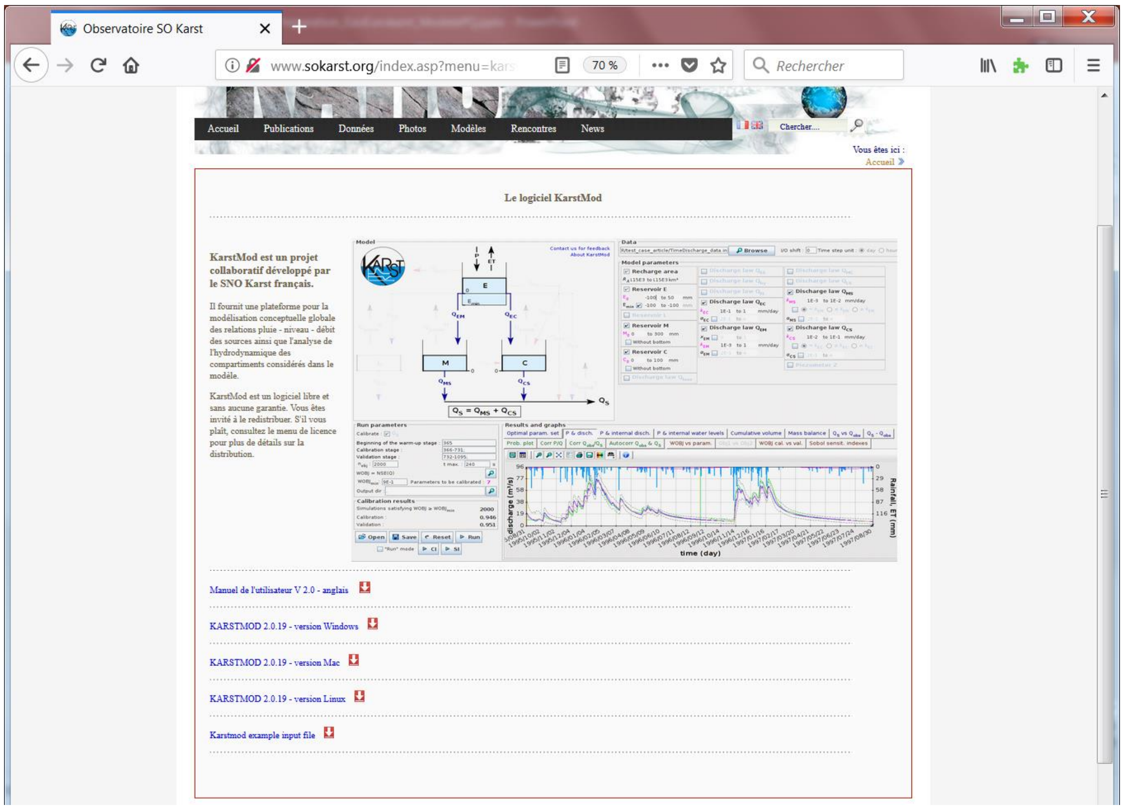
Rainfall-Discharge modeling

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)

Service National d'Observation

Dardennes_input_V2_PluieLimateRecons.txt - Bloc-notes

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 « ! »

