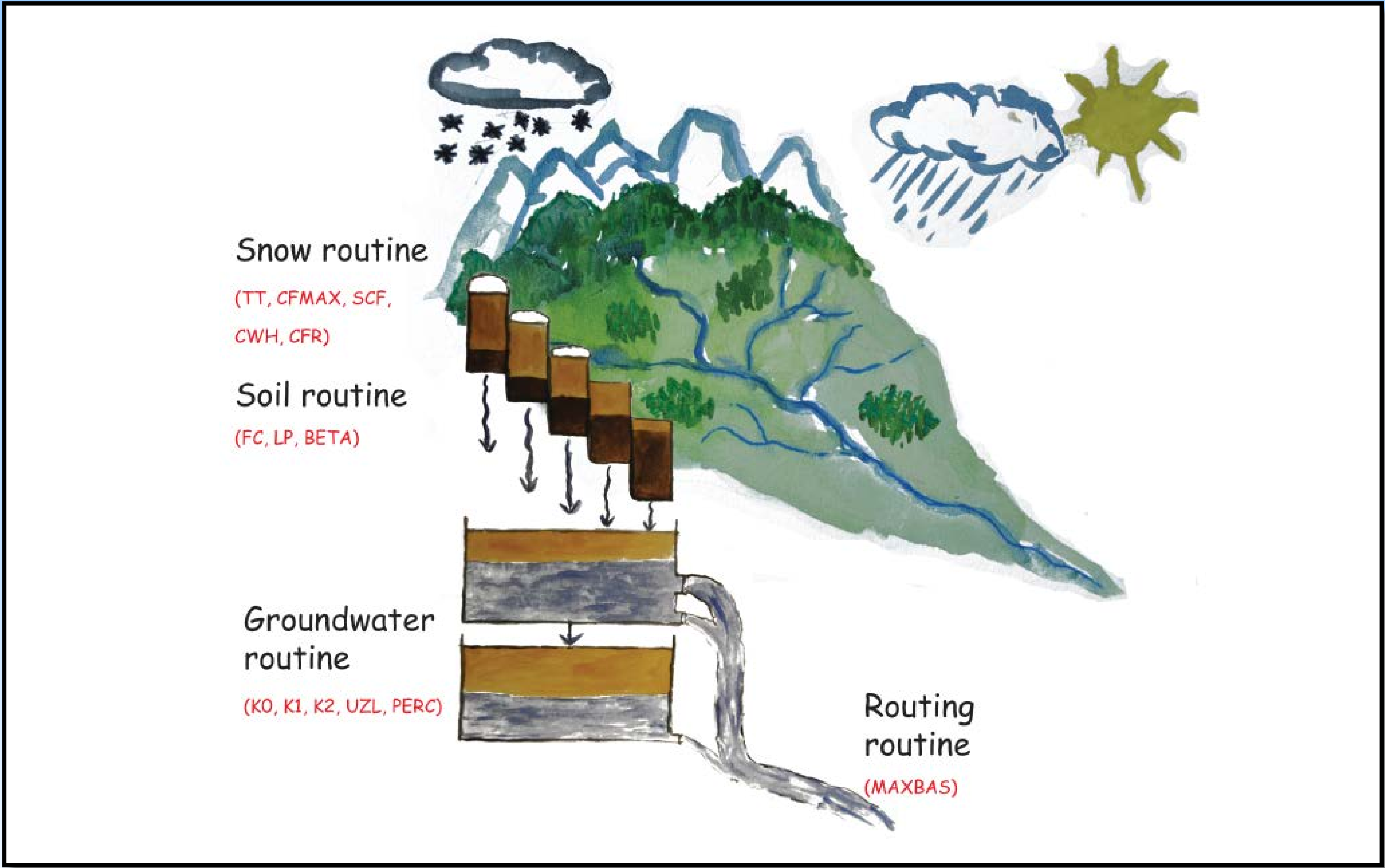
The EGSIEM Autumn School
for Satellite Gravimetry Applications
11.-15. September 2017
Potsdam

The HBV model

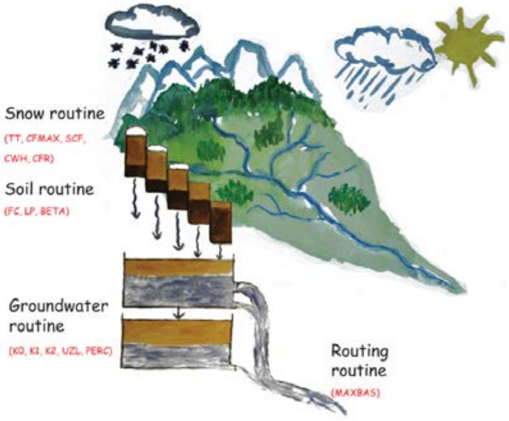
- Developed by Sten Bergström at the Swedish Meteorological and Hydrological Institute (SMHI) (Bergström 1976)
- Since then, numerous model variants have been developed, with a huge number of applications worldwide
- HBV is a conceptual, lumped/semi-distributed hydrological model for runoff (river discharge) and catchment water balance simulations



