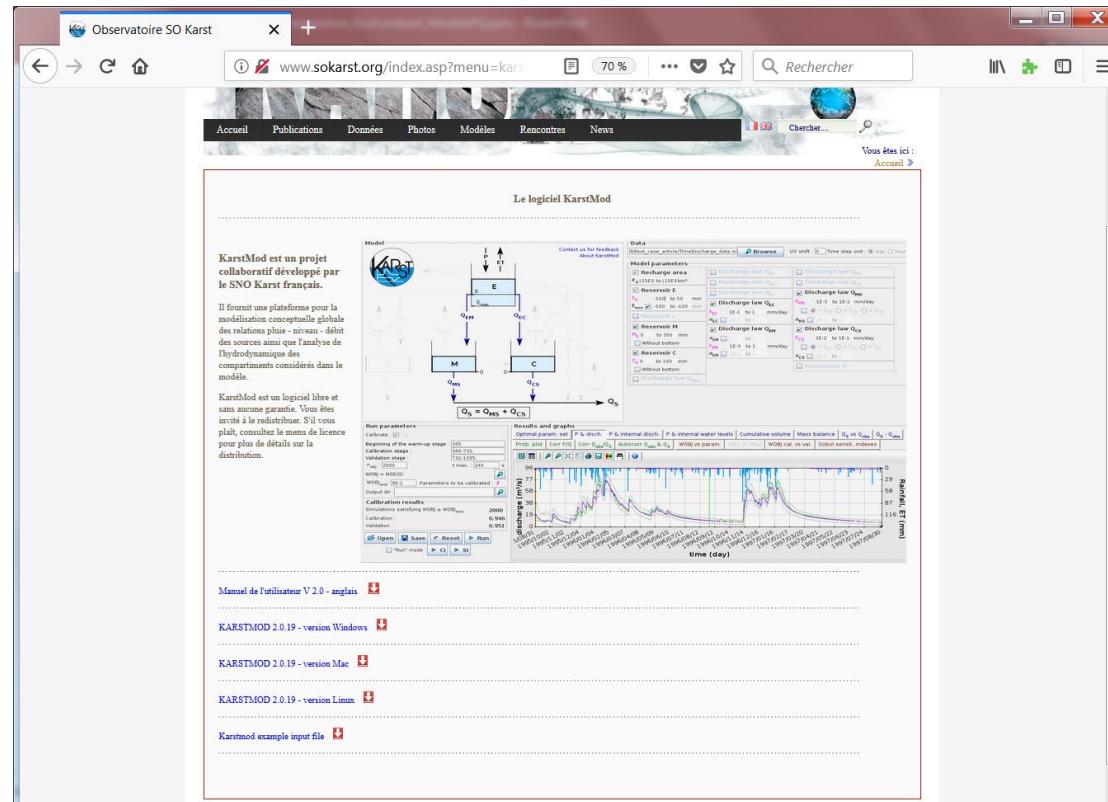


Rainfall-Discharge modeling

KarstMod: a free tool proposed by the Karst National Observation Service (SNO Karst)

<http://www.sokarst.org/index.asp?menu=karstmod>



25/06/2018

Tutorial, proposed by [Bruno Arfib](#) & [Naomi Mazzilli](#)
See also the [KarstMod](#) user guide (Mazzilli & Bertin)

Fichier Edition Format Affichage ?

!date	\$string	P	et	QpumpL	QpumpM	QpumpC	QpumpS	QobsS	Piezo	
20121014	00:00	1	5.63	1.1	0	0	0	0	NOINTERP	0
20121015	00:00	2	0.00	4.2	0	0	0	0	0.005	0
20121016	00:00	3	0.00	2.4	0	0	0	0	0.053	0
20121017	00:00	4	0.32	0.6	0	0	0	0	0.009	0
20121018	00:00	5	0.25	3.5	0	0	0	0	NOINTERP	0
20121019	00:00	6	0.00	4.2	0	0	0	0	NOINTERP	0
20121020	00:00	7	0.00	4.2	0	0	0	0	0.025	0
20121021	00:00	8	22.51	3	0	0	0	0	0.112	0
20121022	00:00	9	14.03	1.3	0	0	0	0	0.153	0
20121023	00:00	10	2.01	1.8	0	0	0	0	0.179	0
20121024	00:00	11	0.13	1.6	0	0	0	0	0.101	0
20121025	00:00	12	5.95	1.3	0	0	0	0	0.066	0
20121026	00:00	13	40.65	0.6	0	0	0	0	0.279	0
20121027	00:00	14	2.54	1.5	0	0	0	0	2.897	0
20121028	00:00	15	0.00	2.9	0	0	0	0	1.480	0
20121029	00:00	16	0.00	2.1	0	0	0	0	0.647	0
20121030	00:00	17	0.00	1	0	0	0	0	0.382	0
20121031	00:00	18	23.13	1.3	0	0	0	0	0.614	0
20121101	00:00	19	4.57	1.1	0	0	0	0	1.858	0
20121102	00:00	20	0.57	1.3	0	0	0	0	1.236	0

Input file for KarstMod

Missing data with
INTERP or NOINTERP

! :start row with
general information
(no data) by « ! »

5.3.1 Input data

The input data file contains the rainfall, evapotranspiration, pumped discharge and observed discharge and hydraulic head values. It is organized in 10 columns separated by tabs (See example in figure 4):

- column 1 - date (either yyyyMMdd or yyyyMMdd HH:mm format).
- column 2 - not used by the model.
- column 3 - rainfall P (mm/day for daily data, or mm/hour for hourly data),
- column 4 - evapotranspiration ET (mm/day for daily data, or mm/hour for hourly data),
- column 5 - discharge Q_{pump}^L pumped into compartment L (m^3/s),
- column 6 - discharge Q_{pump}^M pumped into compartment M (m^3/s),
- column 7 - discharge Q_{pump}^C pumped into compartment C (m^3/s),
- column 8 - discharge Q_{pump}^S pumped at the outlet (m^3/s),
- column 9 - discharge Q_{obs} observed at the outlet (m^3/s),
- column 10 - hydraulic head Z_{obs} measurements (m) (not mandatory).

Missing values of the observed discharge at the outlet can be replaced by the “INTERP” or “NOINTERP” value, depending on whether interpolation of the missing data is allowed (“INTERP”) or not (“NOINTERP”). Decimals can be separated by either points or commas. Exclamation marks are used for header lines.

Create the input data file for KarstMod : export in txt (Tab delimited)

The screenshot shows a Microsoft Excel spreadsheet titled "Dardennes_input_V2_PluitLimateRecons.xlsx". The data consists of 27 rows of measurements, with columns labeled A through P. Columns A, B, C, D, E, F, G, H, I, J, L, M, N, O, and P contain numerical values. Columns K and P are currently empty. The "Save As" menu is open, displaying various file formats. A red arrow points from the text below to the "Text (Tab delimited) (*.txt)" option in the list.

Dardennes_input_V2_PluitLimateRecons.xlsx - Excel

Fichier Accueil Insertion Mise en page Formules Données Révision Affichage Développeur PDF Architect 6 Creator Dites-nous ce que vous voulez faire... Connexion Partager

Coller Presse-papiers Police Alignement Nombre

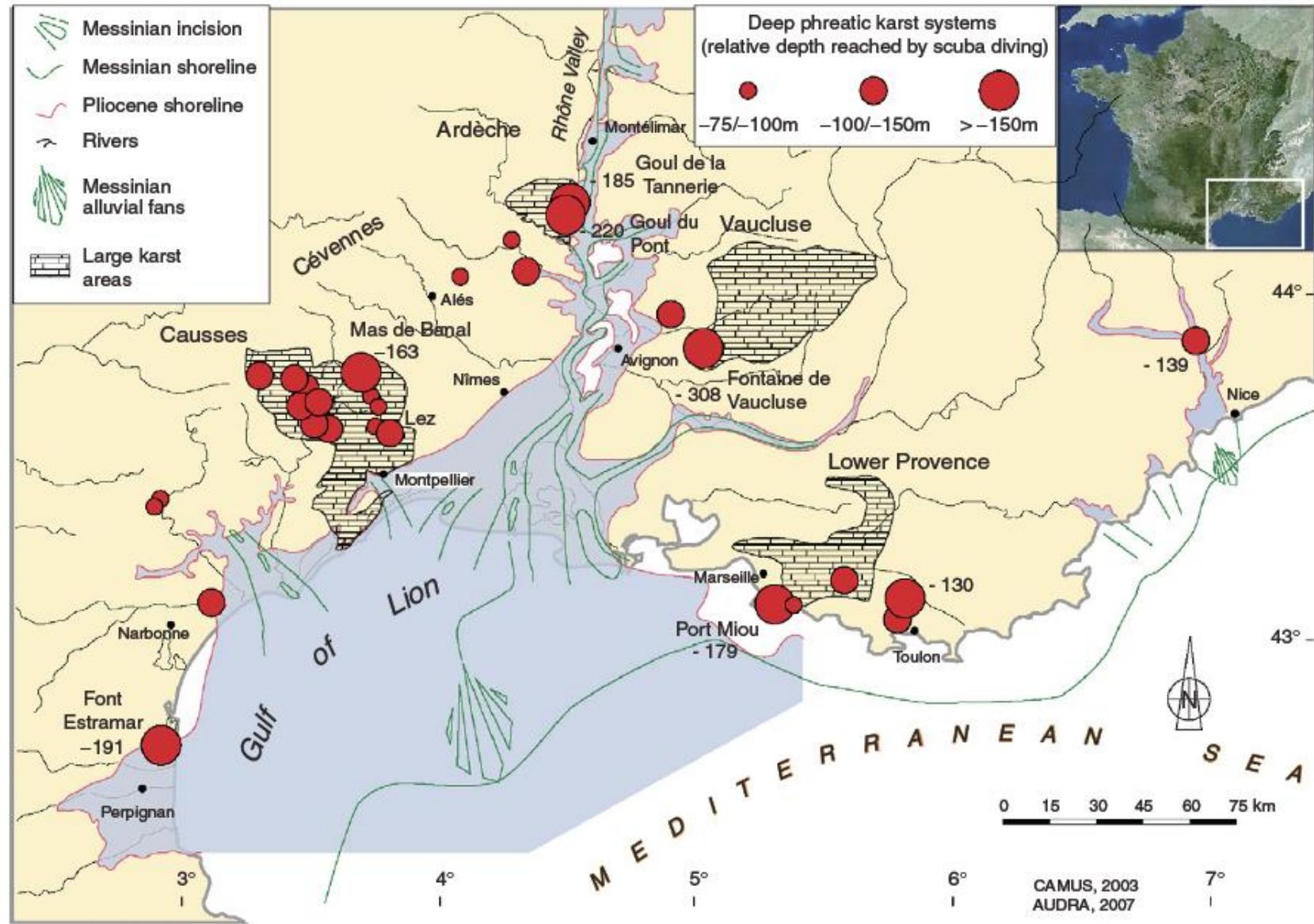
K7

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	ldate	string	P	et	QpumpL	QpumpM	QpumpC	QpumpS	QobsS	Piez						
2	20121014	1	5.63	1.1	0	0	0	0	0	NOINTERP						
3	20121015	2	0.00	4.2	0	0	0	0	0	0.005	NOINTERP					
4	20121016	3	0.00	2.4	0	0	0	0	0	0.053	NOINTERP					
5	20121017	4	0.32	0.6	0	0	0	0	0	0.009	NOINTERP					
6	20121018	5	0.25	3.5	0	0	0	0	0	NOINTERP	NOINTERP					
7	20121019	6	0.00	4.2	0	0	0	0	0	NOINTERP	NOINTERP					
8	20121020	7	0.00	4.2	0	0	0	0	0	0.025	101.64					
9	20121021	8	22.51	3	0	0	0	0	0	0.112	101.72					
10	20121022	9	14.03	1.3	0	0	0	0	0	0.153	103.34					
11	20121023	10	2.01	1.8	0	0	0	0	0	0.179	103.11					
12	20121024	11	0.13	1.6	0	0	0	0	0	0.101	103.35					
13	20121025	12	5.95	1.3	0	0	0	0	0	0.066	103.54					
14	20121026	13	40.65	0.6	0	0	0	0	0	0.279	109.47					
15	20121027	14	2.540	1.5	0	0	0	0	0	2.897	114.18					
16	20121028	15	0.00	2.9	0	0	0	0	0	1.480	113.32					
17	20121029	16	0.00	2.1	0	0	0	0	0	0.647	113.69					
18	20121030	17	0.00	1	0	0	0	0	0	0.382	113.97					
19	20121031	18	24.01	1.3	0	0	0	0	0	0.614	114.68					
20	20121101	19	0.00	1.1	0	0	0	0	0	1.858	118.00					
21	20121102	20	0.11	1.3	0	0	0	0	0	1.236	117.76					
22	20121103	21	4.58	0.3	0	0	0	0	0	0.654	118.16					
23	20121104	22	13.20	0.6	0	0	0	0	0	0.520	118.73					
24	20121105	23	0.00	2.7	0	0	0	0	0	1.901	121.04					
25	20121106	24	0.00	2	0	0	0	0	0	1.772	121.78					
26	20121107	25	0.00	2.2	0	0	0	0	0	0.917	122.27					
27	20121108	26	0.00	1	0	0	0	0	0	0.546	122.60					

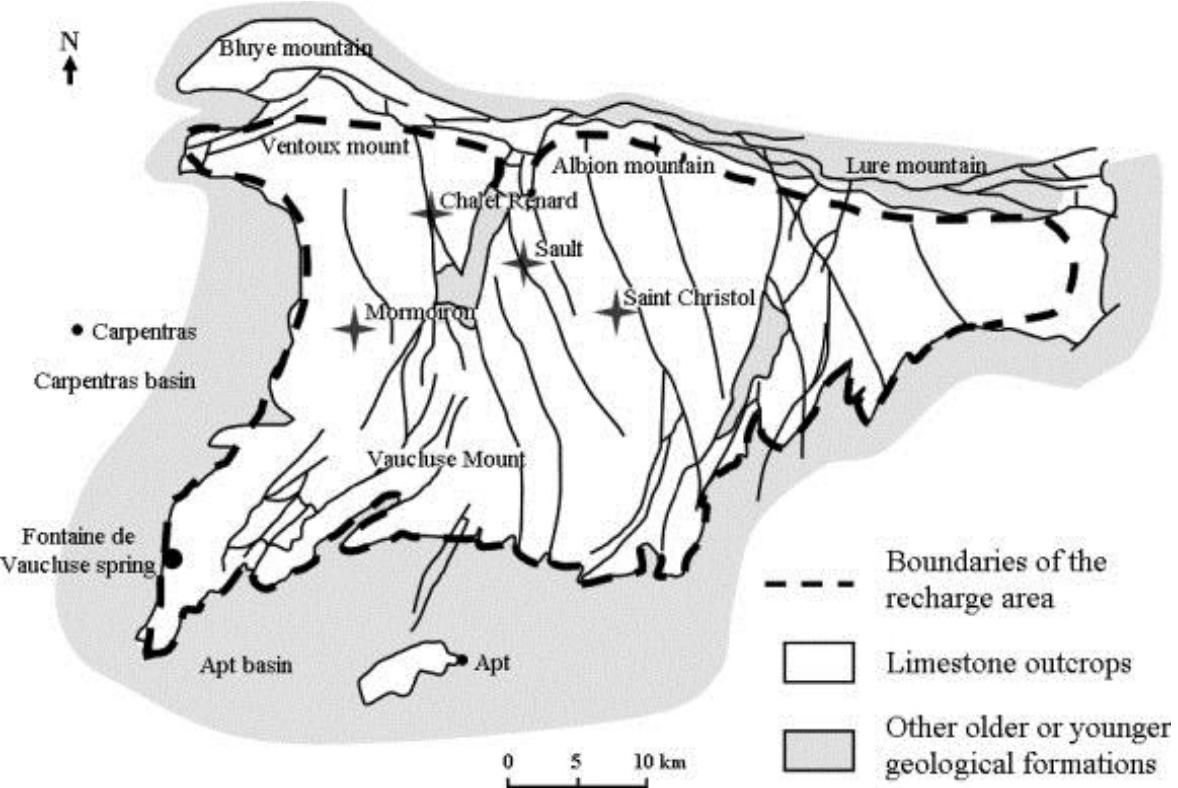
Excel Workbook (*.xlsx)
Excel Macro-Enabled Workbook (*.xlsm)
Excel Binary Workbook (*.xlsb)
Excel 97-2003 Workbook (*.xls)
XML Data (*.xml)
Single File Web Page (*.mht; *.mhtml)
Web Page (*.htm; *.html)
Excel Template (*.xltx)
Excel Macro-Enabled Template (*.xltm)
Excel 97-2003 Template (*.xlt)
Text (Tab delimited) (*.txt)
Unicode Text (*.txt)
XML Spreadsheet 2003 (*.xml)
Microsoft Excel 5.0/95 Workbook (*.xls)
CSV (Comma delimited) (*.csv)
Formatted Text (Space delimited) (*.prn)
Text (Macintosh) (*.txt)
Text (MS-DOS) (*.txt)
CSV (Macintosh) (*.csv)
CSV (MS-DOS) (*.csv)
DIF (Data Interchange Format) (*.dif)
SYLK (Symbolic Link) (*.slk)
Excel Add-In (*.xlam)
Excel 97-2003 Add-In (*.xla)
PDF (*.pdf)

