Modeling the hydrological cycle
- Lecture -

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The EGSIEIM 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
- **\( \Delta S \)**: Storage change
Hydrological processes

Saturation area  Ridge  Debris

Löhnersbach, Salzburger Land, Austria
Spatial and temporal scales in hydrological modelling

- **Physically-based field-scale to catchment models**
- **Global hydrological model**
- **Land-surface models**

- **Flood prediction models**
- **Water balance / water resources models**

- **silt aquifers**
- **clay aquifers**
- **sand aquifers**
- **unconfined aquifers**
- **confined aquifers**

- **Cumulus convection**
- **Fronts**
- **Umbrella storms**
- **Saturation excess overland flow**
- **Infiltration excess overland flow**
- **Subsurface stormflow**
- **Channel flow**
- **Groundwater**
- **Unsaturated flow**
- **Saturated flow**

- **100 yrs**
- **10 yrs**
- **1 yr**
- **1 mon**
- **1 d**
- **1 h**
- **1 min**

- **10^0**
- **10^1**
- **10^2**
- **10^3**
- **10^4**
- **10^5**
- **10^6**

- **1 m**
- **10 m**
- **100 m**
- **1 km**
- **10 km**
- **100 km**
- **1000 km**
- **10000 km**
What is a hydrological model?

Climate input data
- Time series of, e.g.,
  - Precipitation
  - Temperature
  - Solar radiation
  - Air humidity

Model equations
representing water fluxes and storage processes

Model parameters
- describing, e.g., topography,
  vegetation, soil characteristics
- conceptual parameters

Model output
- Time series of, e.g.,
  - Water storage
  - River discharge
  - Groundwater recharge
Detailed physically-based models
Detailed physically-based models

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

\[
\frac{\partial}{\partial x} \left( k_{xx}(\theta) \cdot \frac{\partial \psi}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_{yy}(\theta) \cdot \frac{\partial \psi}{\partial y} \right) + \frac{\partial}{\partial z} \left( k_{zz}(\theta) \cdot \frac{\partial \psi}{\partial x} + 1 \right) = \frac{\partial \theta}{\partial t} - S
\]
Example: Soil water fluxes

Richards equation assumes a homogeneous porous medium

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

Real-world infiltration pattern in a soil

Physically-based model with macropores
Linear storage (bucket approach)

\[ Q = k \cdot S \]

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

\[ Q_t = Q_0 \exp(-t / k) \]
Hydrograph

Conceptual models
Conceptual models

Hydrograph – Recession period

- Peaks
- Intermediate
- Baseflow

In Q (mm/day)

In Q(T1)

In Q(T2)

time (days)
**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.
Conceptual models

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

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

**Q**  Runoff  
**P**  Precipitation  
**S**  Actual soil water content  
**S_{\text{max}}**  Maximum soil water storage  
**\gamma**  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)*

**Soil water content**

- **Wet conditions in winter**
- **Dry conditions in summer**
Representing spatial variability

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

Variable Infiltration Capacity - Three Layer (VIC-3L) Macroscale Hydrologic Model

Cell Energy and Moisture Fluxes

Grid Cell Vegetation Coverage

Variable Infiltration Curve

Point Infiltration Capacity, $i$

$\frac{b}{1 - (1 - A)^i}$

Mosaic approach

Distribution function

(Beispiel: VIC-Modell)
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
Land Surface Models

- Land surface description in climate models
- Water balance
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- Vertical water fluxes, several soil layers
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Global hydrological models

- Water balance for grid cells / river basins
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- Daily – monthly temporal resolution
- Conceptual process representation
Types of hydrological models

- **Deterministic Models**
  - Black-Box-Models
  - Conceptual Models
  - Physically-based Models

Degree of causality
Types of hydrological models

Spatial discretization

Lumped model

Spatially distributed model

Semi-distributed model
Large-scale models of continental hydrology

WaterMIP (Water Model Intercomparison Project)

- Global Hydrological Model
- Land Surface Hydrological Model
- Vegetation Model

Haddeland et al. 2011, J. Hydrometeor.
Harding et al. 2011, J. Hydrometeor.
### WaterMIP (Water Model Intercomparison Project)