HBV model structure



Snow routine I

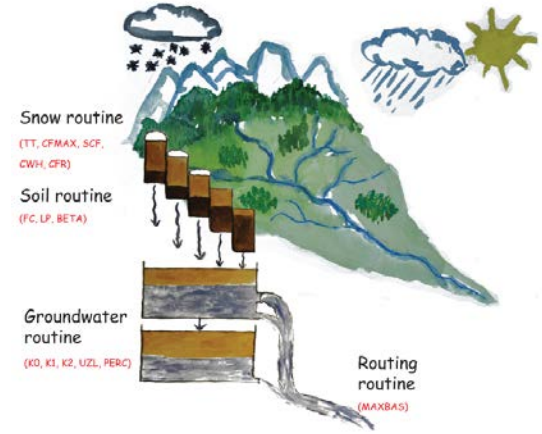


- Accumulation of precipitation as snow if air temperature *T* < threshold temperature *TT* (*TT* is close to 0°C)
- All precipitation which is simulated to be snow is multiplied by a correction factor *SFCF* [-]
- **Degree-day method** for snowmelt *M* :
  $M = CFMAX * (T-TT)$ [mm d^{-1}]

  CFMAX degree-day factor [mm d^{-1} °C^{-1}]

  CFMAX typically around 4 mm d^{-1} °C^{-1}, lower values for forested areas compared to open areas

Snow routine II

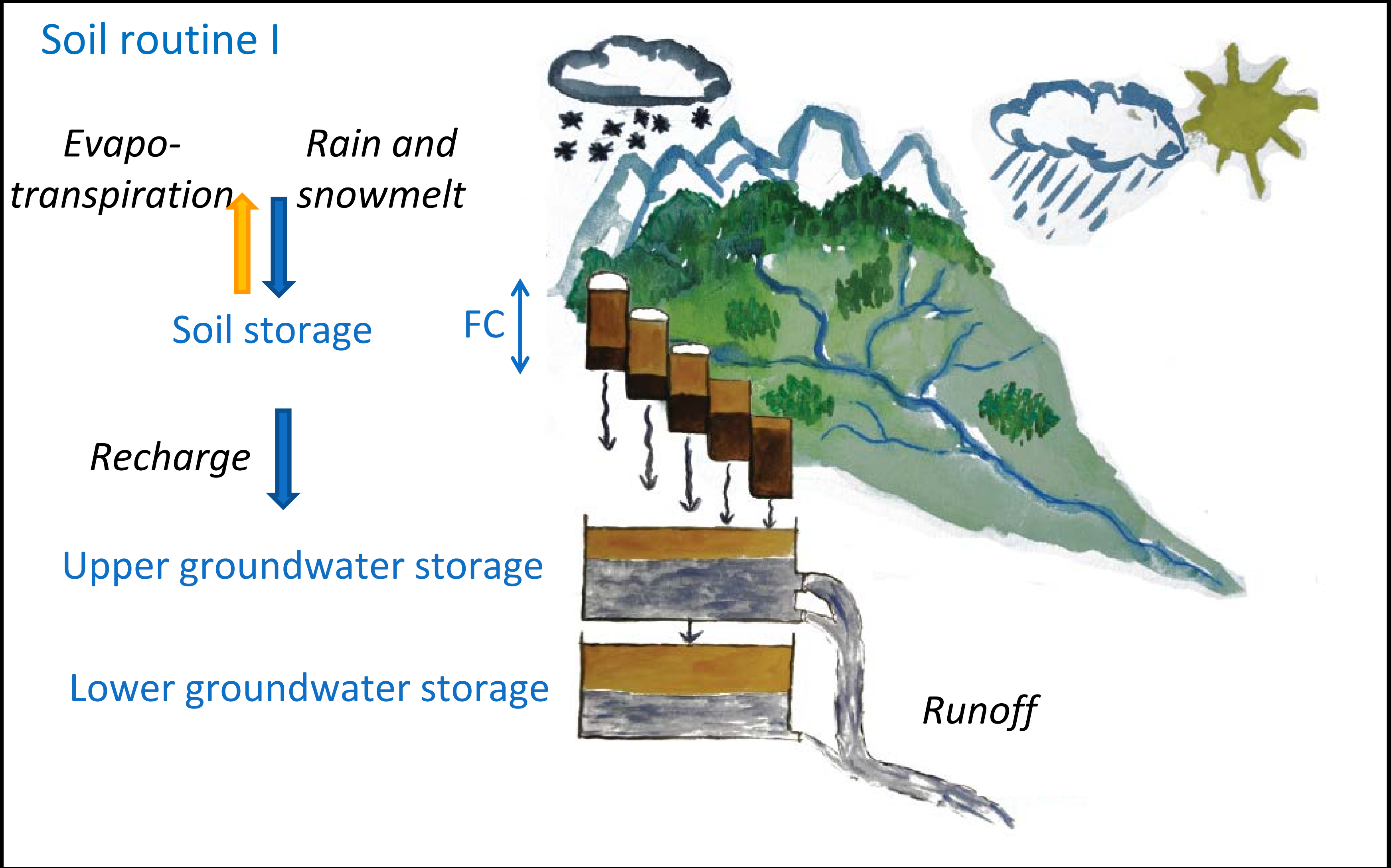


- Snow pack retains melt water until amount exceeds a certain portion *CWH* (usually 0.1) of the water equivalent of the snow pack.