Create the input data file for KarstMod :
« Save as » Type : Text (Tab delimited)

Case study : Fontaine de Vaucluse (France)



Case study : Fontaine de Vaucluse (France)



- $BV \approx 1100 \text{ km}^2$
- $Q_{\max} \approx 150 \text{ m}^3/\text{s}$
- $Q_{\min} \approx 3,0 \text{ m}^3/\text{s}$

Modeling papers :
Fleury et al. 2007
Mazzilli et al. 2017



Open KarstMod

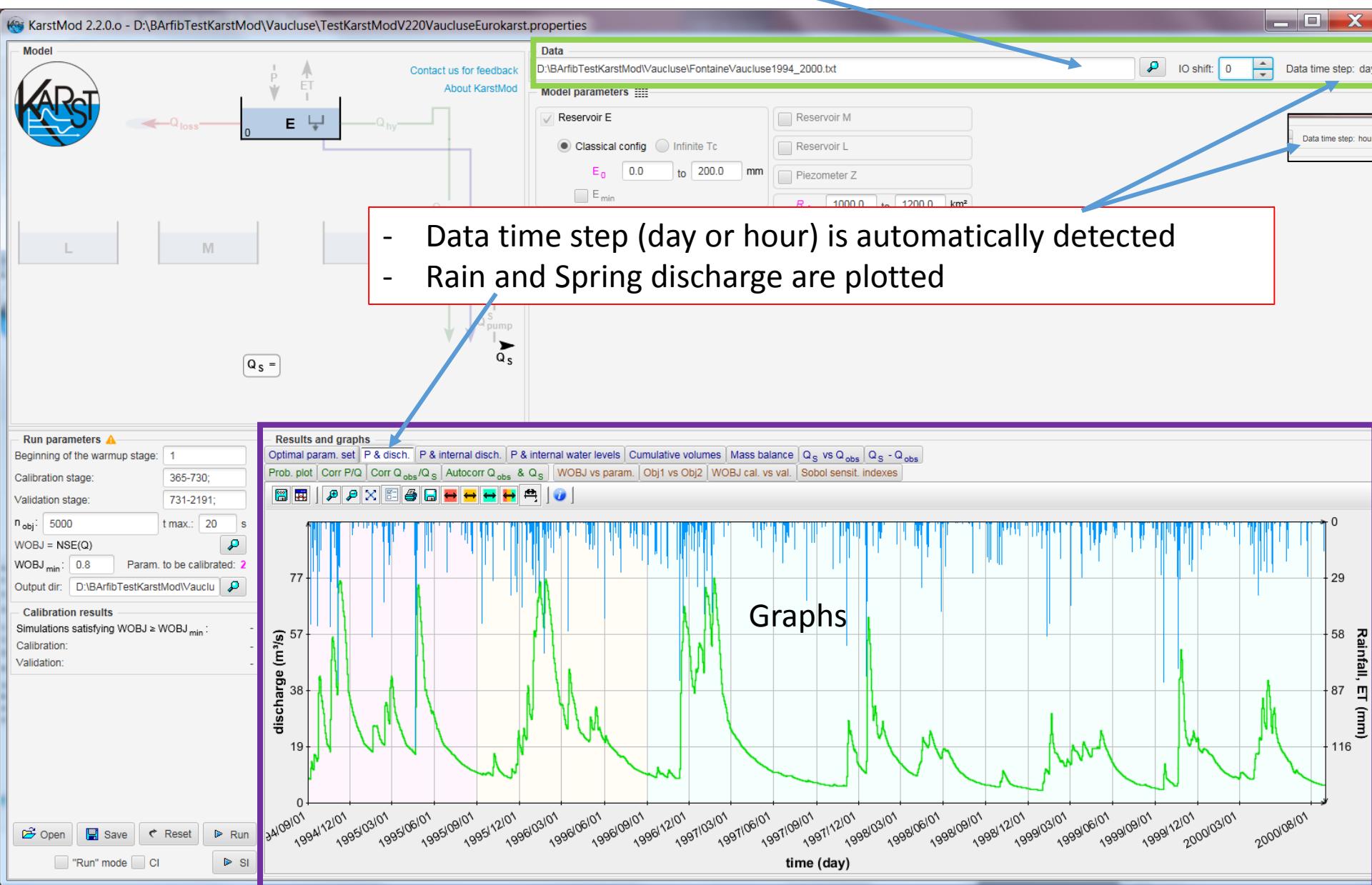
7 sub-windows

The screenshot displays the KarstMod 2.20.n software interface with seven main sub-windows:

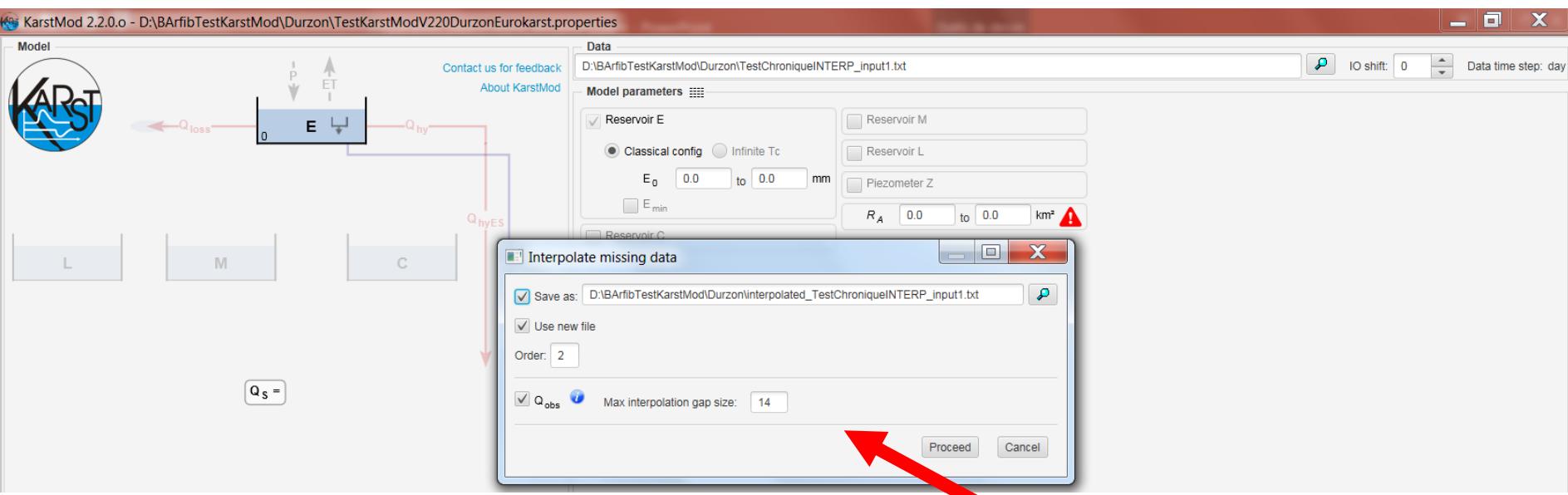
- Model structure:** Shows a schematic of a karst system with reservoirs L, M, and C, and flow paths labeled I, P, ET, and E.
- Model parameters:** Shows model parameters for Reservoir E, Reservoir M, Reservoir L, and Reservoir C, with a warning icon for R_A .
- Calibration results:** Displays calibration statistics: Beginning of the warmup stage: 0, Calibration stage: 0, Validation stage: 0, n_obj: 0, WOBJ = NSE(Q), WOBJ_min: 0.4, Param. to be calibrated: 0, Output dir: ..
- Graphs:** A large window showing discharge (m³/s) over time (day). It includes Rainfall, ET (mm) data and various plot tools.
- Data:** A window for managing data files, showing options for Path to data file, Model parameters, and a warning icon for R_A .
- Run parameters:** A window containing tabs for Optimal param. set, P & disch., P & internal disch., P & internal water levels, Cumulative volumes, Mass balance, Q_S vs Q_{obs} , and $Q_S - Q_{obs}$. It also lists validation plots: Prob. plot, Corr P/Q, Corr Q_{obs}/Q_S , Autocorr Q_{obs} & Q_S , WOBJ vs param., Obj1 vs Obj2, WOBJ cal. vs val., and Sobol sensit. indexes.
- Command bar:** A toolbar at the bottom with buttons for Open, Save, Reset, and Run.

First model

1 : open Data file (.txt or .in)



Interpolate missing data in the input data file for KarstMod



In case of INTERP data in the Input file, KarstMod opens a pop-up window when loading the input file.

A new input file can be automatically saved by KarstMod (named « interpolated_... ») with the results of the interpolation utility (Lagrange polynomial interpolation)

5.2.3 Filling gaps in discharge or piezometric data

Gaps indicated with the “INTERP” value in the observed discharged or piezometric levels times series can be filled using a Lagrange polynomial interpolation. The interpolation utility pops up when the input data file is loaded. The order of the interpolation is defined by the user. The interpolation may be restricted to gaps shorter than a user-defined number of steps.

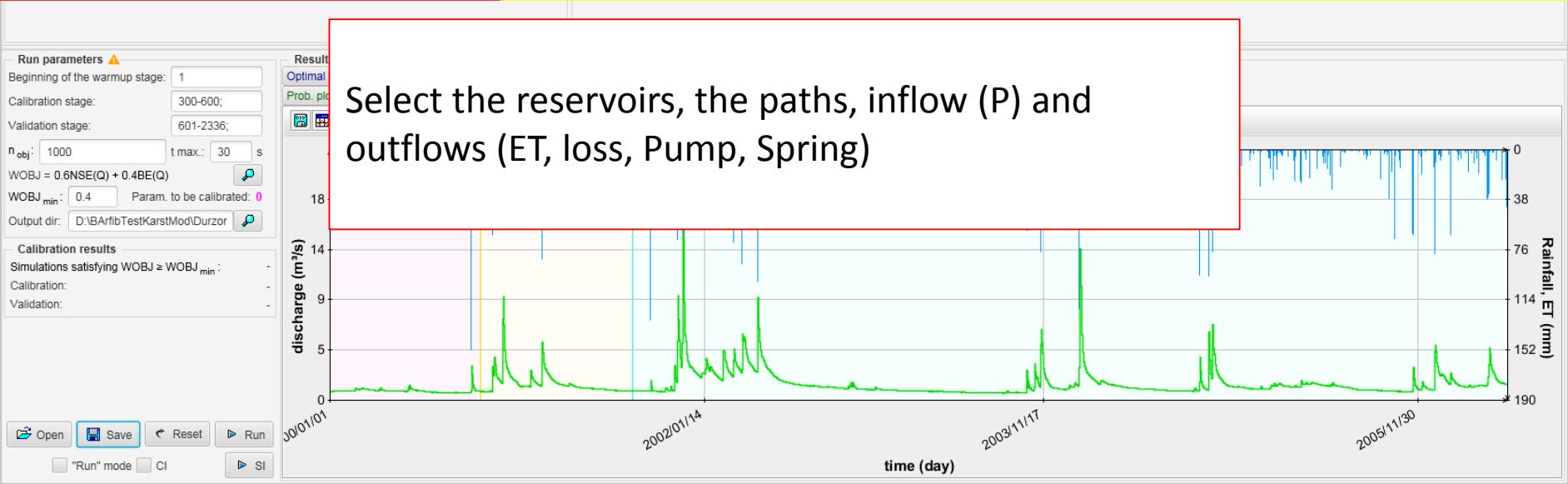
Gaps indicated with the “NOINTERP” value and gaps indicated with an “INTERP” value but with a length greater than the maximum gap interpolation lenght defined by the user are not filled.

First model

2 : Model structure and model parameters

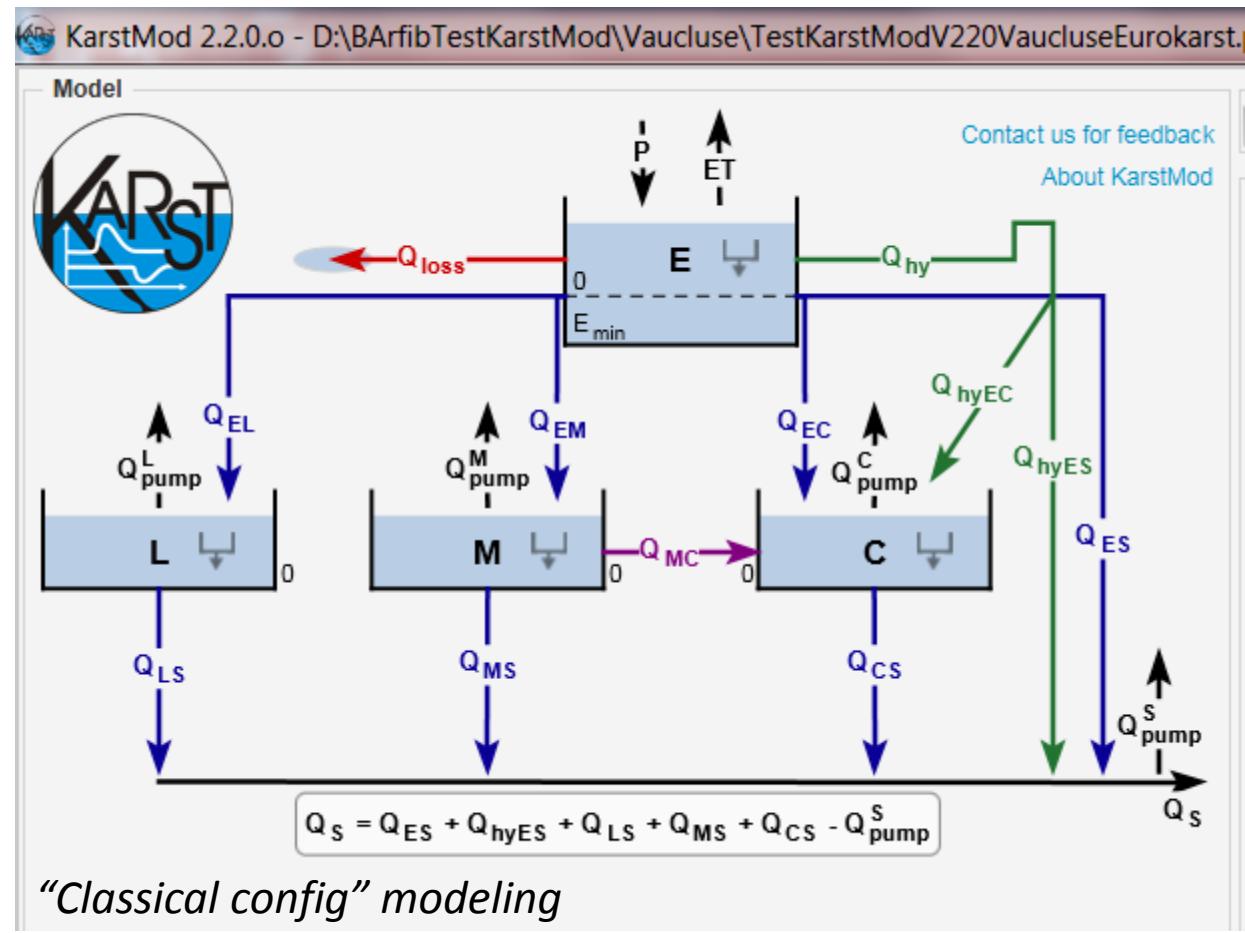
The screenshot shows the KarstMod 2.2.0.0 software interface. On the left, under 'Model structure', there is a diagram of a karst system with reservoirs L, M, and C, and paths E and P. Arrows indicate flow from reservoirs to paths, and from paths to the surface. Labels include Q_{loss} , Q_{hy} , Q_{hyE} , Q_{ES} , Q_s , and Q_{pump}^S . A red box highlights the reservoirs and paths. On the right, under 'Model parameters', there is a configuration panel for Reservoir E. It includes a 'Classical config' radio button, input fields for E_0 (0.0 to 0.0 mm), E_{min} (unchecked), and R_A (0.0 to 0.0 km²), and checkboxes for Reservoir M, Reservoir L, Piezometer Z, and Reservoir C. A yellow box highlights the parameter configuration area.

Select the reservoirs, the paths, inflow (P) and outflows (ET, loss, Pump, Spring)



You need a conceptual scheme of hydrogeological functioning of your karst hydrosystem :

- Soil reservoir and reserve?
- Hysteretic law?
- 0, 1, 2 or 3 lower reservoirs?
- Pumping?
- Loss?
- Interconnection between lower reservoirs?