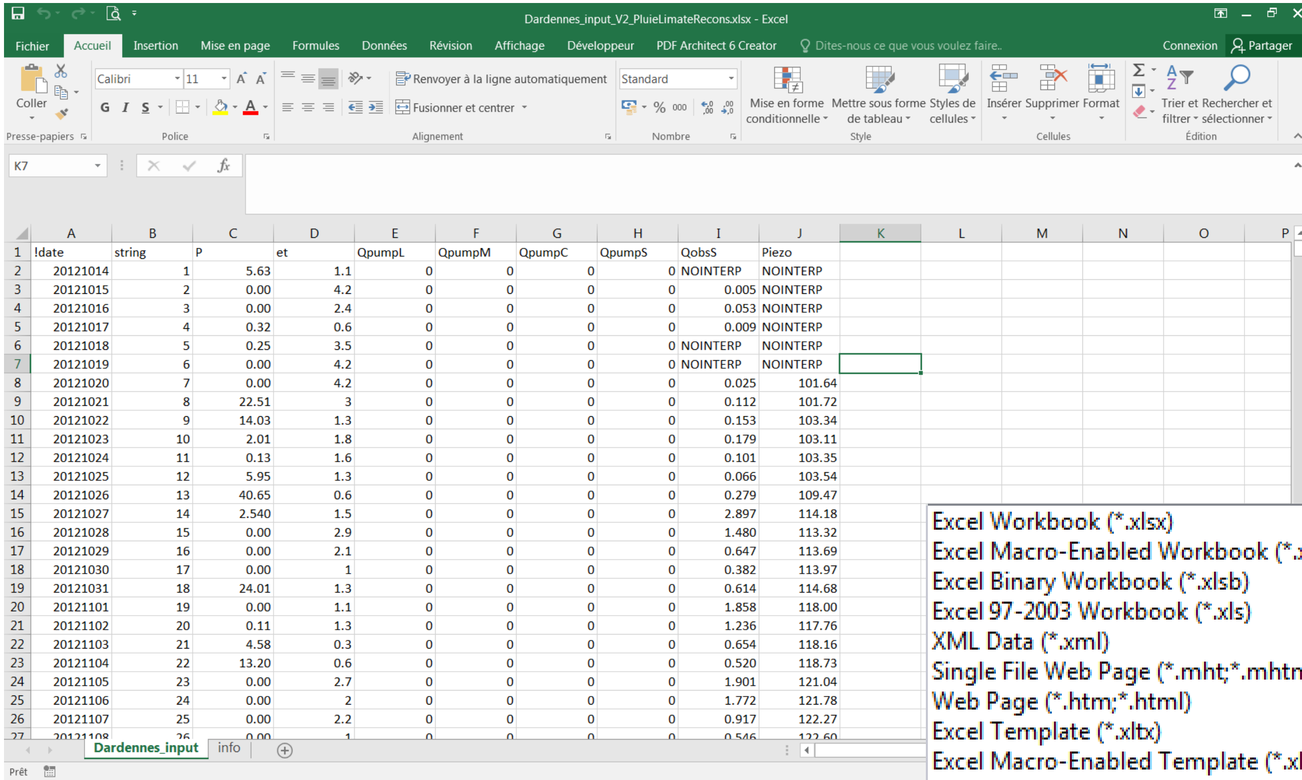
5.3.1 Input data

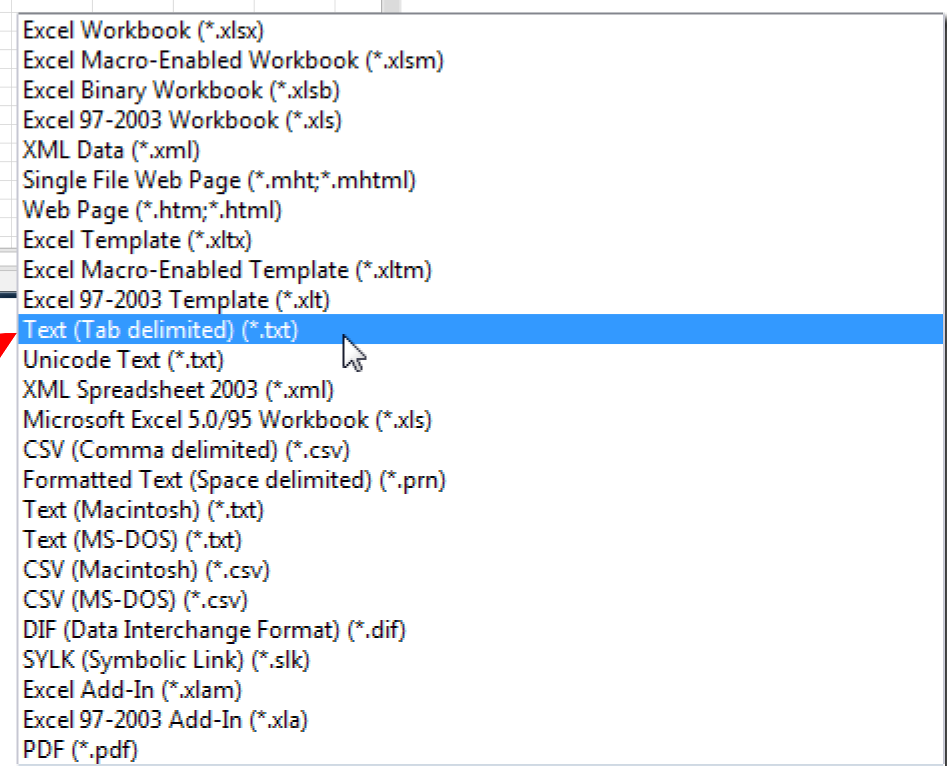
The input data file contains the rainfall, evapotranspiration, pumped discharge and observed discharge and hydraulic head values. It is organized in 10 columns separated by tabs (See example in figure 4):