- When air temperatures decreases below *TT*, liquid water in the snowpack refreezes again
  $M = CFR * CFMAX * (TT - T)$ [mm h^{-1}]
  CFR = ~ 0.05 [-]

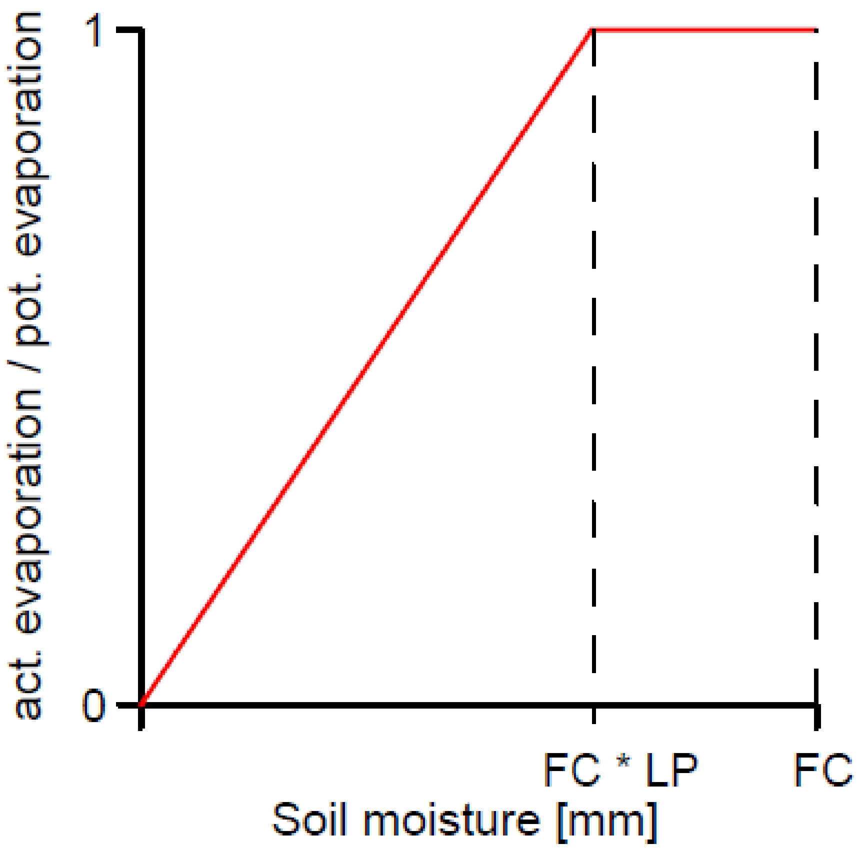
HBV model equations

Soil routine I



HBV model equations

Soil routine II

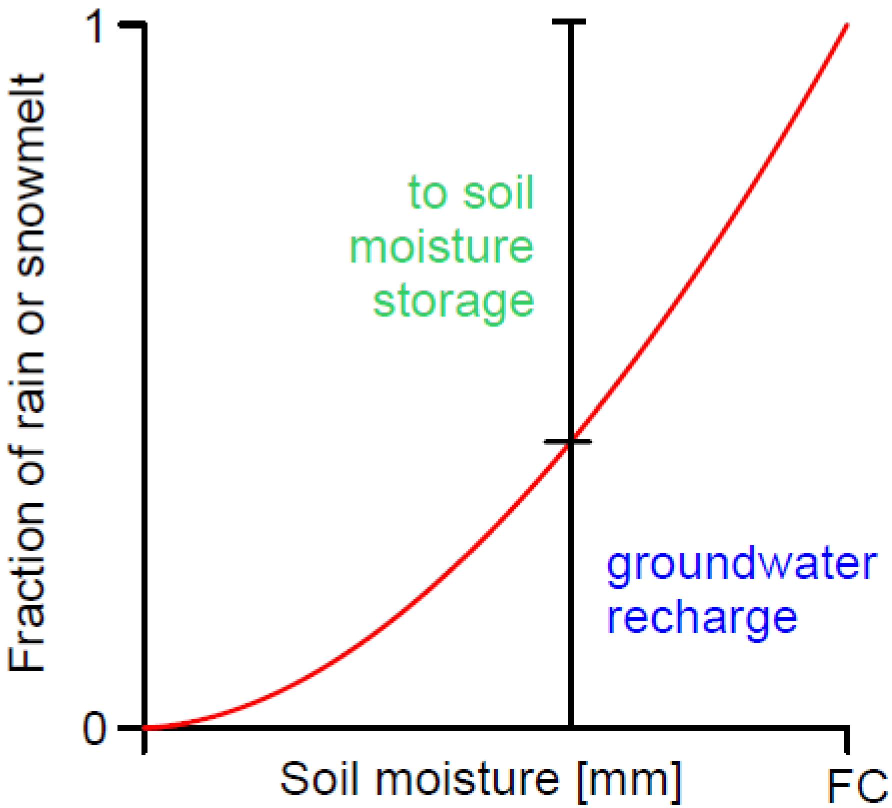


- *FC* : soil moisture storage capacity [mm]
- *LP* : factor defining when actual evapotranspiration is reduced for soil moisture below maximum [-]