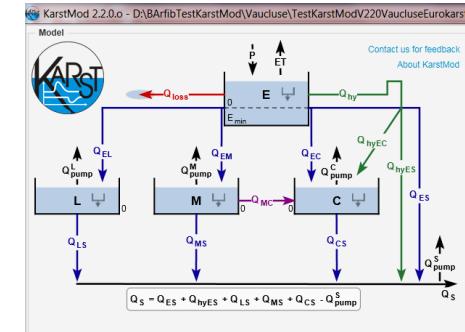


You need a conceptual scheme of hydrogeological functionning of your karst hydrosystem :

- Soil reservoir and reserve?
- Hysteretic law?
- 0, 1, 2 or 3 lower reservoirs?
- Pumping?
- Loss?
- Interconnection between lower reservoirs?

Your choice depends on :

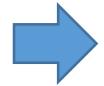
- The functioning of the case study
- Your level of knowledge of the functioning of the case study
- The goal(s) of the modeling



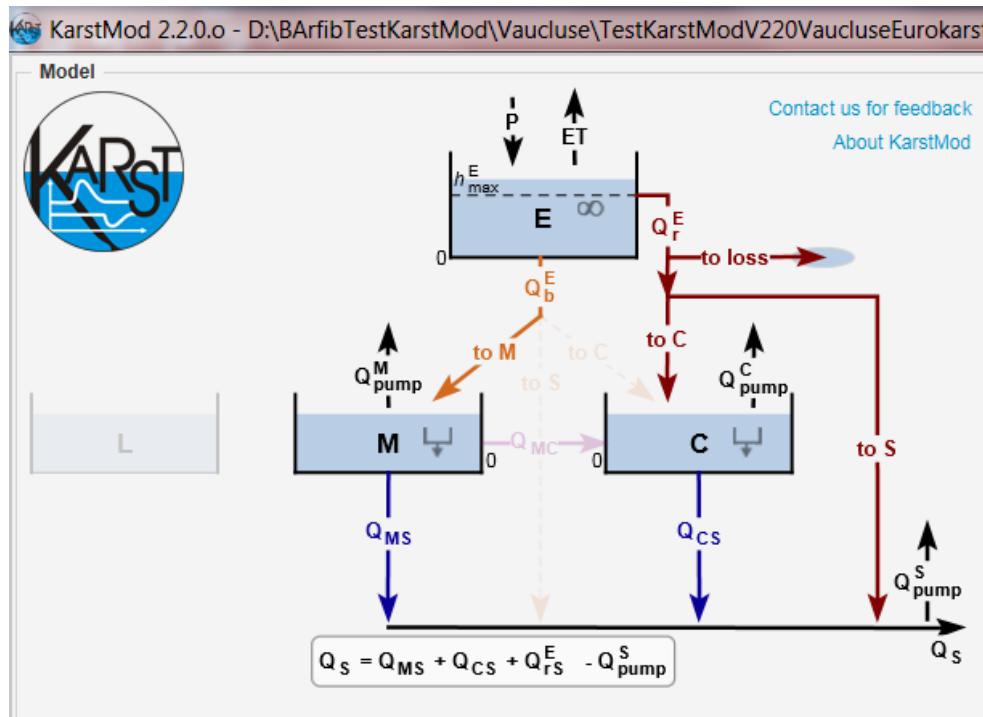
2 modeling configuration available for each reservoir



Classical config. (Mallet's law)



Infinite characteristic time config.



Infinite Tc :

- Reservoir is partitionning into n sub-reservoirs with linear discharge laws, all running in parallel → $Q_{b,E}$
- When the water level E_i becomes larger than h_{Emax} , the ith sub-reservoir is bypassed and the corresponding overflow $Q_{r,i}^E$ is routed directly to the spring (or to the reservoir C or to loss).

First model 1 | 2 : Model structure and model parameters

Classical configuration. Linear discharge law.

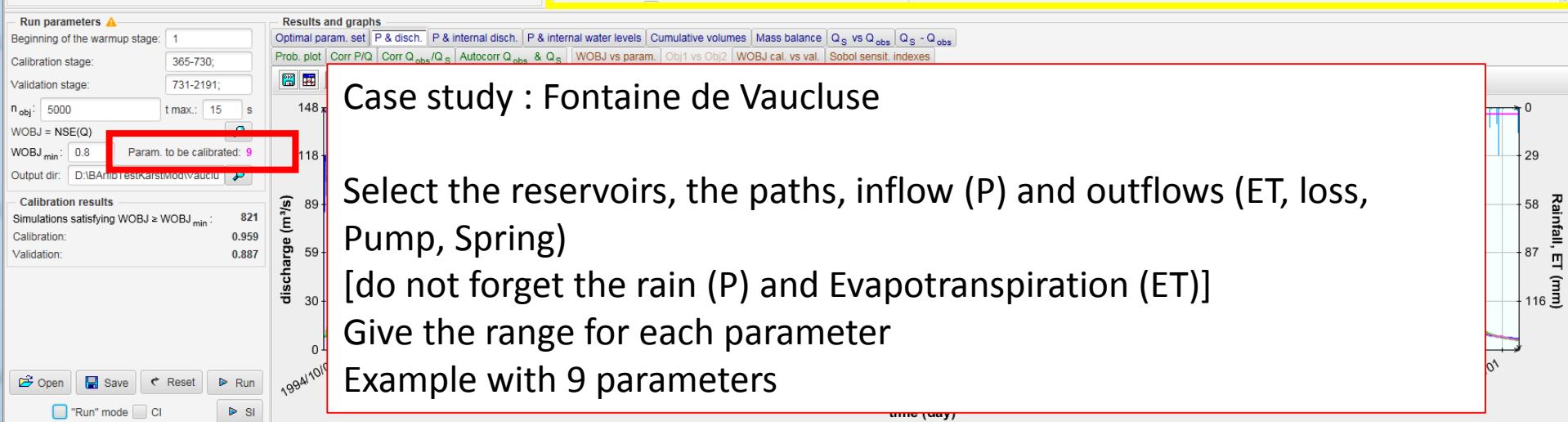
$$Q_{AB} = k_{AB} \left(\frac{A}{L_{ref}} \right)^{\alpha_{AB}}$$

A: height of water in reservoir A
 $\alpha = 1$

Model structure

Model parameters

Choose Classical config or Infinite Tc for each reservoir



First model 2 : Model structure and model parameters

Classical configuration. Non linear discharge law.

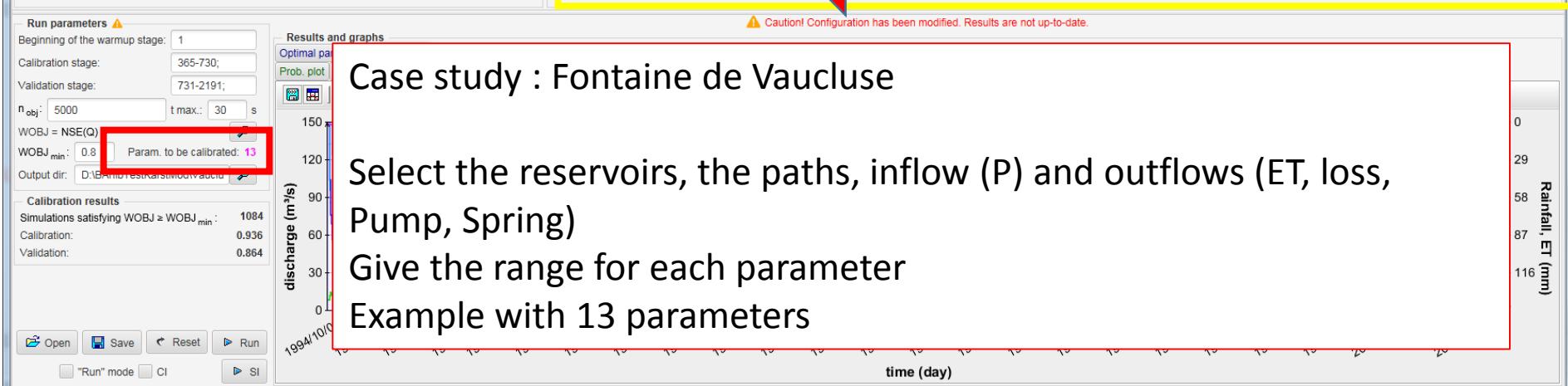
$$Q_{AB} = k_{AB} \left(\frac{A}{L_{ref}} \right)^{\alpha_{AB}}$$

A: height of water in reservoir A
 $\alpha \neq 1$

The screenshot shows the KarstMod 2.2.0 software interface. On the left, the 'Model' tab displays a schematic of three reservoirs (E, M, C) connected by various flow paths. Reservoir E has inflow P and outflow ET. Reservoir M has inflow Q_EM and outflow Q_MS. Reservoir C has inflow Q_ES and outflow Q_CS. Arrows indicate flows between reservoirs and to the surface. On the right, the 'Model parameters' tab is open, showing configuration options and parameter ranges for Reservoir E, Reservoir M, and Reservoir C. Red arrows point from the 'Model structure' section to the reservoir configurations and from the 'Model parameters' section to the specific parameter settings. A yellow box highlights the parameter input area.

Model structure

Model parameters



Case study : Fontaine de Vaucluse

Select the reservoirs, the paths, inflow (P) and outflows (ET, loss, Pump, Spring)
 Give the range for each parameter
 Example with 13 parameters

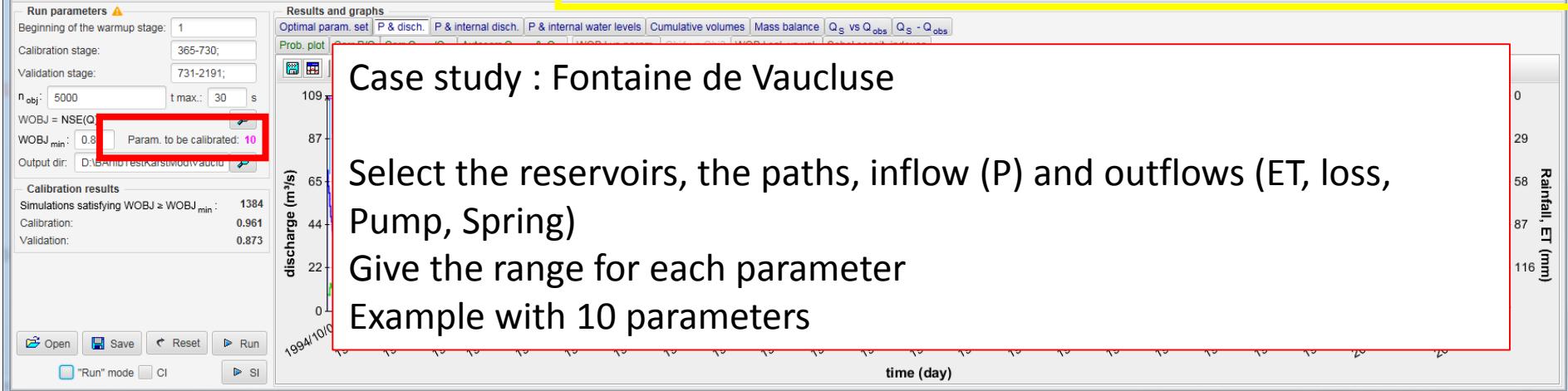
First model 3 | 2 : Model structure and model parameters

Infinite characteristic time config.

The screenshot shows the KarstMod 2.2.0.0 interface. On the left, the 'Model' tab displays a schematic of three reservoirs: E (top), M (middle), and C (bottom). Reservoir E receives inflow P and loses water through ET. Reservoir M receives inflow from E and pump Q_Mpump, and loses water through pump Q_{MS}. Reservoir C receives inflow from M and pump Q_Cpump, and loses water through pump Q_{CS} and a spring Q_S. Arrows indicate flow paths: 'to M' from E, 'to S' from M, 'to C' from M, 'to loss' from E, and 'to S' from C. A box labeled 'Q_S = Q_{MS} + Q_{CS}' is at the bottom. On the right, the 'Data' tab shows parameter settings for reservoirs E, M, and C under 'Infinite Tc' configuration. A red arrow points to the 'Infinite Tc' radio button for reservoir E. The 'Model parameters' tab also lists these configurations.

Model structure

Model parameters



- The warm-up period corresponds to the time interval after which the initialization bias is deemed negligible. Simulation results from the warm-up period are not considered in the calibration. Therefore, discharge measurements at the outlet are not required during this period.
- The calibration period corresponds to the time interval over which the calibration is performed, that is, model performance during this time period is used to select the optimal parameter set.
- The validation period corresponds to the time interval over which the model performance is evaluated, but not used for calibration purpose.

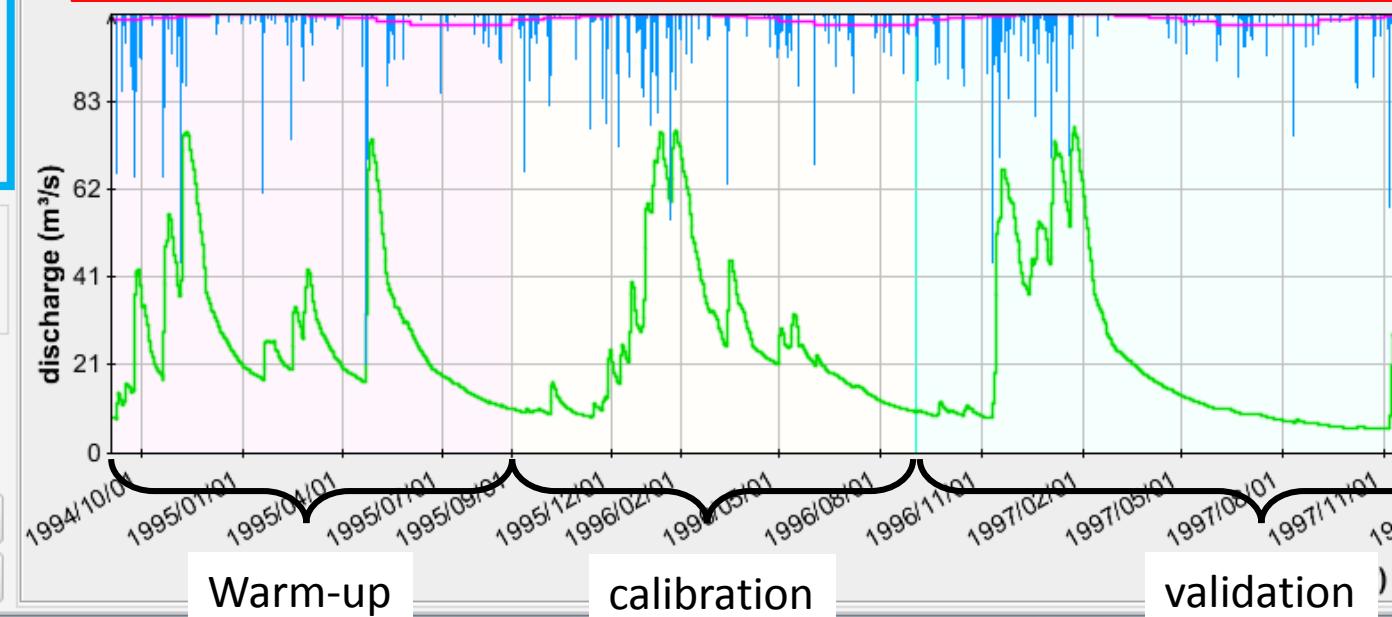
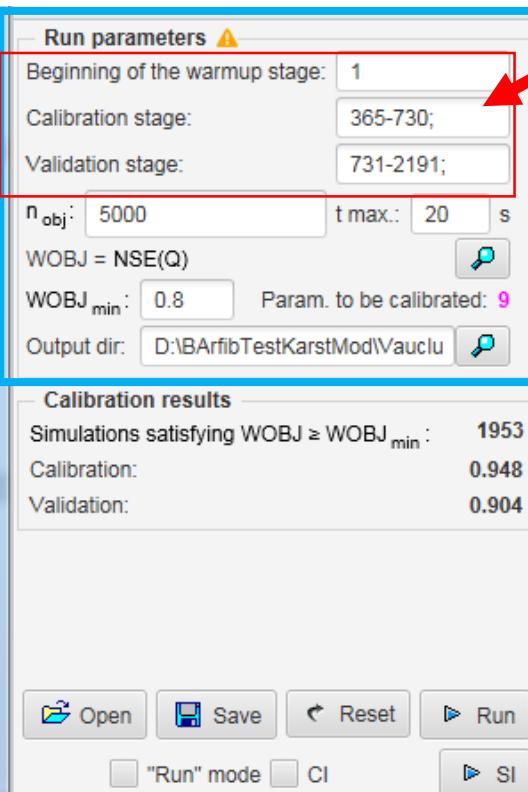
Index starts at 0.