- 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^{L}_{pump} pumped into compartment L (m^3/s),
- column 6 - discharge Q^{M}_{pump} pumped into compartment M (m^3/s),
- column 7 - discharge Q^{C}_{pump} pumped into compartment C (m^3/s),
- column 8 - discharge Q^{S}_{pump} pumped at the outlet (m^3/s),
- column 9 - discharge Q_{obs} observed at the outlet (m^3/s),
- column 10 - hyraulic 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.

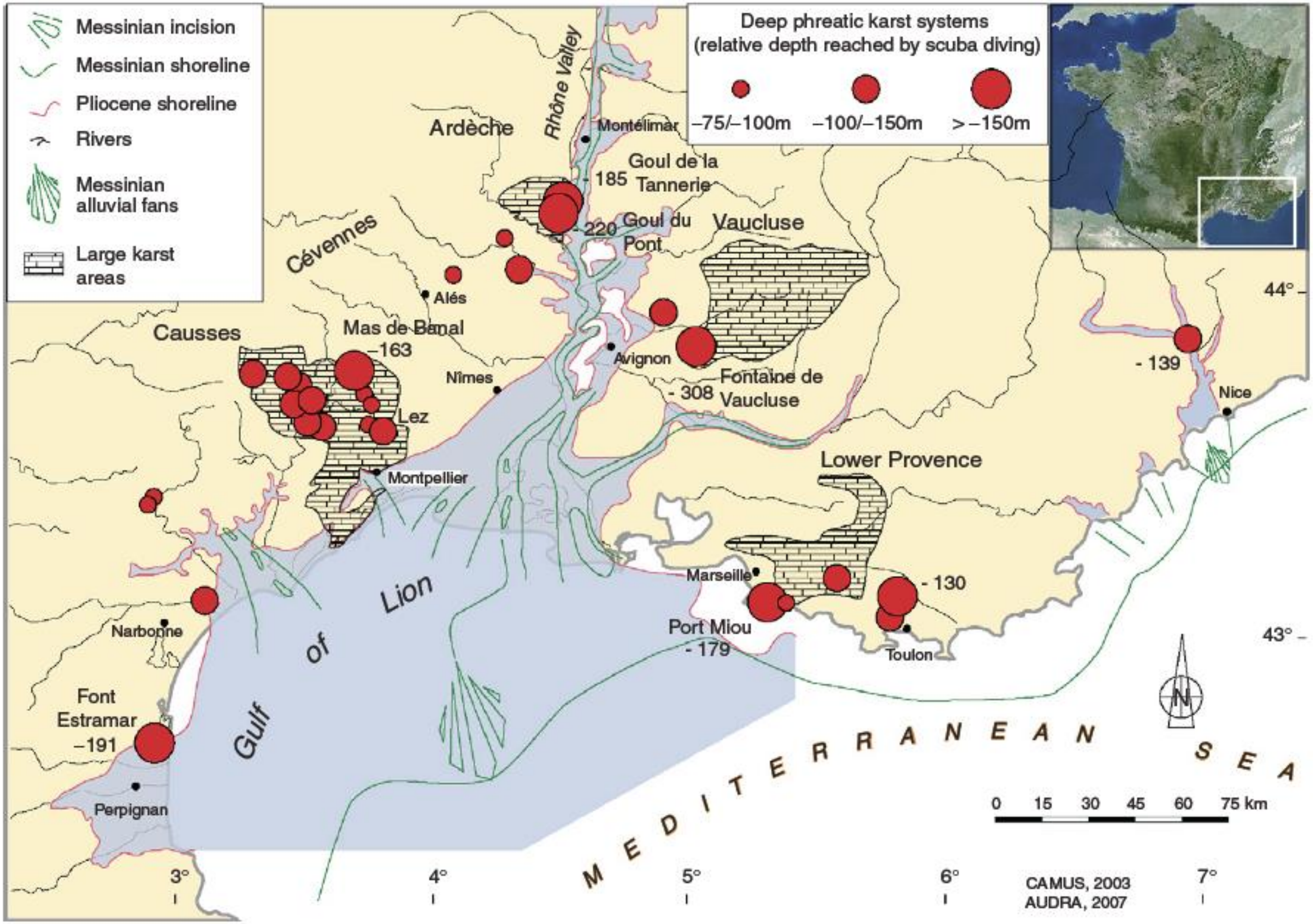
Create the input data file for KarstMod : export in txt (Tab delimited)