Soil routine III

$$\frac{\text{Recharge}}{\text{Rain} + \text{Snowmelt}} = \left(\frac{SM}{FC}\right)^{BETA}$$

- *FC* : soil moisture storage capacity [mm]
- *BETA*: shape parameter [-]



HBV model equations

Soil routine I

Evapo-transpiration

Rain and snowmelt

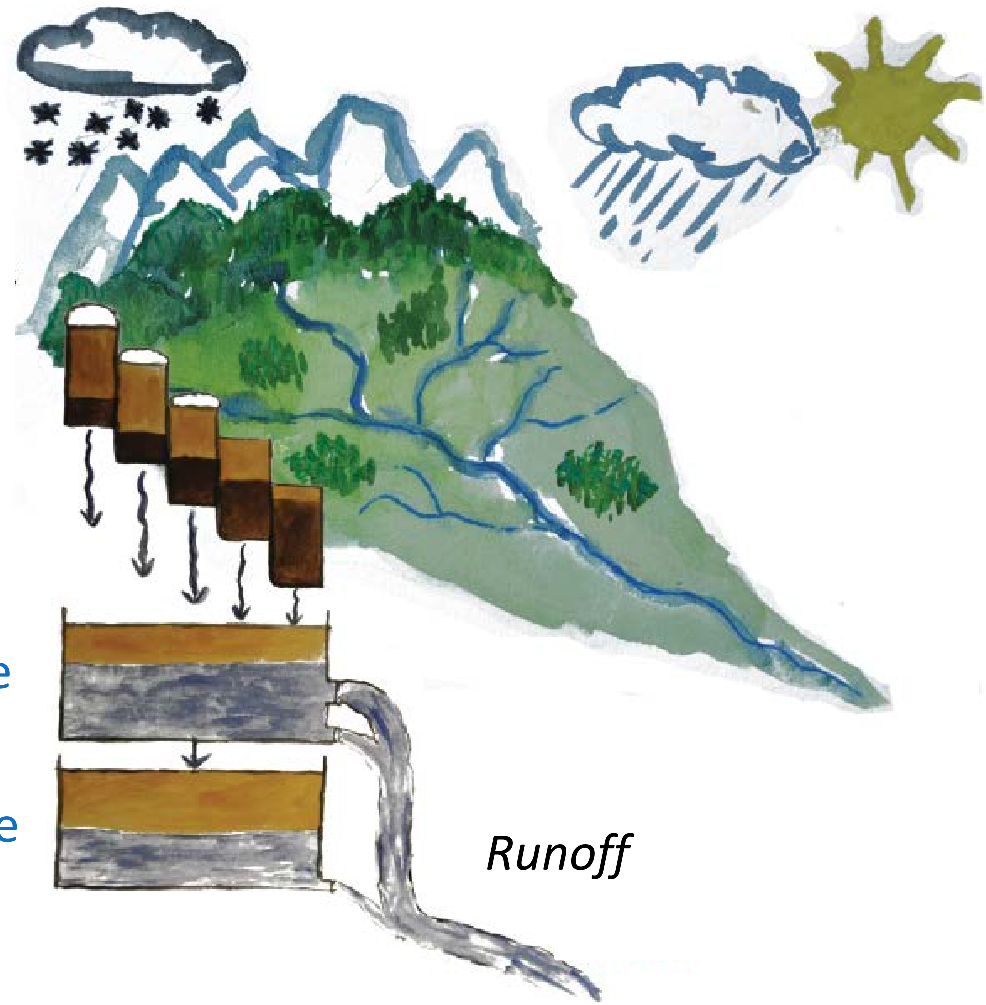
Soil storage

FC

Recharge

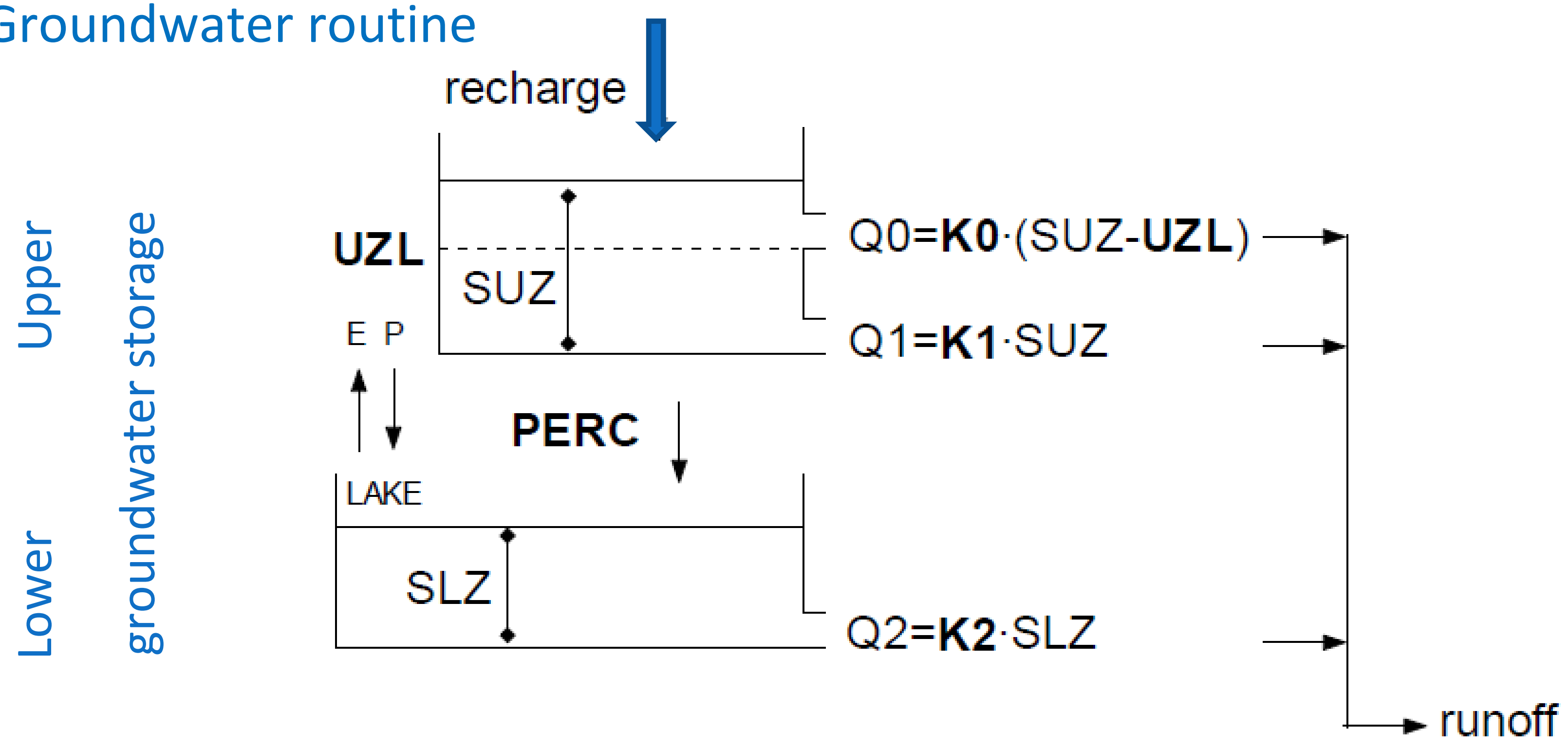
Upper groundwater storage

Lower groundwater storage



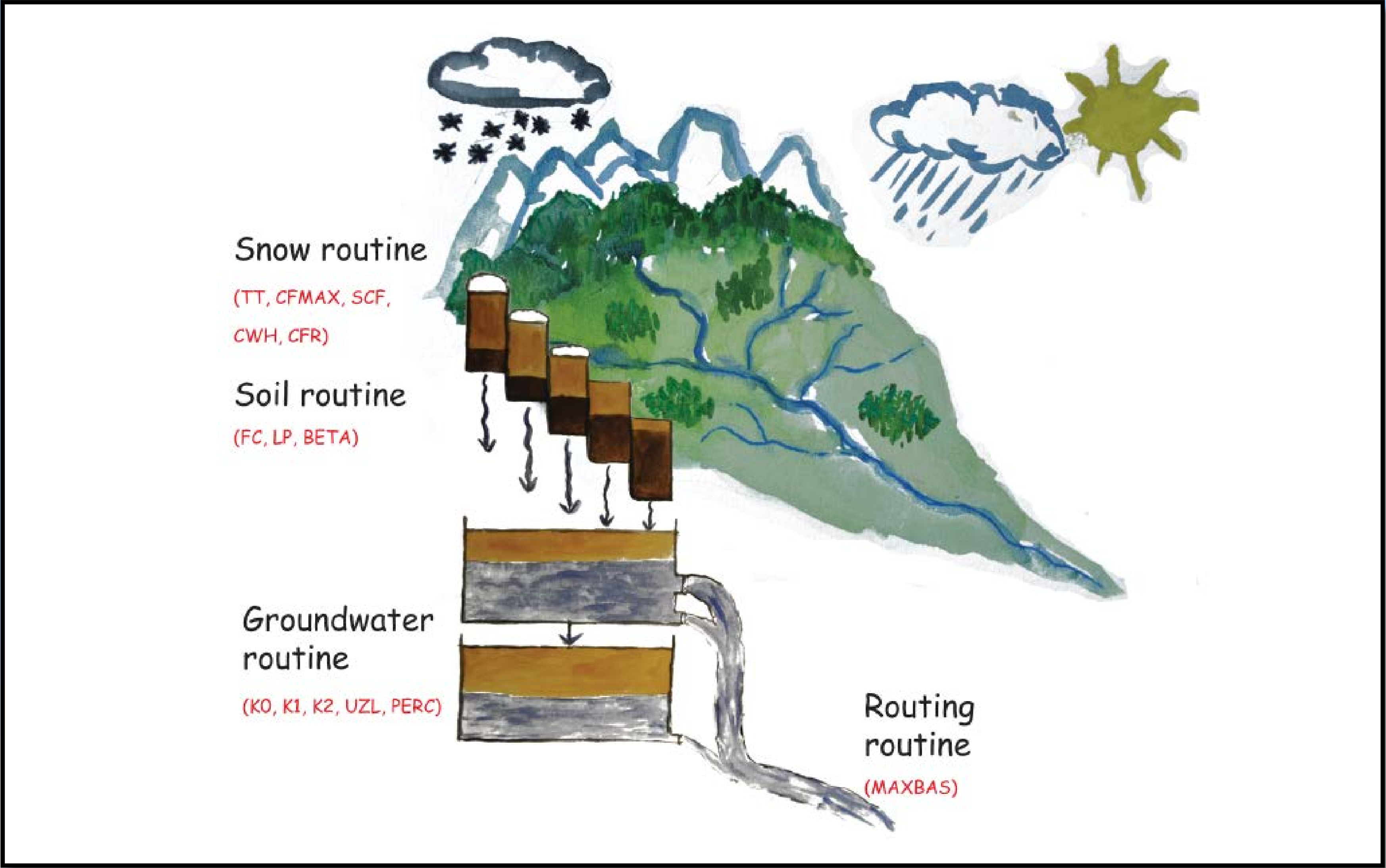
HBV model equations