From day 2 to day 365 : warm-up

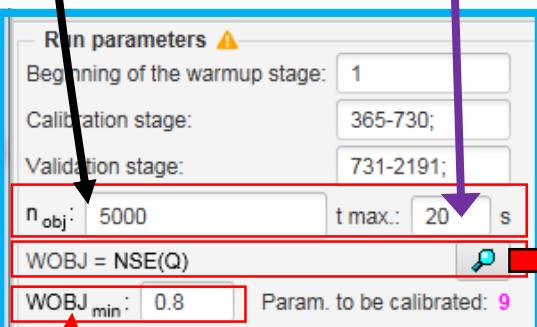
From day 366 to 731 : calibration

From day 732 to the end : validation

Possibility to use discontinuous validation and calibration periods



- the number n_{obj} of simulations to conduct and requiring verification of the condition $WOBJ > WOBJ_{min}$ over the calibration period (box grayed out in “run” mode),
- the maximum execution time t_{max} beyond which the simulation is stopped, even if the number of simulations that have obtained an objective function value higher than the $WOBJ_{min}$ value remains less than n_{obj} (box grayed out in “run” mode),



- the threshold value $WOBJ_{min}$

- the objective $WOBJ$ function $WOBJ$, parametrizable via the adjoining button

Objective function from $-\infty$ to 1 : best performance = 1

Nash-Sutcliffe efficiency

$$NSE = 1 - \frac{\sum (U_S - U_{obs})^2}{\sum (U_{obs} - \bar{U}_{obs})^2}$$

Volumetric efficiency

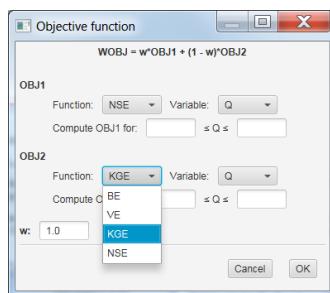
$$VE = 1 - \frac{\sum |U_S - U_{obs}|}{\sum U_{obs}}$$

Modified balance error

$$BE = 1 - \left| \frac{\sum U_S - \sum U_{obs}}{\sum U_{obs}} \right|$$

Kling Gupta efficiency

$$KGE = 1 - \sqrt{(r - 1)^2 + (\alpha - 1)^2 + (\beta - 1)^2}$$



$$WOBJ = w \cdot OBJ1 + (1-w) \cdot OBJ2$$

The directory where the output files are saved.

5.3.2 Output files

The KarstMod configuration (model structure, calibration parameters and optimal parameter set) can be saved and / or loaded in a configuration file (*.cm.properties).

After each run, three output files are generated automatically:

- params_best.csv contains the parameter set that yields the highest value of the objective function over the calibration period,
- discharge_out.csv contains the simulated discharge time series for the parameter set that yields the highest value of the objective function over the calibration period,
- params_out.csv contains all parameter sets that verify $W_{OBJ} > W_{OBJ_{min}}$ over the calibration period.

In run mode, the files are prefixed 'run'

Run pa
Beginning
Calibratio
Validation
n_obj.: 5000 t max.: 20 s

WOBJ = NSE(Q)

WOBJ_{min}: 0.8 Param. to be calibrated: 9

Output dir: D:\BArfibTestKarstMod\Vaclus

Calibration results

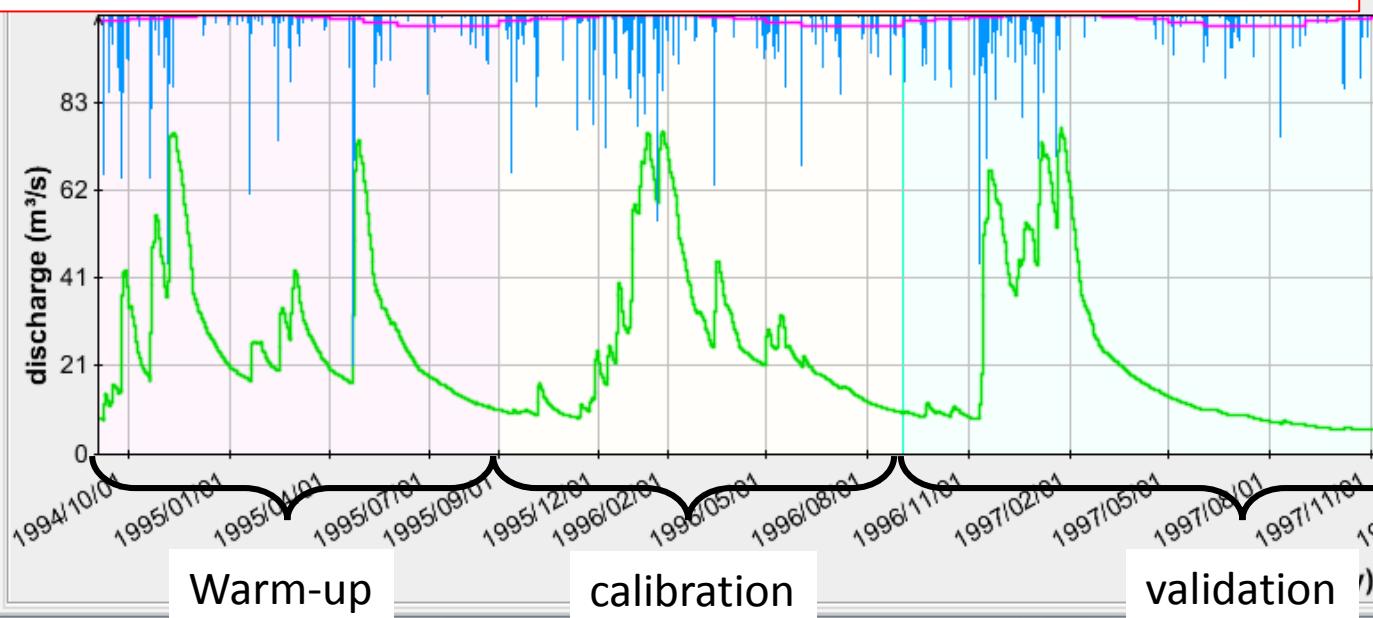
Simulations satisfying $W_{OBJ} \geq W_{OBJ_{min}}$: 1953

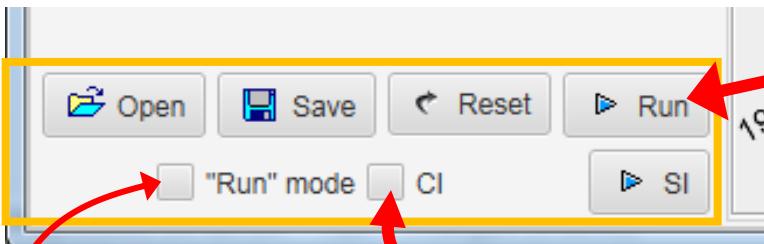
Calibration: 0.948

Validation: 0.904

Open Save Reset Run

"Run" mode CI SI





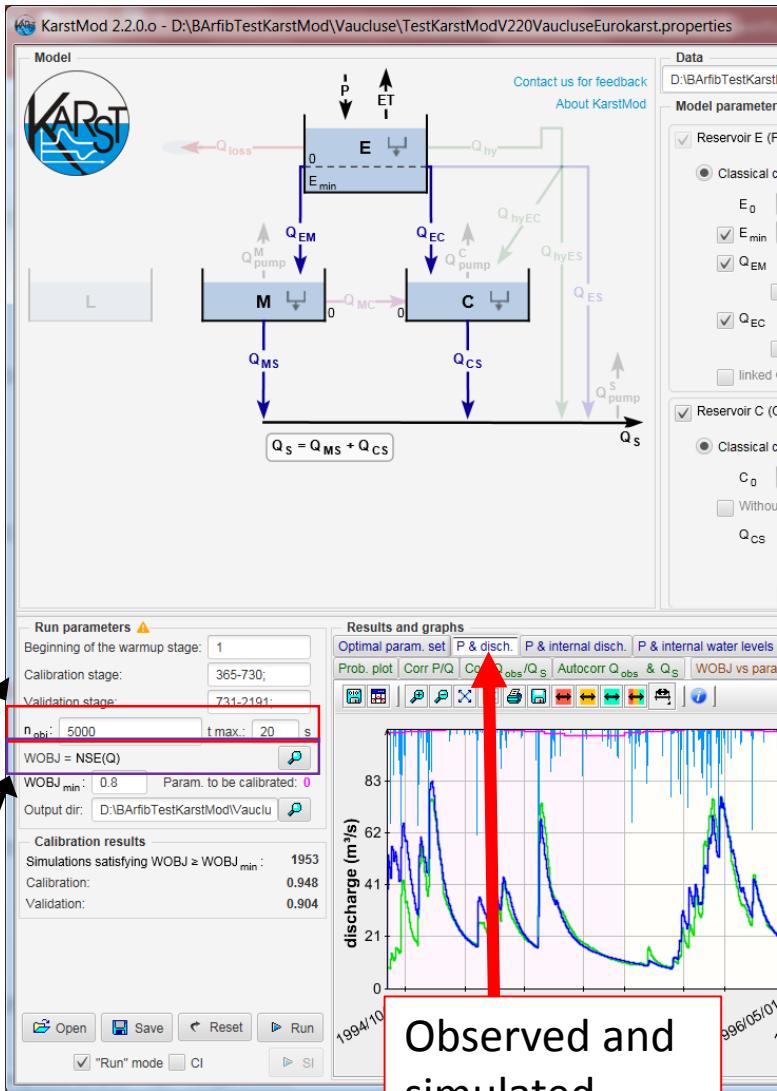
To start the model fitting, click : Run

Check box to add confidence interval plot on results

- ↶ Reset : sets all parameters to their default value
- 💾 Save : save the configuration (model structure, parameter values, simulation parameters) into a text file (CTRL+S) in the output directory specified in the “calibration results” area
- 📁 Open : opens a previously saved configuration (CTRL+O)
- ▶ Run : launches the model (CTRL+R) and:
 - shows the results (resulting parameters, objective function and graphics)
 - writes the output files
- ▶ CI : launches the Confidence Interval plot on the “P & Disch.” graph (block Results and Graphs)
- ▶ SI : calculates the Sobol Sensitivity Indexes and write the results in the “Sobol Sensit. Indexes” tab (block Results and Graphs)

A special option : the « run mode » allows to run the model without fitting parameters. This mode is useful to test a specific set of parameters, or to test by trial-error the effect of one parameter (useful in classroom).

Classical configuration. Linear discharge law.

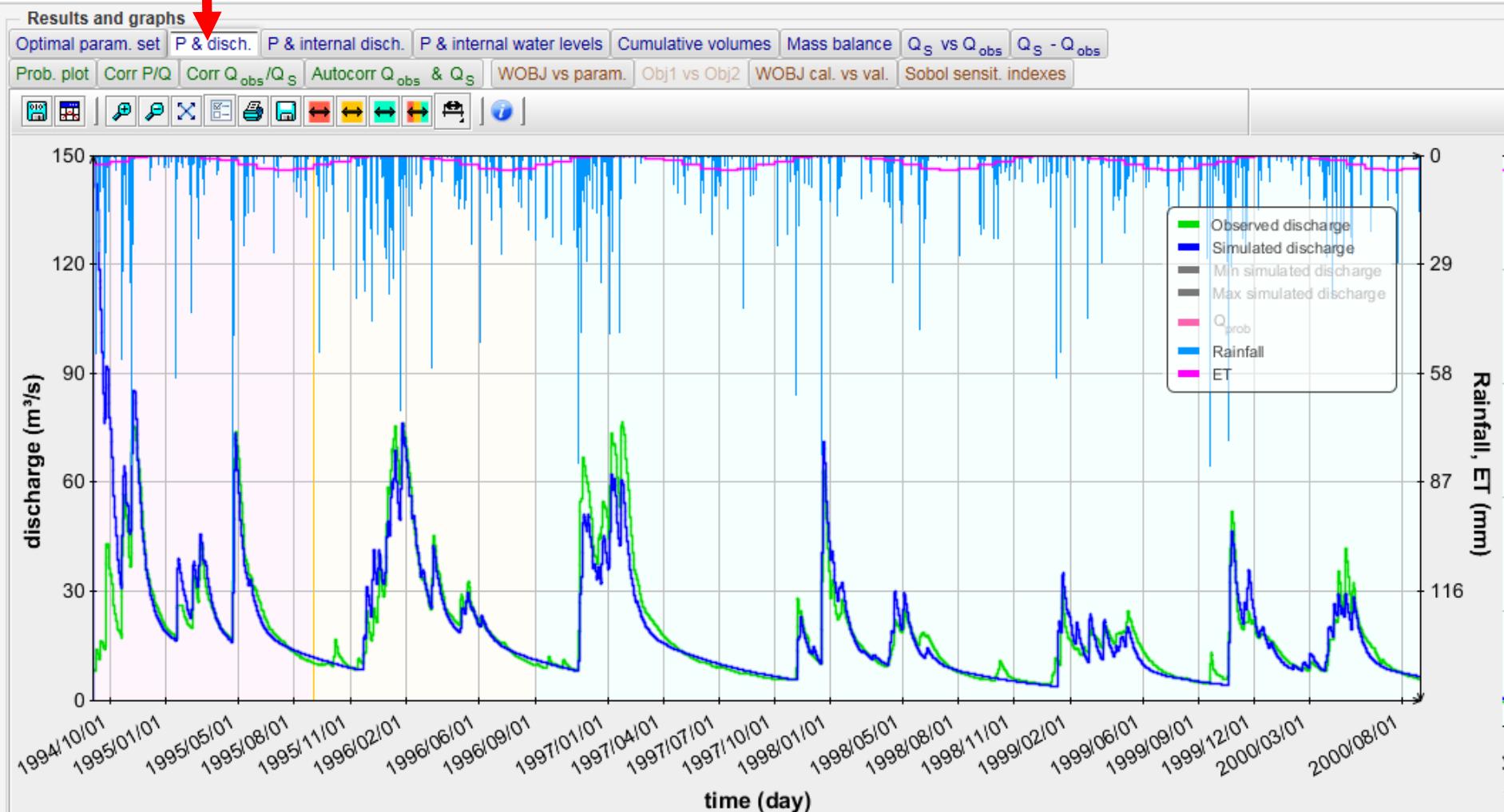


Number of simulations according to n_{obj} and t_{max} , for $WOBJ > WOBJ_{min}$

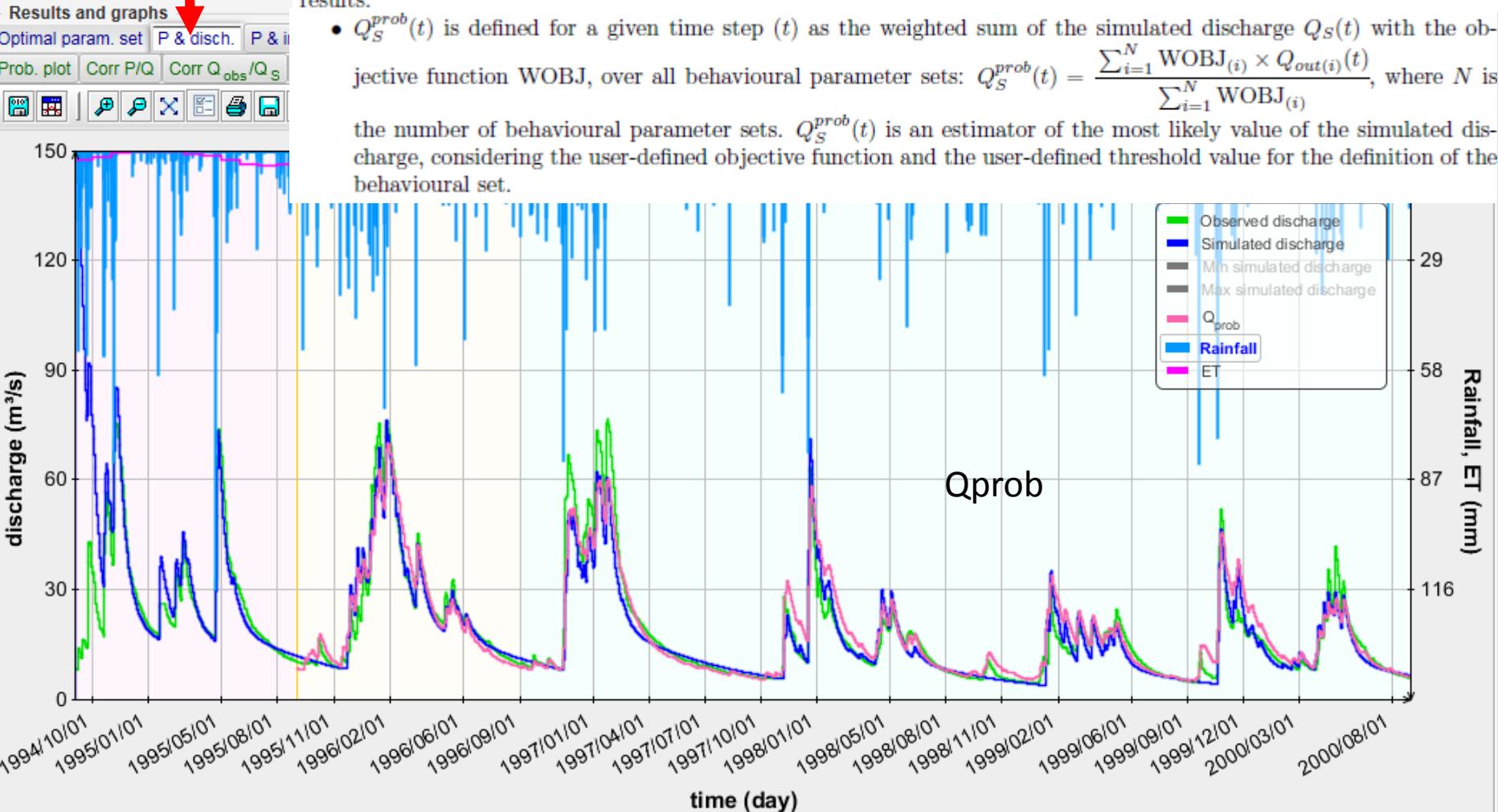
Calibration results	
Simulations satisfying $WOBJ \geq WOBJ_{min}$:	1953
Calibration:	0.948
Validation:	0.904