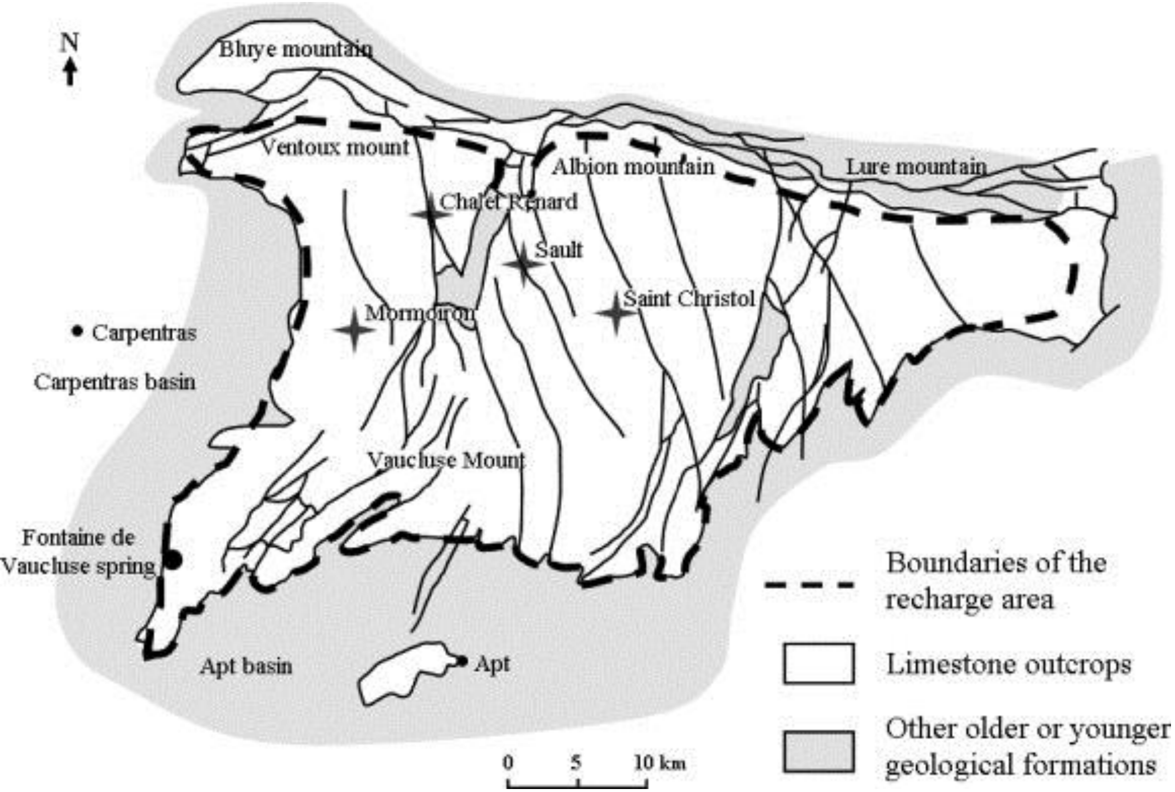


Create the input data file for KarstMod :
« Save as » Type : Text (Tab delimited)