Groundwater routine



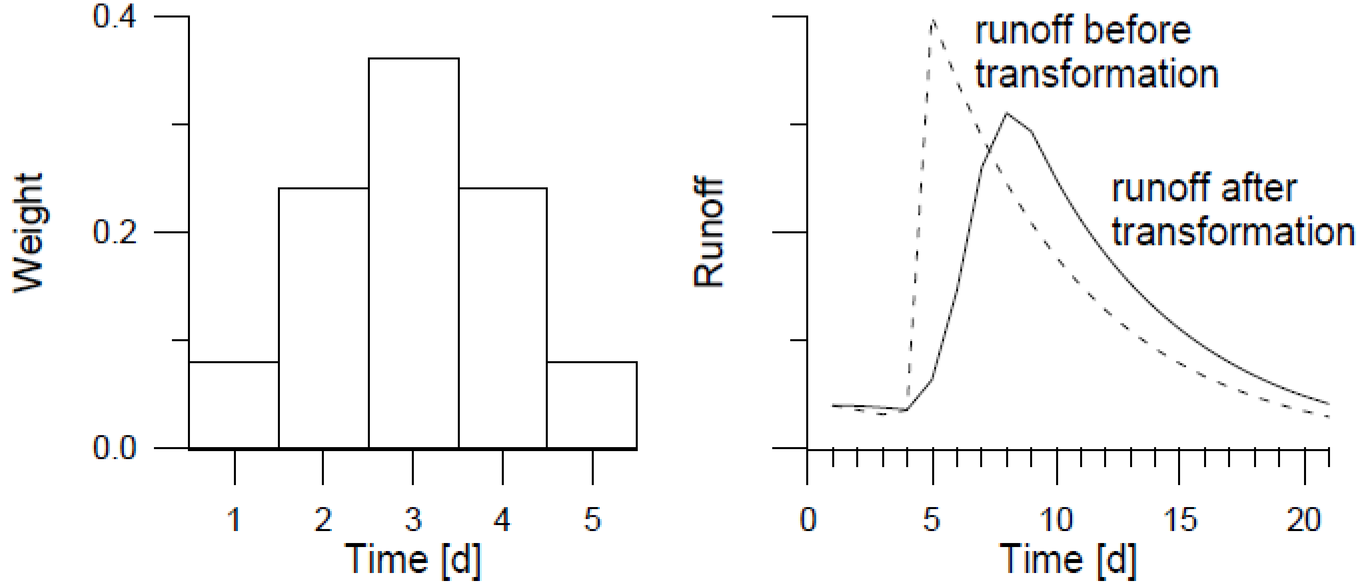
- *K0, K1, K2* Storage coefficients [d^{-1}]
- *PERC* maximum percolation rate from upper to lower GW [mm d^{-1}]
- *UZL* threshold storage value for generation of fast runoff [mm]