Objective function for the calibration and validation periods

Observed and simulated discharge



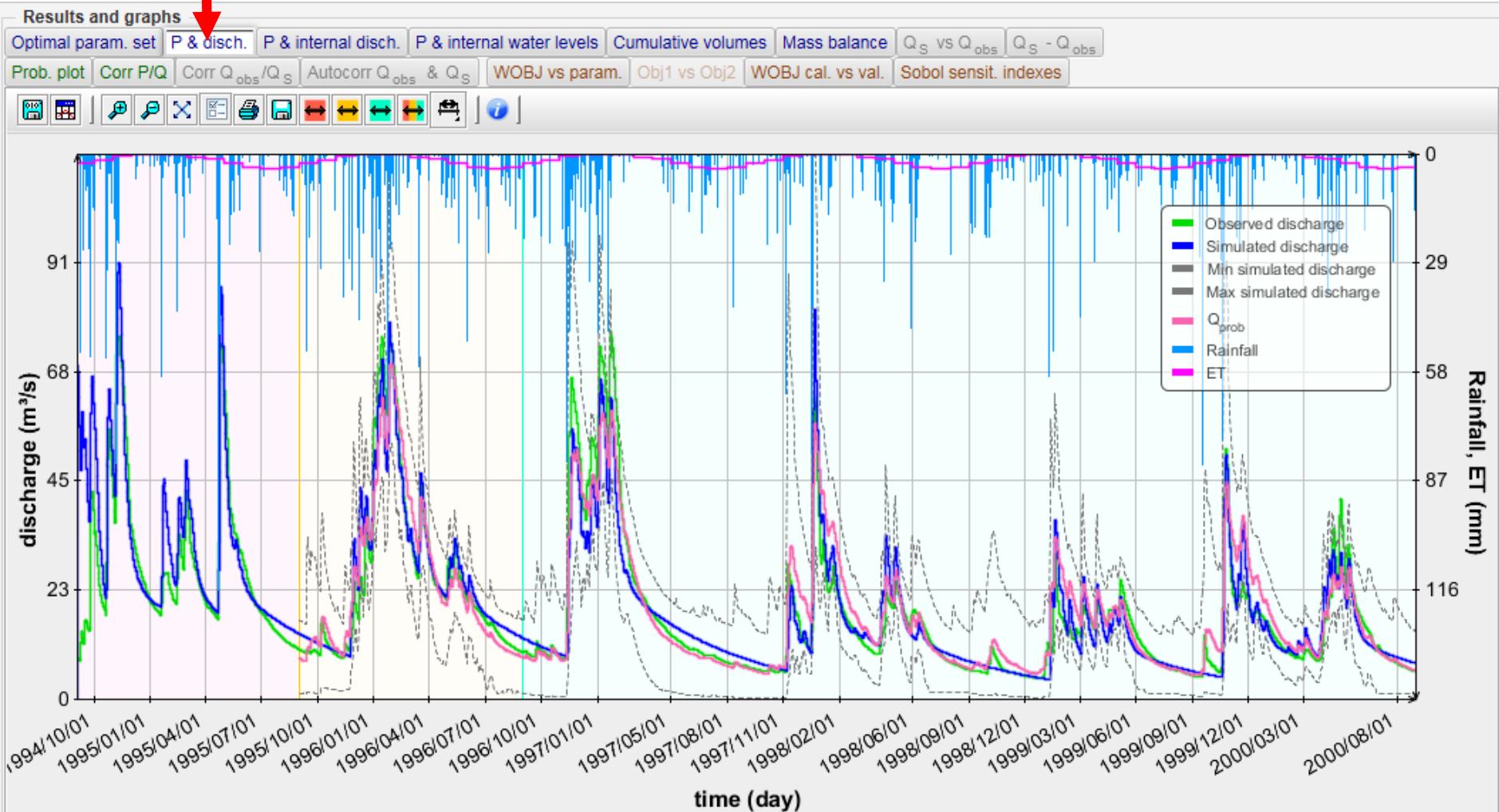
Observed and simulated discharge



Observed and simulated discharge

Parametric uncertainty of the simulation results

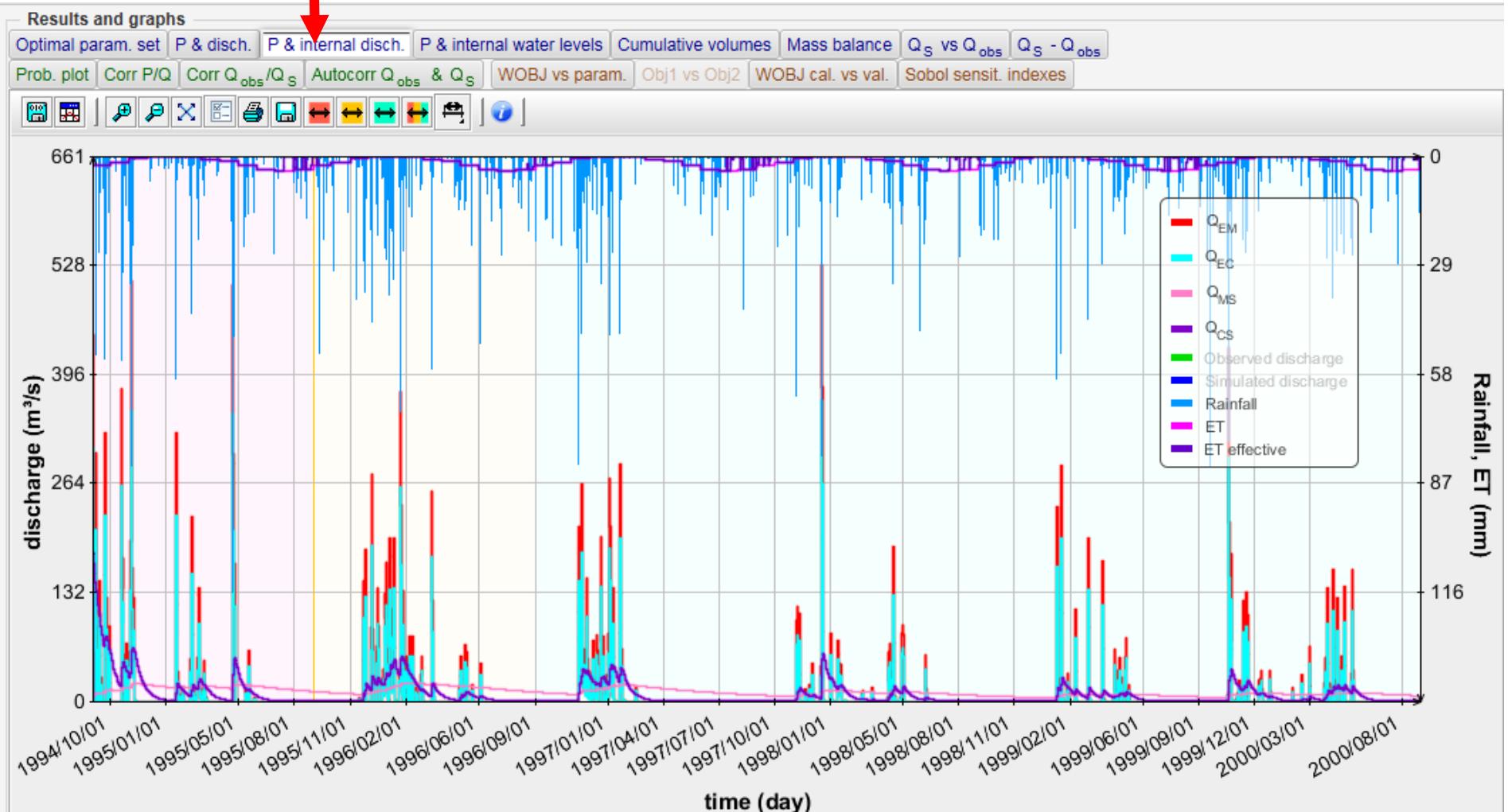
Qprob + Confidence interval plots



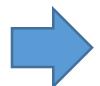
Rainfall and internal discharge



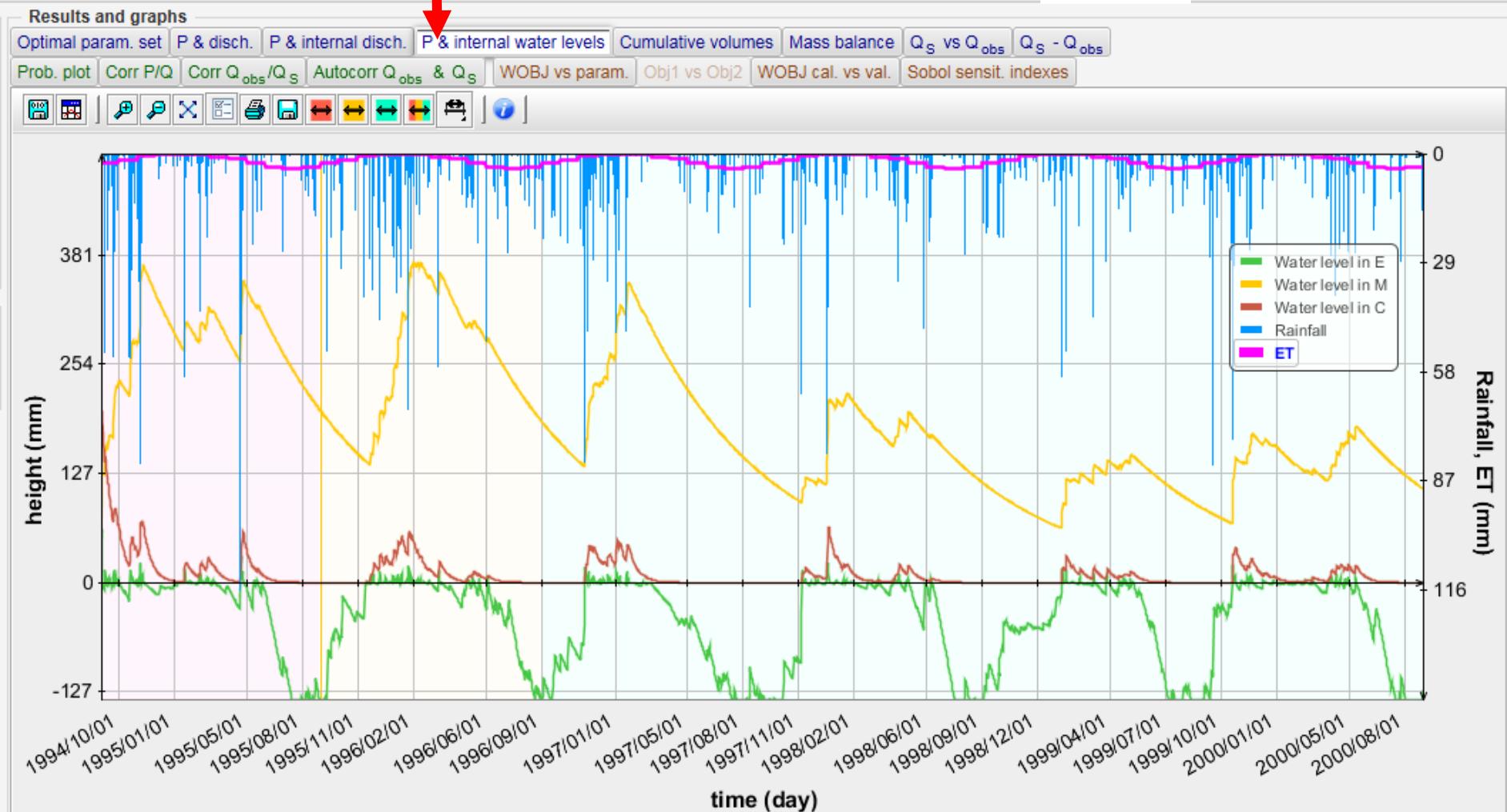
- Usefull to separate baseflow and quickflow
- Check if all the reservoirs are used for flow



Rainfall and internal water levels

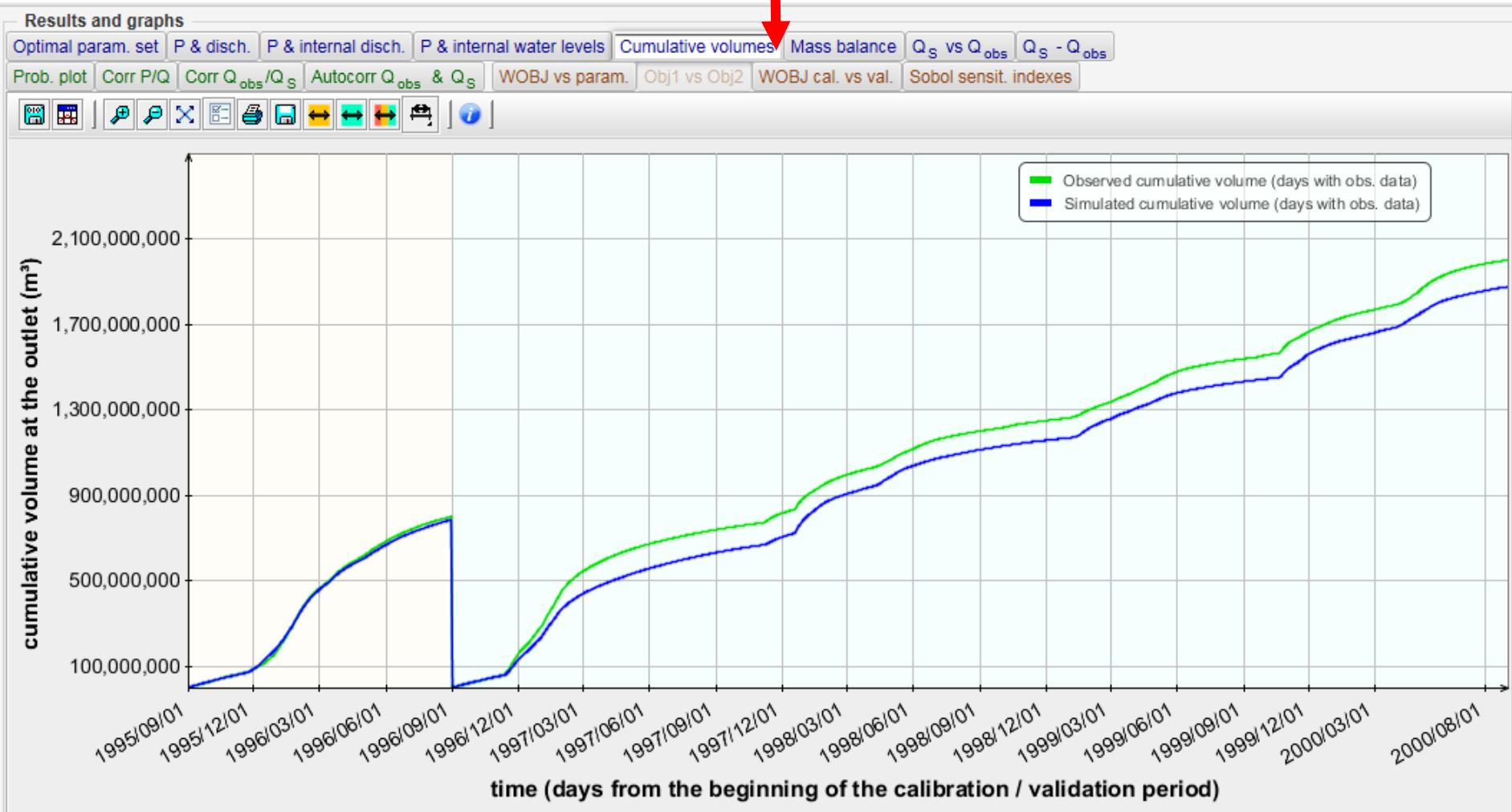


- To check if the model is not loosing or storing some water in reservoirs
- To check the effect of the warm-up period
- To simulate water level $Z = Z_0 + \frac{A}{w}$