Case study : Fontaine de Vaucluse (France)



Case study : Fontaine de Vaucluse (France)

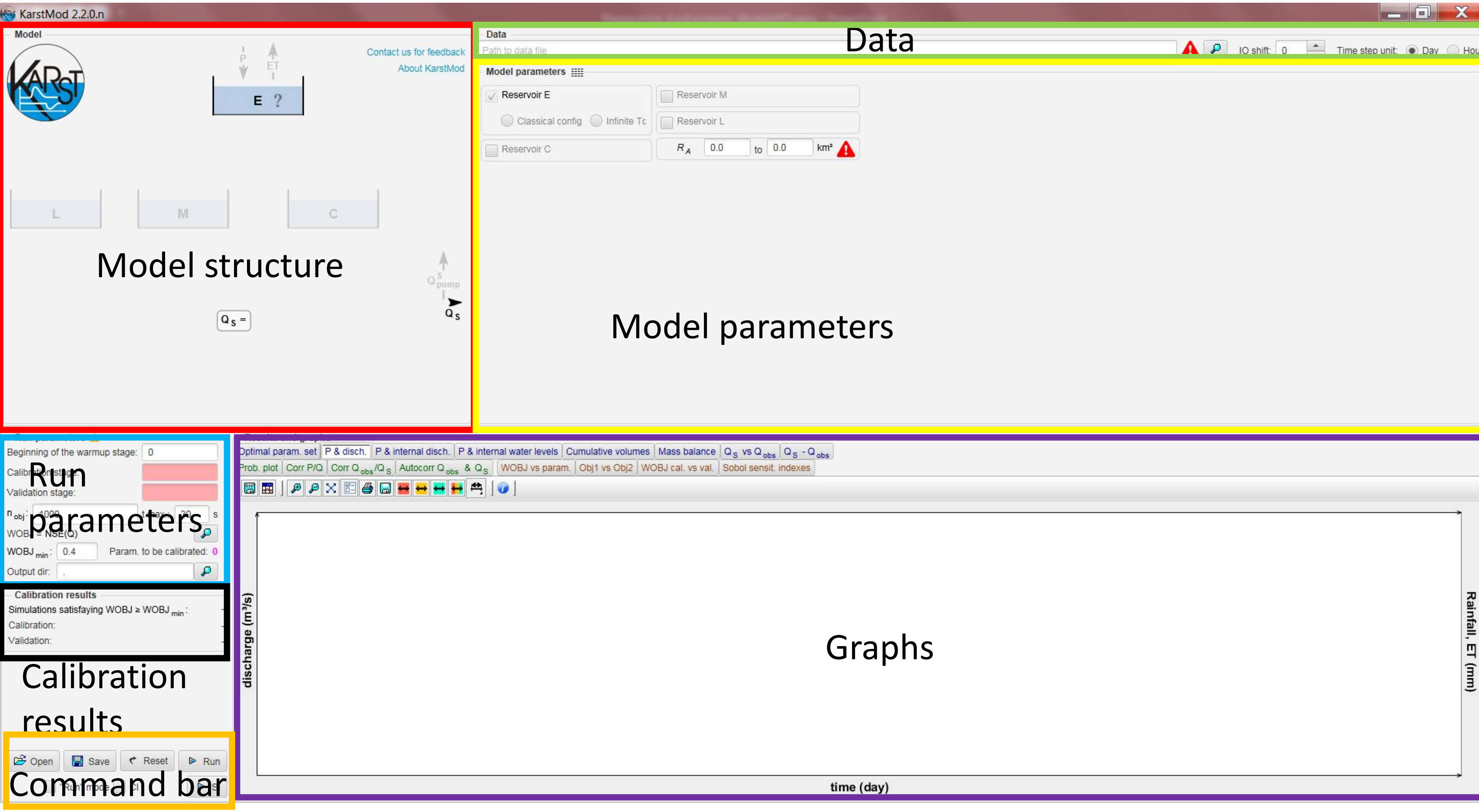


- BV ≈ 1100 km²
- Q_{max} ≈ 150 m^3/s