<table>
<thead>
<tr>
<th>Model name</th>
<th>Model time step</th>
<th>Meteorological forcing variables</th>
<th>Energy balance</th>
<th>Evapotranspiration scheme</th>
<th>Runoff scheme</th>
<th>Snow scheme</th>
<th>Reference(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GWAVA</td>
<td>Daily</td>
<td>P, T, W, Q, LWn, SW, SP</td>
<td>No</td>
<td>Penman-Monteith</td>
<td>Saturation excess / Beta function</td>
<td>Degree day</td>
<td>Meigh et al. (1999)</td>
</tr>
<tr>
<td>H08</td>
<td>6 h</td>
<td>R, S, T, W, Q, LW, SW, SP</td>
<td>Yes</td>
<td>Bulk formula</td>
<td>Saturation excess / Beta function</td>
<td>Energy balance</td>
<td>Hanasaki et al. (2008a)</td>
</tr>
<tr>
<td>LPJmL</td>
<td>Daily</td>
<td>P, T, LWn, SW</td>
<td>No</td>
<td>Priestley-Taylor</td>
<td>Saturation excess</td>
<td>Degree day</td>
<td>Bondnert et al. (2007), Rost et al. (2008)</td>
</tr>
<tr>
<td>MPI-HM</td>
<td>Daily</td>
<td>P, T</td>
<td>No</td>
<td>Thornthwaite</td>
<td>Saturation excess / Beta function</td>
<td>Degree day</td>
<td>Hagemann and Gates (2003), Hagemann and Dimmenil (1998)</td>
</tr>
<tr>
<td>VIC</td>
<td>Daily/3 h</td>
<td>P, Tmax, Tmin, W, Q, LW, SW, SP</td>
<td>Snow season</td>
<td>Penman-Monteith</td>
<td>Saturation excess / Beta function</td>
<td>Energy balance</td>
<td>Liang et al. (1994)</td>
</tr>
</tbody>
</table>

**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

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Haddeland et al. 2011, *J. Hydrometeor.*
Large-scale models of continental hydrology

WaterMIP (Water Model Intercomparison Project)

Global simulation results (mean annual values 1985-1999)

What is a hydrological model?

Climate input data
- Time series of, e.g.,
  - Precipitation
  - Temperature
  - Solar radiation
  - Air humidity

Model equations
- representing water fluxes and storage processes

Model parameters
- describing, e.g., topography, vegetation, soil characteristics
- conceptual parameters

Model output
- Time series of, e.g.,
  - Water storage
  - River discharge
  - Groundwater recharge
### Vegetation parameters (partly time-variable)
- Leaf area index
- Albedo
- Interception storage capacity
- Stomata resistance
- Aerodynamic roughness
- Canopy height
- 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
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
Climate input data
Time series of, e.g.,
- Precipitation
- Temperature
- Solar radiation
- Air humidity

Model input data

Model equations
representing water
fluxes and storage
processes

Model parameters
- describing, e.g., topography,
  vegetation, soil characteristics
- conceptual parameters

Modify (Calibrate)

Evaluate model
performance

Stop if
acceptable

Model output
Time series of, e.g.,
- Water storage
- River discharge
- Groundwater recharge

Observed data

Calibration of hydrological models
Water balance of a river basin:

\[ P = E + Q + \Delta S \]

- **P**: Precipitation
- **E**: Evapotranspiration
- **Q**: Runoff (measured time series of river discharge)
- **\( \Delta S \)**: Water storage change

Model input

Simulated in the model based on meteorological input data

Traditional calibration variable
Calibration of hydrological models

Water balance of a river basin:

\[ P = E + Q + \Delta S \]

- **P**: Precipitation
- **E**: Evapotranspiration
- **Q**: Runoff (measured time series of river discharge)
- **\Delta S**: Water storage change

Model input:

Traditional calibration variable

Simulated in the model based on meteorological input data
Calibration of hydrological models

River discharge at Hainburg, Austria (Danube river, basin area 104 000 km²)
Calibration of hydrological models – Performance criteria