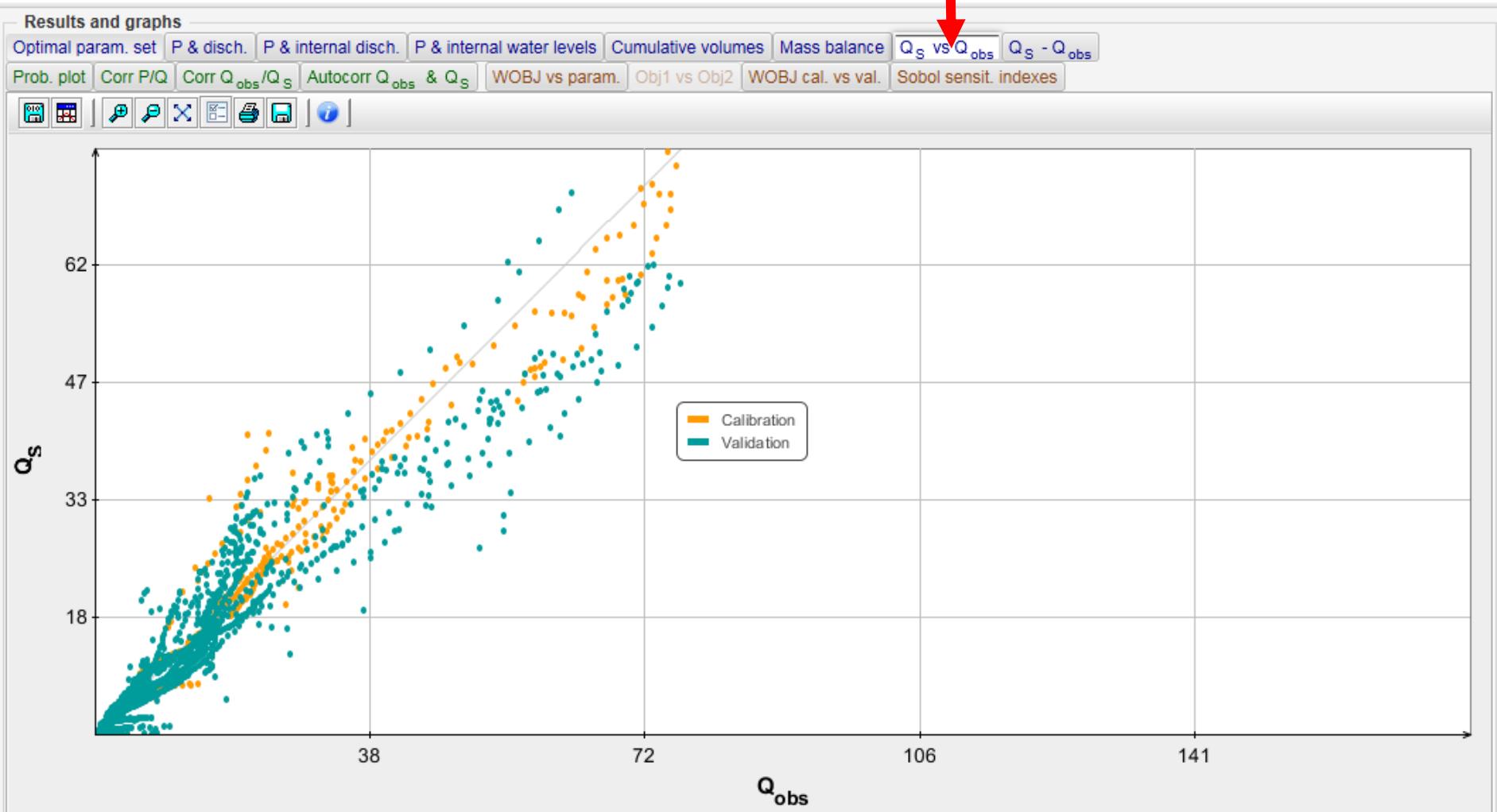
- - To check the balance error

Cumulative volumes



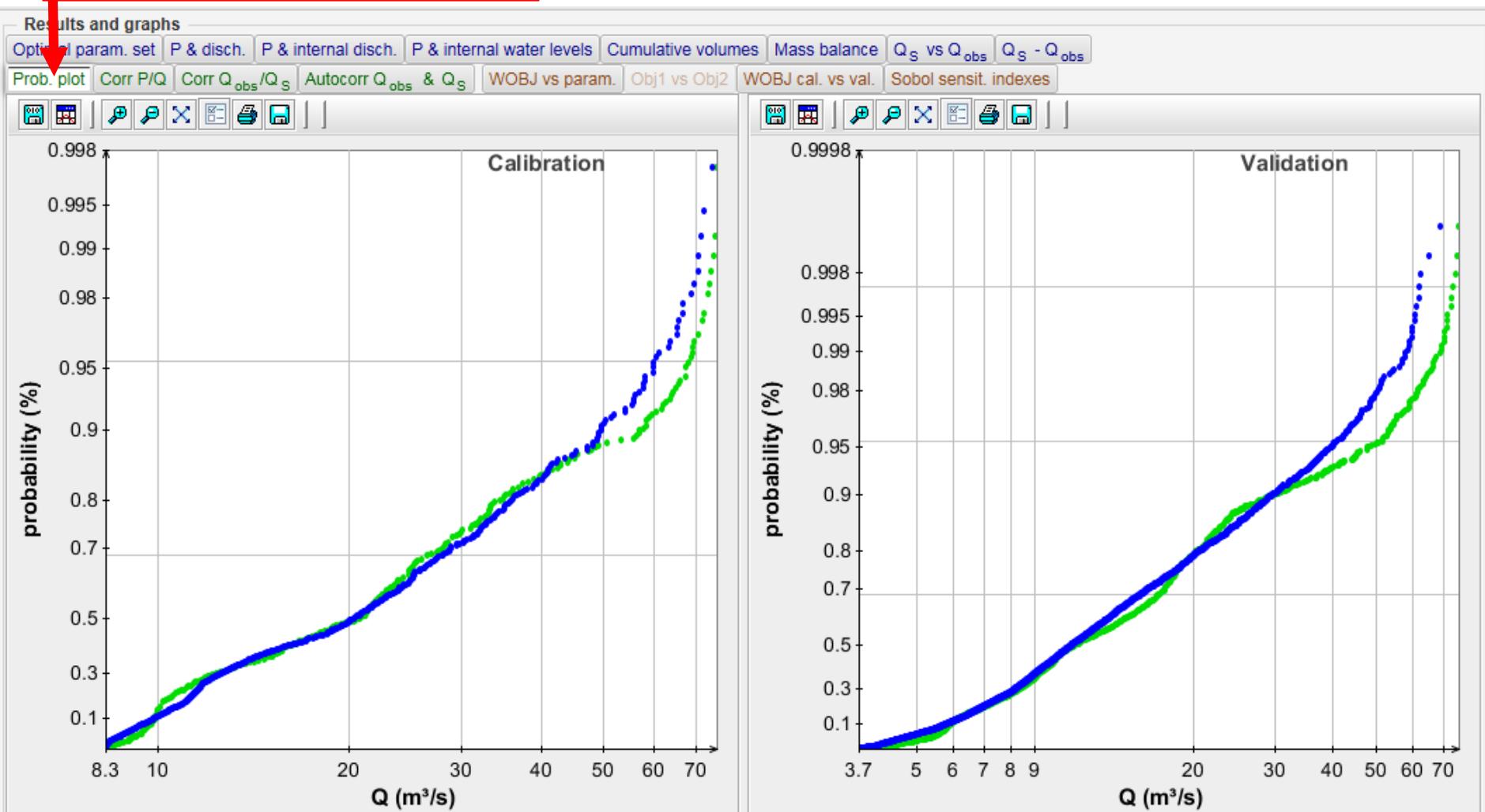
- - To check for systematic drift

Qsimulated VS Qobserved



- - To check for thresholds (input or output) in time series

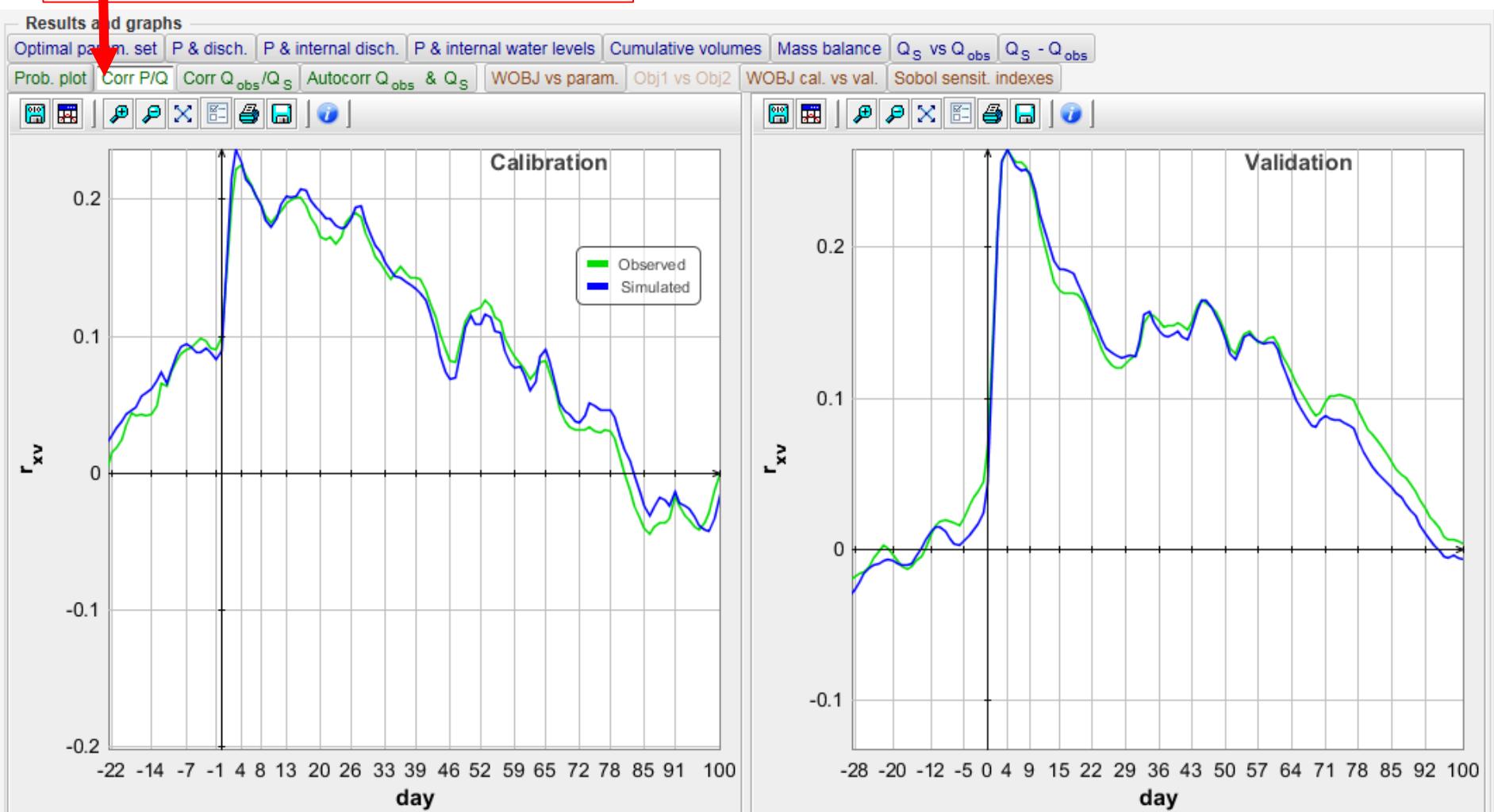
Cumulative probability plot



- A tool for karst hydrograph characterization and aquifer functioning rating
- To compare observed and simulated discharge
- To check for time-lag between rain and discharge variation



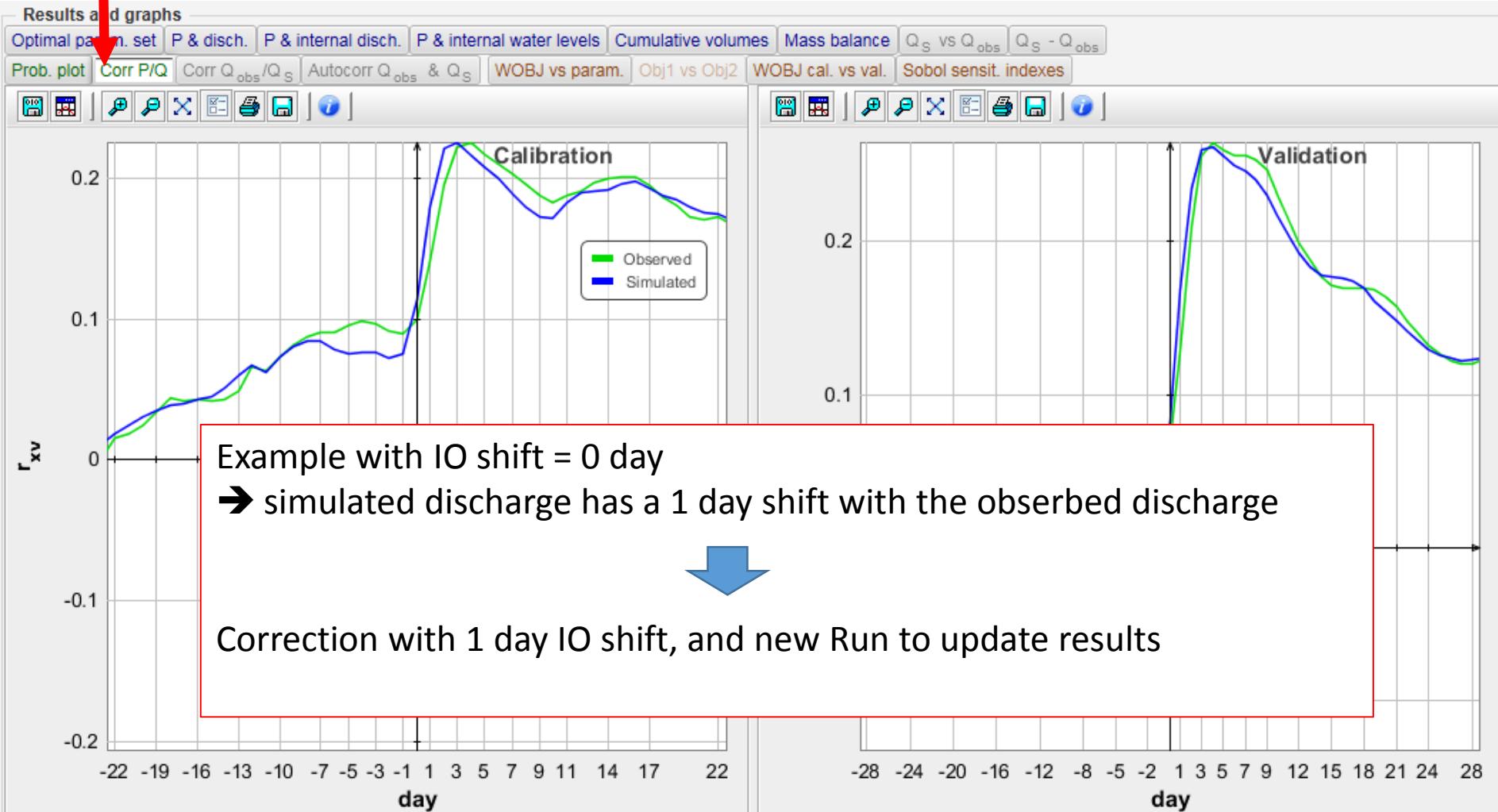
Cross correlogram Rain-Discharge





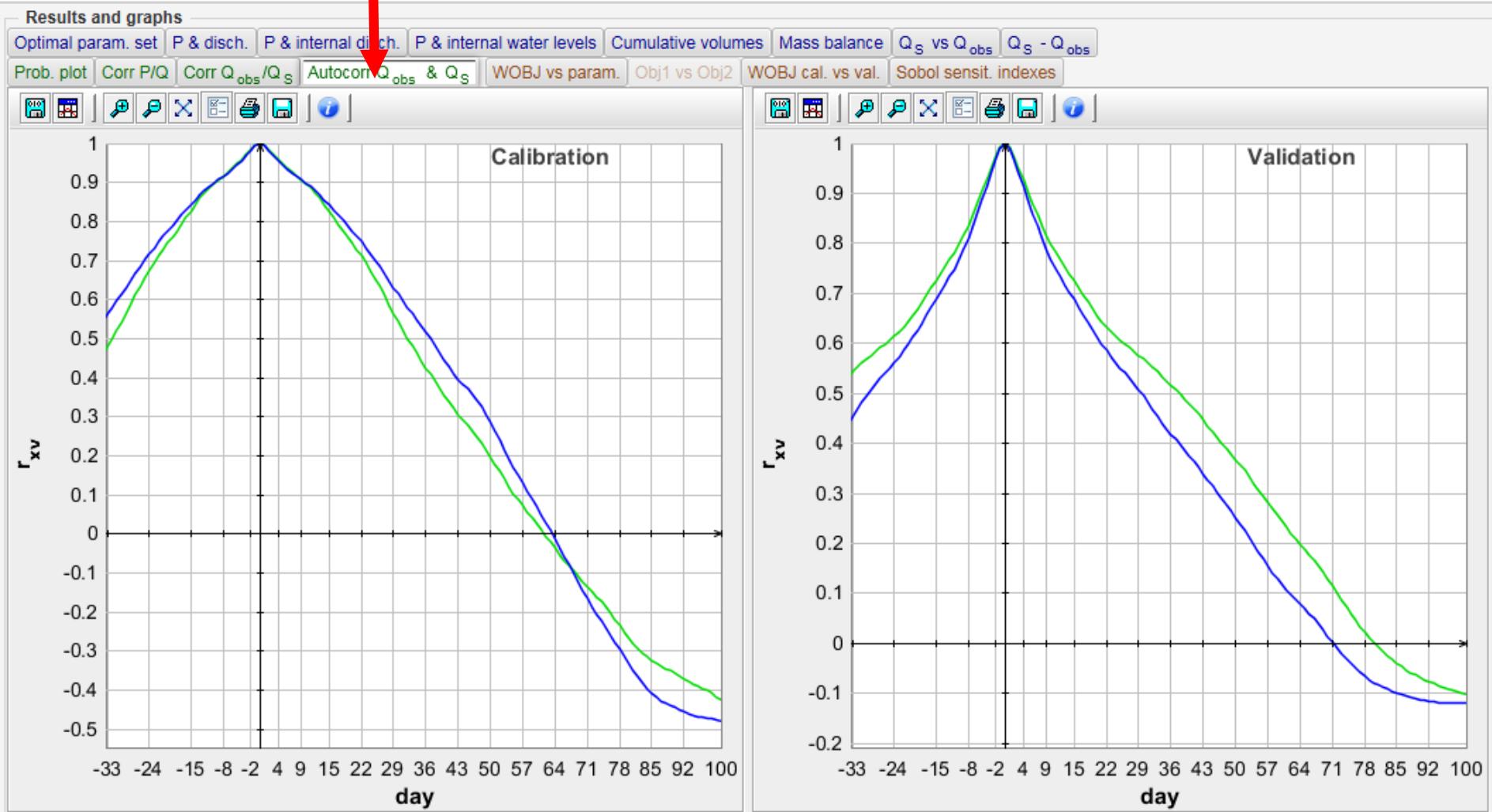
- To check for time-lag between rain and discharge variation : correction with the IO shift tool of KarstMod