HBV model structure



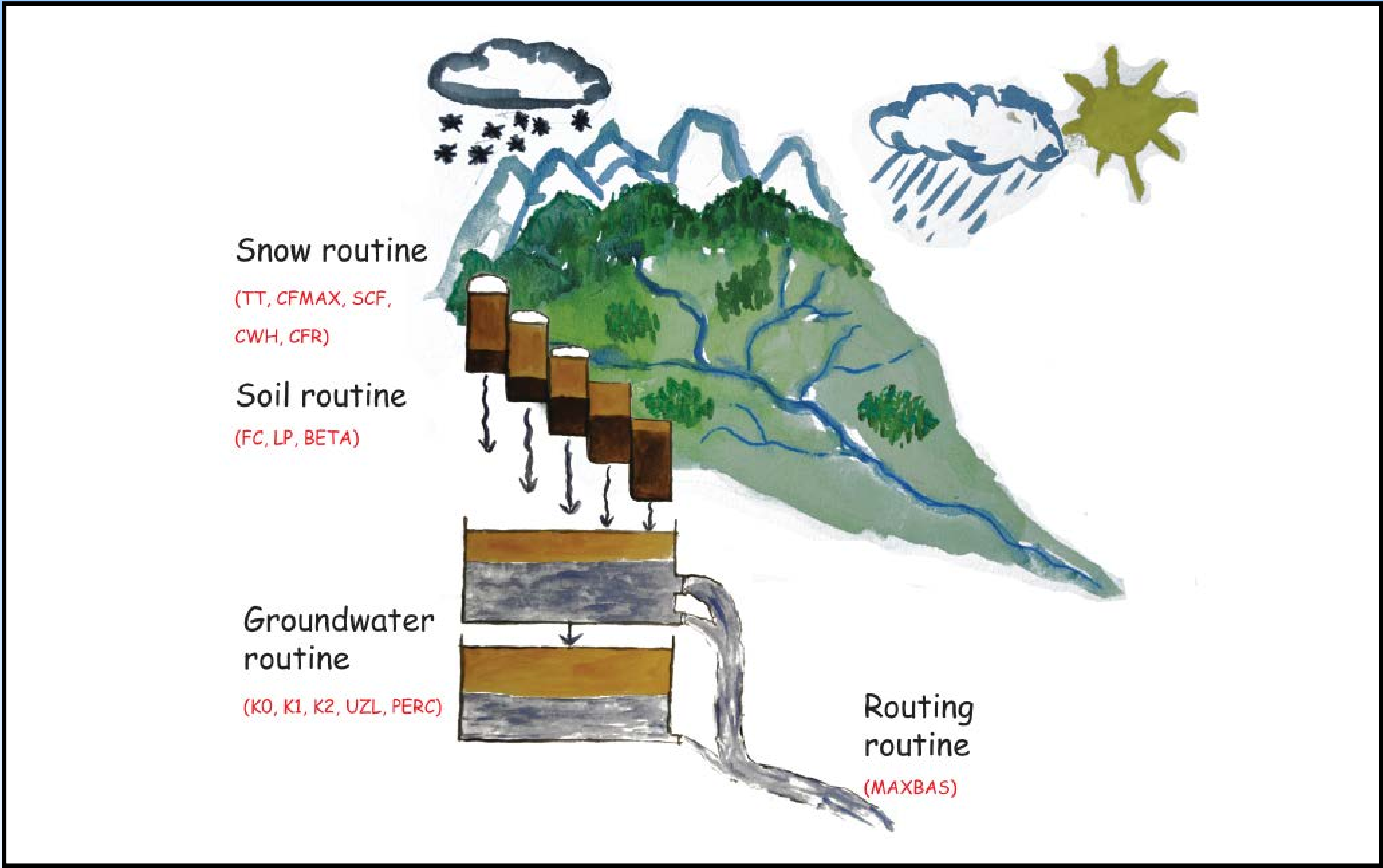
HBV model equations

Routing routine



- *MAXBAS* Parameter that represents the length of the equilateral triangular weighting function [d]