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

\[ \text{Nash–Sutcliffe efficiency} = 1 - \frac{1}{\frac{1}{n} \sum_{t=1}^{n} (O_t - P_t)^2} \]

\[ \text{logEff} = 1 - \frac{\frac{1}{n} \sum_{t=1}^{n} (\log O_t - \log P_t)^2}{\frac{1}{n} \sum_{t=1}^{n} (\log O_t - \log \bar{O})^2} \]

Efficiency values \([-\infty;1]\]
1: optimal fit
0: model is not better than the mean of the observations

\[ P_t \quad \text{simulated discharge at time t} \]
\[ O_t \quad \text{observed discharge at time t} \]
\[ n \quad \text{number of observations (time steps)} \]
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.
Climate input data
- Precipitation
- Temperature
- Solar radiation
- Air humidity

Model equations
representing water fluxes and storage processes

Model parameters
- describing, e.g., topography, vegetation, soil characteristics
- conceptual parameters

Model output
- Water storage
- River discharge
- Groundwater recharge

Model equations

Modify (Calibrate)

Evaluate model performance

Observed data
usually river discharge

Stop if acceptable
Calibration of hydrological models

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

Simulated basin-average soil moisture for the two model versions

(Data from Merz & Blöschl, TU Wien)
Calibration of hydrological models

Climate input data
Time series of, e.g.,
- Precipitation
- Temperature
- Solar radiation
- Air humidity

Model equations
Representing water fluxes and storage processes

Model parameters
- Describing, e.g., topography, vegetation, soil characteristics
- Conceptual parameters

Modify (Calibrate)

Evaluate model performance

Model output
Time series of, e.g.,
- Water storage
- River discharge
- Groundwater recharge

Observed data
Usually river discharge

Stop if acceptable
Climate input data
- Precipitation
- Temperature
- Solar radiation
- Air humidity

Model input data
- Water storage
- River discharge
- Groundwater recharge

Model output
- Water storage
- River discharge
- Groundwater recharge

Model parameters
- Describing, e.g., topography, vegetation, soil characteristics
- Conceptual parameters

Model equations
- Representing water fluxes and storage processes

Evaluate model performance

Modify (Calibrate)

Stop if acceptable

Observed data
- River discharge
- GRACE water storage

Multi-criterial calibration of hydrological models
The global water cycle

Continental water balance

P = AET + Q + ΔS

P: Precipitation
AET: Evapotranspiration
Q: Runoff
ΔS: Storage change
Total continental water storage change

\[ \Delta S = \Delta S_{\text{canopy}} + \Delta S_{\text{snow}} + \Delta S_{\text{soil}} + \Delta S_{\text{gw}} + \Delta S_{\text{lakes}} + \Delta S_{\text{wetl}} + \Delta S_{\text{river}} \]
1) WaterGAP Global Hydrology model (WGHM)

Total continental water storage change $\Delta S$:

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

Soil depth = root zone

2) Land Dynamics (LaD) World

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

Soil depth = root zone

3) Global Land Data Assimilation System (GLDAS)

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

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.)
Water balance of a river basin:

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

P: Precipitation
E: Evapotranspiration
Q: Runoff (**measured time series of river discharge**)
$\Delta S$: Water storage change (**basin-average values from GRACE**)

Traditional calibration variable
Additional calibration variable
Multi-criterial calibration of hydrological models

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

Total continental water storage change

\[ \Delta S = \Delta S_{\text{canopy}} + \Delta S_{\text{snow}} + \Delta S_{\text{soil}} + \Delta S_{\text{gw}} + \Delta S_{\text{lakes}} + \Delta S_{\text{wetl}} + \Delta S_{\text{river}} \]
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

Evaluate by complementary observation data

Calibrated model

Werth & Güntner (2010), HESS
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)

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

- River flow velocity
- HBV gamma (runoff coefficient)
- Baseflow coefficient
- Interception storage capacity
- Wetland depth
- Root depth

parameter uncertainty / equifinality

high parameter value

low parameter value

original

calibrated
Calibration of hydrological models

Parameter uncertainty – parameter equifinality

- SZM vs Efficiency
- T₀ vs Efficiency
- SRₘₐₓ vs Efficiency
- Tₙ vs Efficiency
Multi-criterial calibration of hydrological models