Cross correlogram Rain-Discharge



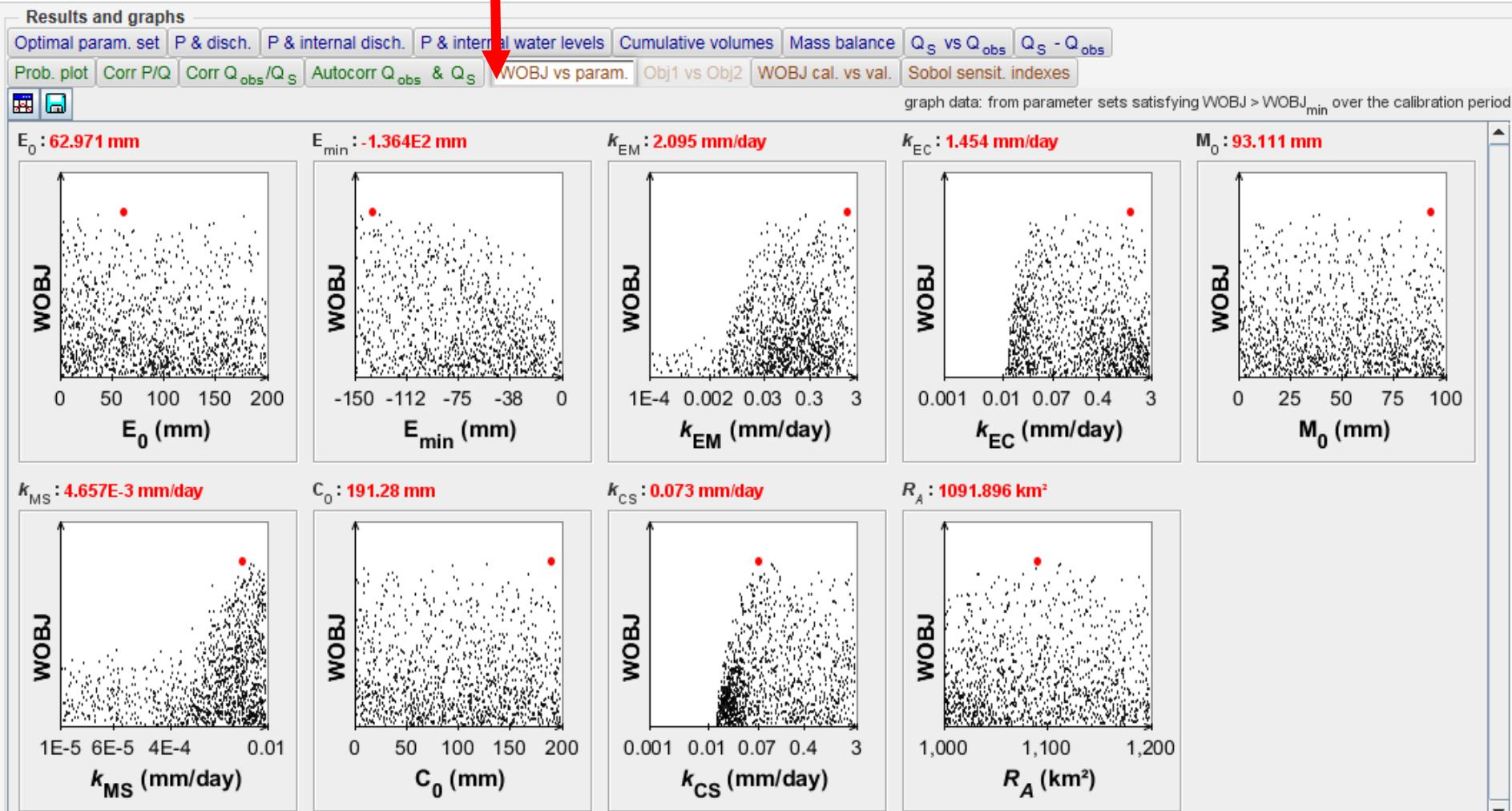
- - A tool for karst hydrograph characterization and aquifer functioning rating
- To compare observed and simulated discharge

Discharge correlogram





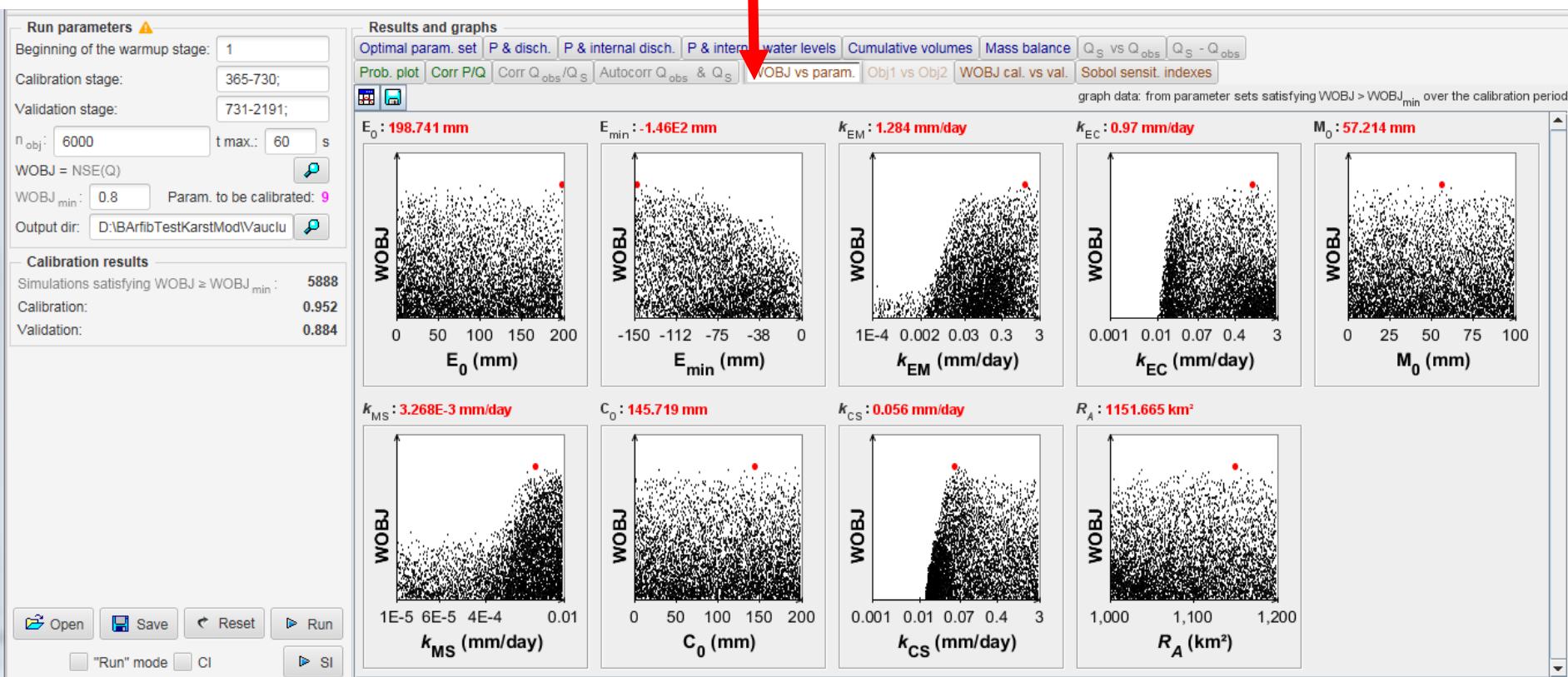
Objective function VS parameter value



New example with more results (parameter sets satisfying $W_{OBJ} > W_{OBJmin}$)

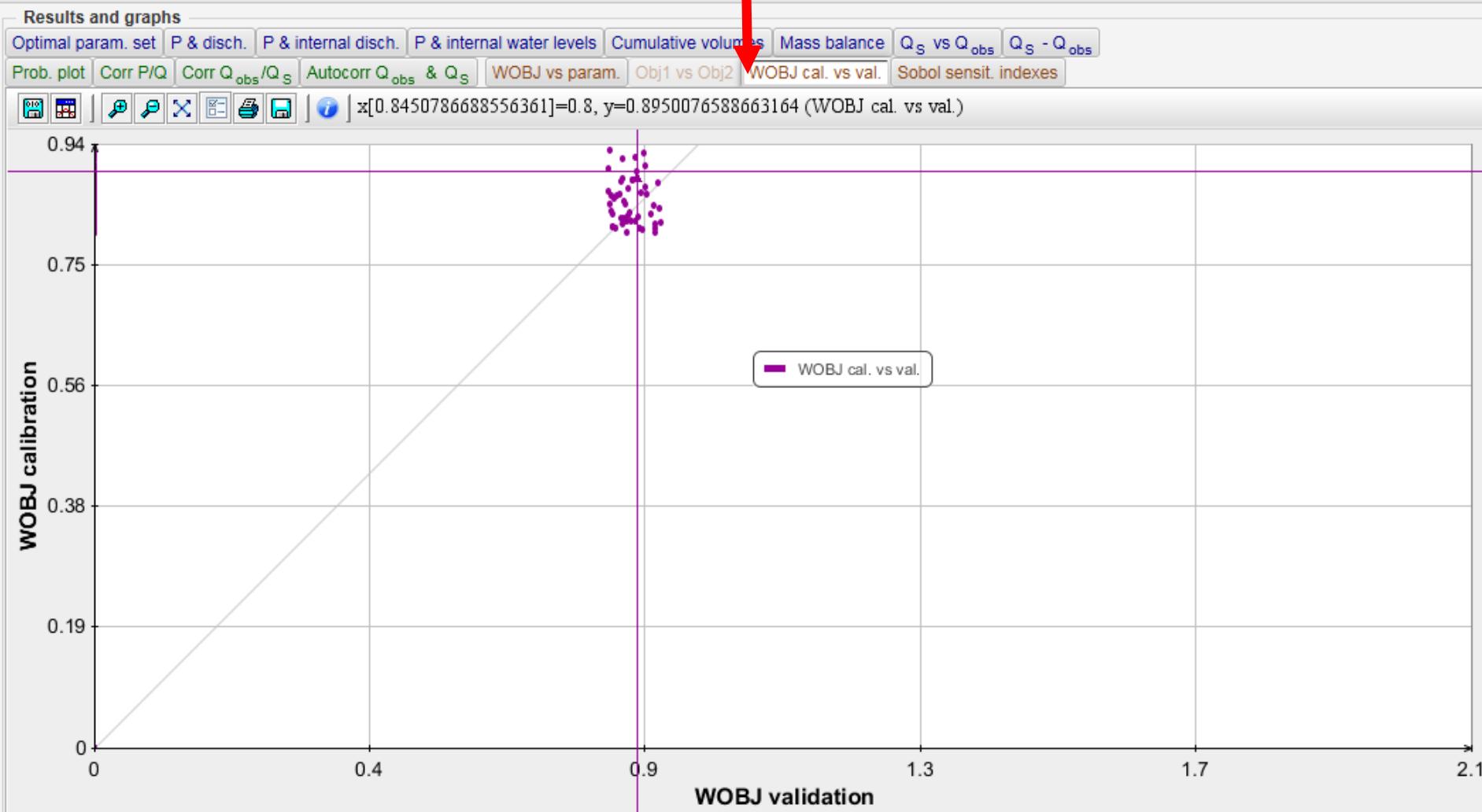
- At the end of the equifinality analysis, a new Run can be performed.
- The range of the parameter KEM, KMS and KCS can be reduced.
- The results of these graphs can be compared with the results of the Sobol sensitivity index