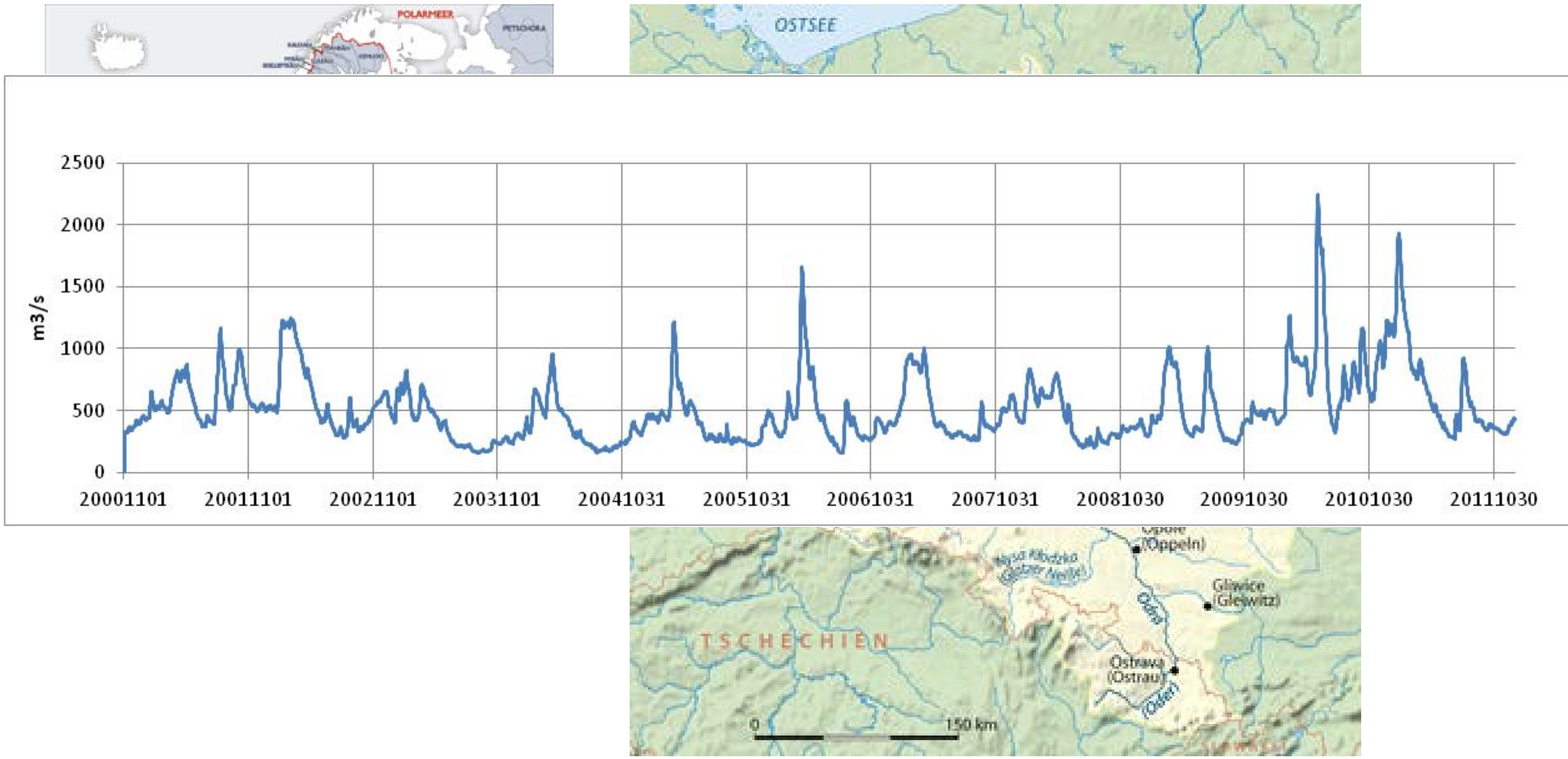
HBV model structure



Application of the HBV model for the Odra river basin

- Gauging station Hohensaaten-Finow (catchment area 109560 km²)

- River discharge Gauging station Hohensaaten Finow (2000-2011)



Exercise 1

Calibration of HBV, period 2000-2011

- Select catchment / folder Odra
- Model settings: Standard version, use *UZL* and *K0* in SUZ-box
- Select simulation period: hydrological years 11/2001 – 10/2011
- Catchment settings: use 1 elevation zone, 1 vegetation zone
- Keep the following parameters at fixed values:
  CFR=0.05, *CWH*=0.10
- Vary all other parameters to optimize the simulation of
  - the water balance (differences should be close to 0 mm)
  - river discharge time series (using Nash-Sutcliffe model efficiency as performance criteria for discharge)

Exercise 2

Calibration of HBV for selected wet and dry years

- Evaluate the performance of the best parameter set of Exercise 1 for
  - the wet year 11/2010 – 10/2011
  - the dry year 11/2002 – 10/2003

- Recalibrate the model for
  - the wet year (model efficiency as performance critieria)
  - the dry year (model efficiency of logQ as performance critieria)

- Compare and discuss the resulting parameter sets

- For the different optimal parameter sets, discuss the respective runoff and storage dynamics (e.g., contribution of different storage compartments to Q, characteristics of storage variability)

Exercise 3

Parameter sensitivity / uncertainty

- For the entire simulation period (and/or dry or wet years), run Monte Carlo simulations:
- Define adequate parameter ranges based on experience of previous exercises
- Make Monte Carlo runs by varying individual parameters separately, or several parameters at the same time
- Make 'dotty plots' (parameter values versus preformance criterion), discuss parameter sensitivities. Which parameters can be reasonably constrained?

Reference for HBV-light and modelling exercises:

- Prof. Jan Seibert,
  Department of Geography, University of Zurich, Switzerland

- Seibert, J. & Vis, M. J. P. (2012): Teaching hydrological modeling with a user-friendly catchment-runoff-model software package. Hydrology and Earth System Sciences (HESS), 16, 3315–3325.