Time-variable leaf area index, albedo, ET

ΔS (total)

Surface water storage from multiple satellite products (optical, radar, altimetry)
Climate input data
- Precipitation
- Temperature
- Solar radiation
- Air humidity

Model equations
representing water fluxes and storage processes

Model output
- Water storage
- River discharge
- Groundwater recharge

Model parameters
- describing, e.g., topography,
  vegetation, soil characteristics
- conceptual parameters

Evaluate model performance

Modify (Calibrate)

Stop if acceptable

Observed data
- river discharge
- GRACE water storage
- soil moisture
- water level (altimetry)
- ET products
- ….
Multi-criterial calibration of hydrological models

Climate input data
- Time series of, e.g.,
  - Precipitation
  - Temperature
  - Solar radiation
  - Air humidity

Model equations
representing water
fluxes and storage
processes

Model parameters
- describing, e.g., topography,
  vegetation, soil characteristics
- conceptual parameters

Modify (Calibrate)

Evaluate model
performance

Model output
- Time series of, e.g.,
  - Water storage
  - River discharge
  - Groundwater recharge

Data assimilation

Observed data
- river discharge
- GRACE water storage
- soil moisture
- water level (altimetry)
- ET products
-....

Stop if acceptable
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
Integration of GRACE data into large-scale hydrological models

Literature:

General introduction to hydrological modelling:


Multi-criterial calibration with GRACE data:

Modeling the hydrological cycle
- Practical -

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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**
  - (TT, CFMAX, SCF, CWH, CFR)

- **Soil routine**
  - (FC, LP, BETA)

- **Groundwater routine**
  - (KO, K1, K2, UZL, PERC)

- **Routing routine**
  - (MAXBAS)
Snow routine I

- Accumulation of precipitation as snow if air temperature $T < \text{threshold temperature } TT$ ($TT$ is close to $0^\circ \text{C}$)

- All precipitation which is simulated to be snow is multiplied by a correction factor $SFCF$ [-]

- **Degree-day method** for snowmelt $M$:
  
  $$M = CFMAX \times (T - TT) \quad \text{[mm d}^{-1}]$$

  $CFMAX$ degree-day factor $[\text{mm d}^{-1} \, ^\circ \text{C}^{-1}]$

  $CFMAX$ typically around 4 mm d$^{-1} \, ^\circ \text{C}^{-1}$, 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

  $$M = CFR \times CFMAX \times (TT - T) \text{ [mm h}^{-1}]$$

  $$CFR = \sim 0.05 \text{ [-]}$$
HBV model equations

Soil routine I

- Evapotranspiration
- Rain and snowmelt
- Soil storage
- Recharge
- Upper groundwater storage
- Lower groundwater storage
- Runoff

Recharge
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

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

- \textit{FC}: soil moisture storage capacity [mm]
- \textit{BETA}: shape parameter [-]

**Diagram:**

- The graph illustrates the fraction of rain or snowmelt that contributes to soil moisture storage and groundwater recharge.
- The equation shows how the recharged water is distributed between soil moisture and groundwater recharge as a function of soil moisture and the shape parameter.

**Equation:**

\[
\text{Recharge} = \left( \frac{SM}{FC} \right)^{BETA} \times (\text{Rain} + \text{Snowmelt})
\]
Soil routine I

Evapo-transpiration → Rain and snowmelt

Soil storage → Recharge

Upper groundwater storage → Lower groundwater storage

Recharge → FC

Runoff
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

Snow routine
(TT, CFMAX, SCF, CWH, CFR)

Soil routine
(FC, LP, BETA)

Groundwater routine
(K0, K1, K2, UZL, PERC)

Routing routine
(MAXBAS)
Routing routine

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

Snow routine
(TT, CFMAX, SCF, CWH, CFR)

Soil routine
(FC, LP, BETA)

Groundwater routine
(K0, K1, K2, UZL, PERC)

Routing routine
(MAXBAS)
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)
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

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

- 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 performance 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