Objective function VS parameter value

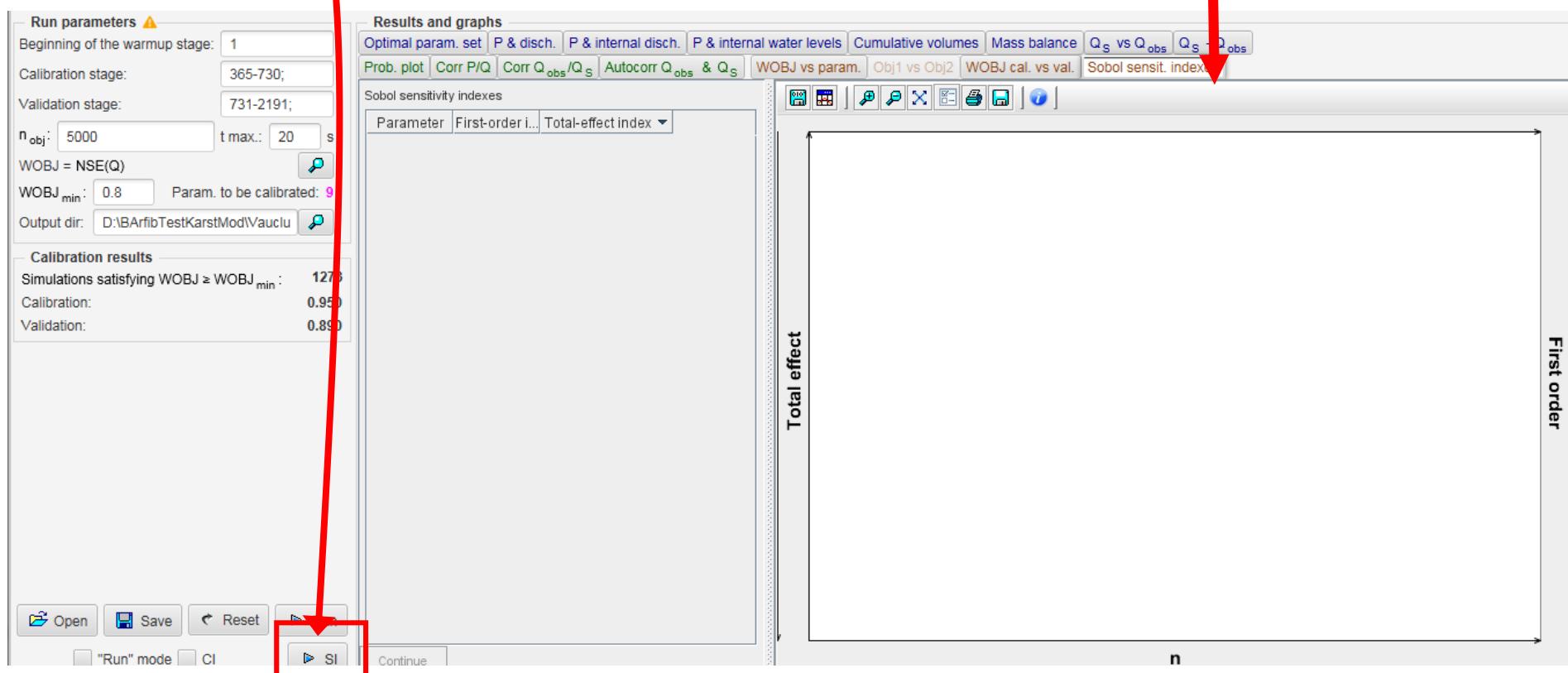




Objective function calibration VS validation

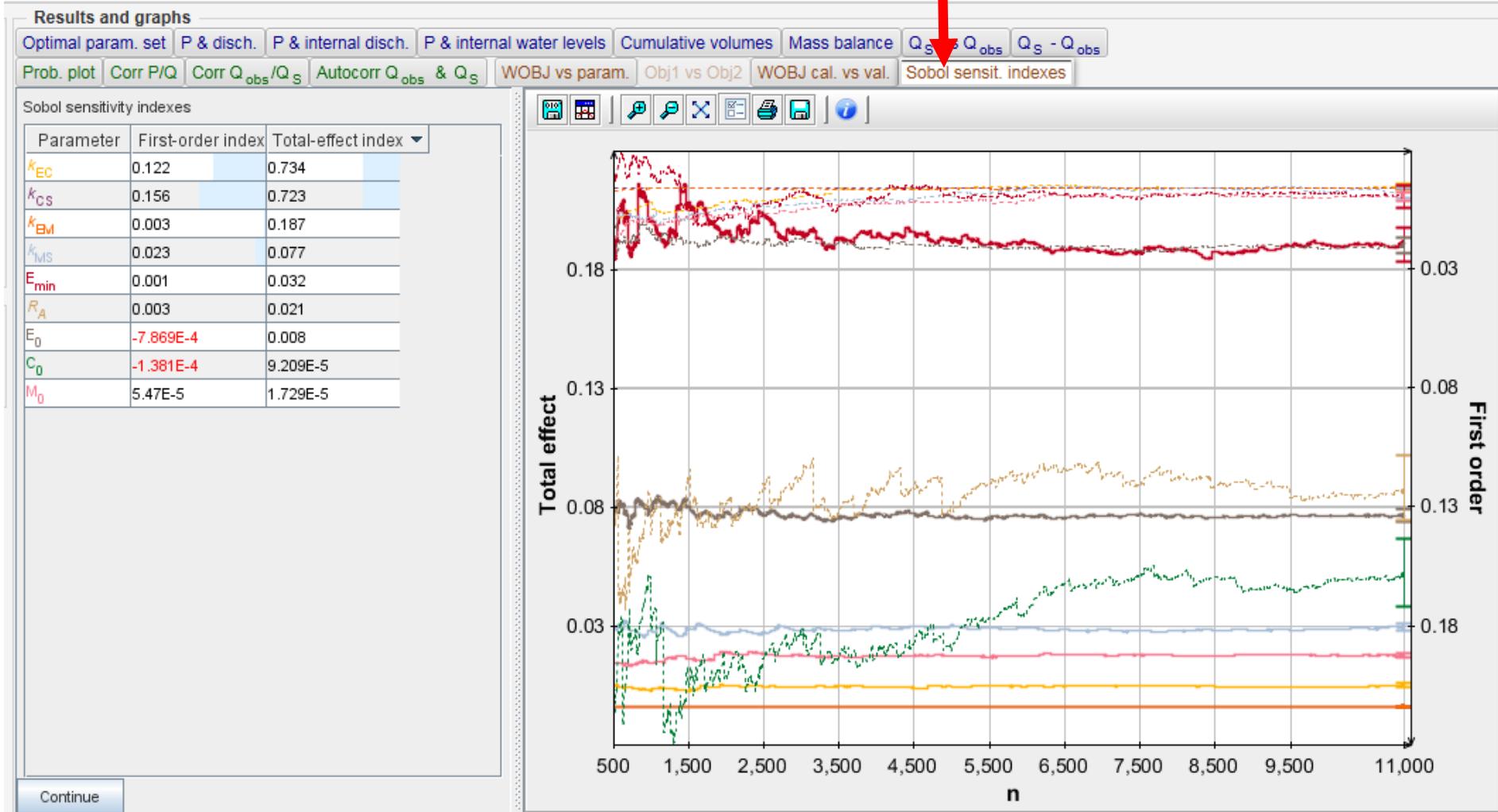


Run the « SI » tool



Sobol sensitivity index

Sobol sensitivity index



You need a conceptual scheme of hydrogeological functioning of your karst hydrosystem :

- Soil reservoir and reserve?
- Hysteretic law?
- 1, 2 or 3 lower reservoirs?
- Pumping?
- Loss?
- Interconnection between lower reservoirs?

Your choice depends on :

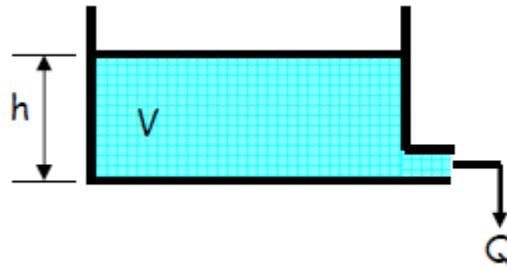
- The functioning of the case study
- Your level of knowledge of the functioning of the case study
- The goal(s) of the modeling

Your first model is fine?



Start a new model or explore the output files

Supplementary material : Hysteretic function



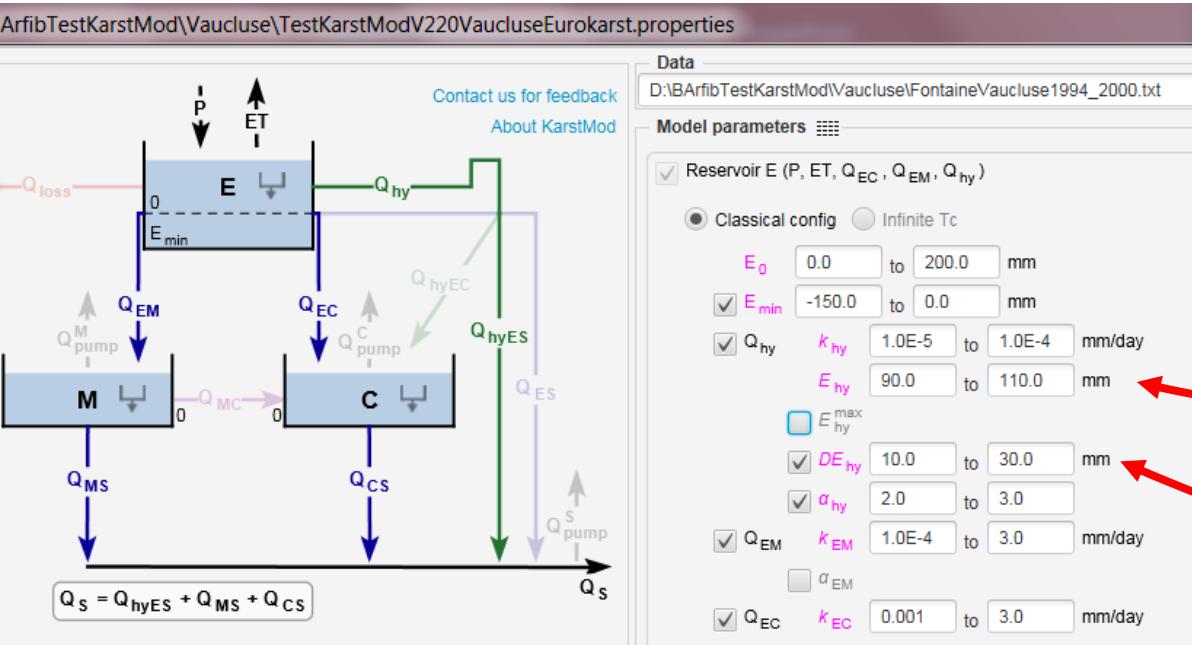
Linear function between height of water and specific discharge (Qt: L/T)

$$Q_t = K \cdot h$$

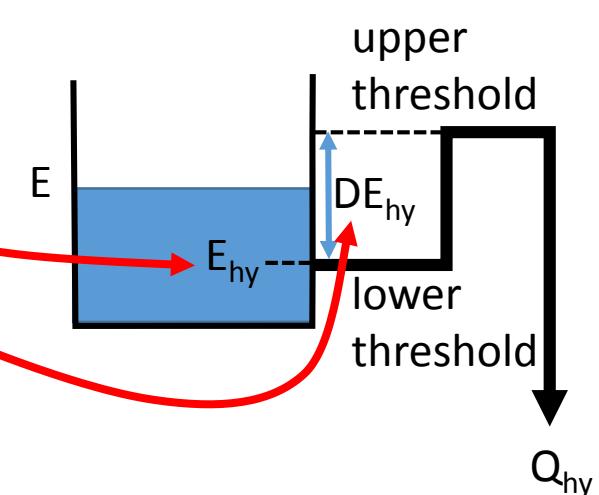
Discharge = $Q_t \cdot S$, with S = Recharge area

Non linear function

$$Q_t = K \cdot h^\alpha$$



Hysteretic function



If $DE_{hy}=0$ (also named ΔE_{hy}), the hysteretic function simplifies to a threshold discharge function

$$Q_{hy} = \varepsilon_{HY} \times k_{hy} \left(\frac{E - E_{hy}}{L_{ref}} \right)^{\alpha_{hy}}$$

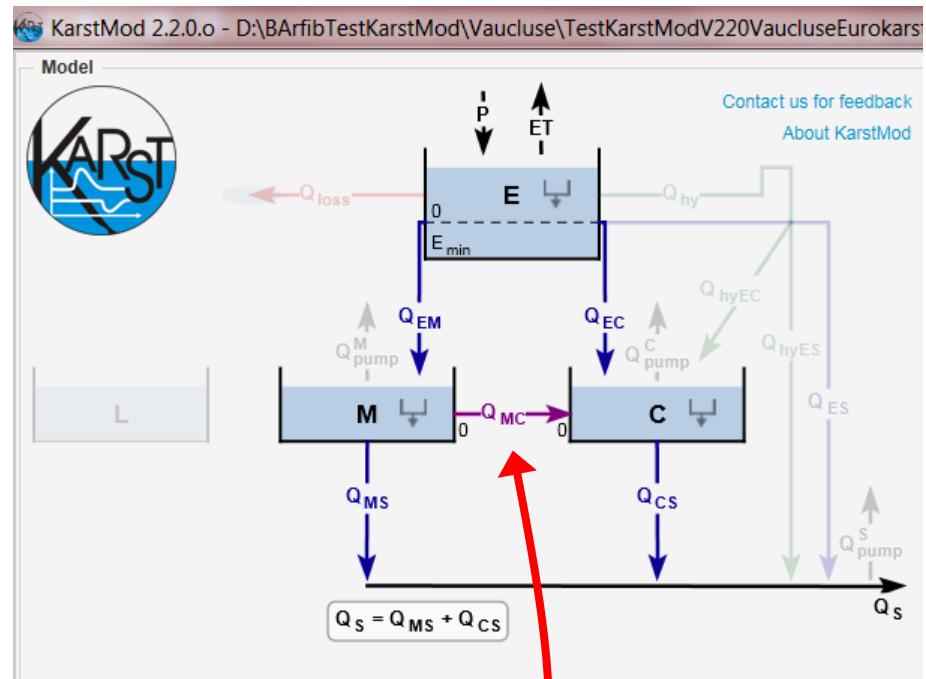
$$Q_{hyEC} = x_{hy} \times Q_{hy}$$

$$Q_{hyES} = (1 - x_{hy}) \times Q_{hy}$$

$$\begin{cases} \varepsilon_{HY} = 0 \\ E = E_{hy} + \Delta E_{hy} \end{cases} \Rightarrow \varepsilon_{HY} = 1$$

$$\begin{cases} \varepsilon_{HY} = 1 \\ E = E_{hy} \end{cases} \Rightarrow \varepsilon_{HY} = 0$$

Supplementary material : Exchange function Q_{MC}



Exchange function (Q_{MC}) The Q_{MC} function is defined as follows:

$$Q_{MC} = k_{MC} \times \text{sgn}(M - C) \times \left| \frac{M - C}{L_{ref}} \right|^{\alpha_{MC}} \quad (5)$$

where k_{MC} [L/T] is the specific discharge coefficient, and α_{MC} [-] is a positive exponent.

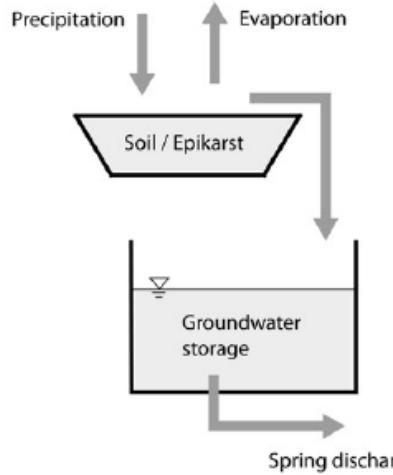
Warning Q_{MC} is defined as the algebraic flow from compartment M to compartment C. Negative Q_{MC} values mean that the current direction of flow is from C to M.

Warning When the inter-compartment flux Q_{MC} is activated, the M and C compartments must be either both bottomless, or both with bottom. Q_{MC} activation also requires the classical configuration to be selected for both M and C.

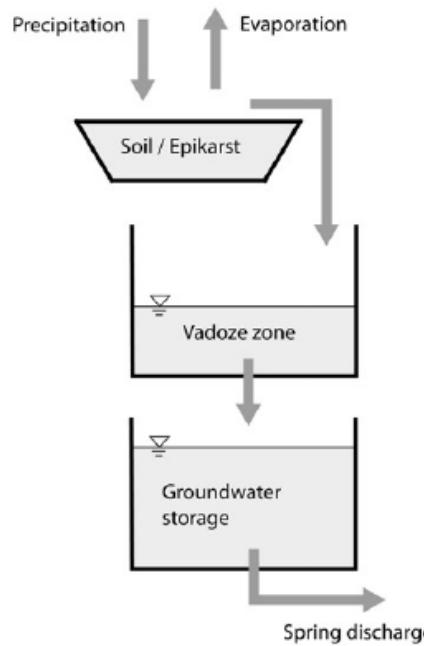
Few structures for conceptual models

A. Hartmann et al./Journal of Hydrology 468–469 (2012) 130–138

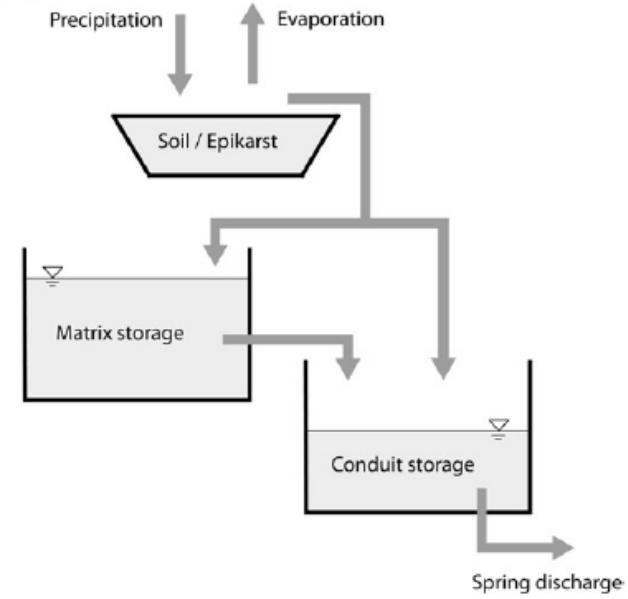
(a)



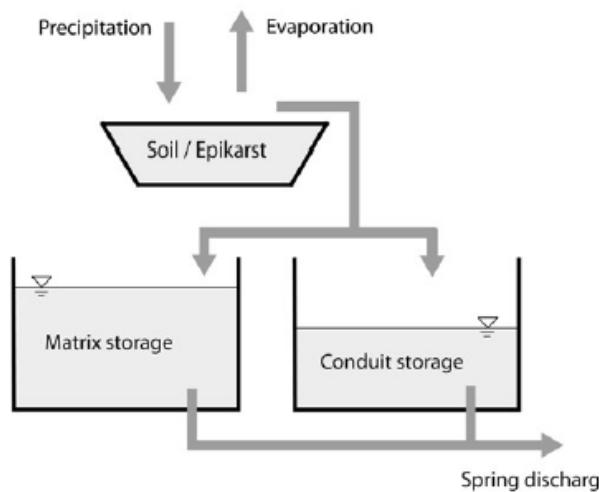
(b)



(c)



(d)



(e)

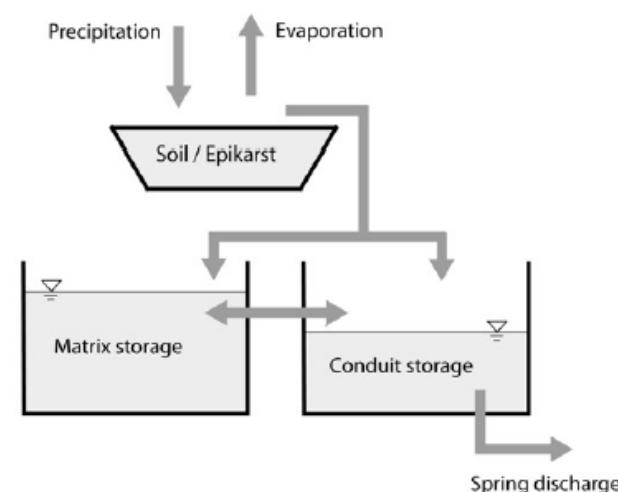


Fig. 3. The hydrological model ensemble: (a) simple model, (b) serial model, (c) combined model, (d) parallel model, and (e) exchange model.