- Q_{min} ≈ 3,0 m^3/s

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

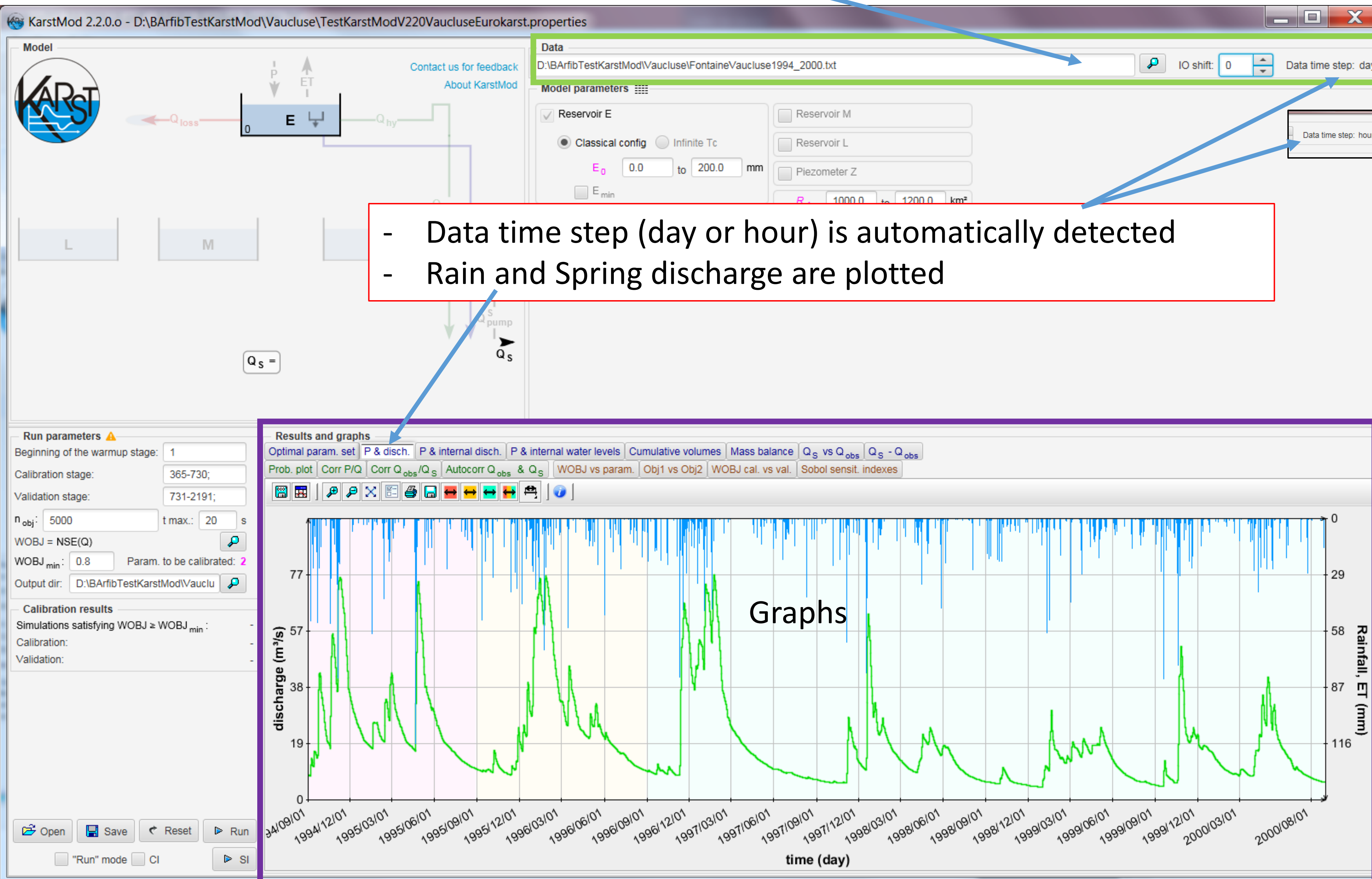
Open KarstMod

7 sub-windows



First model

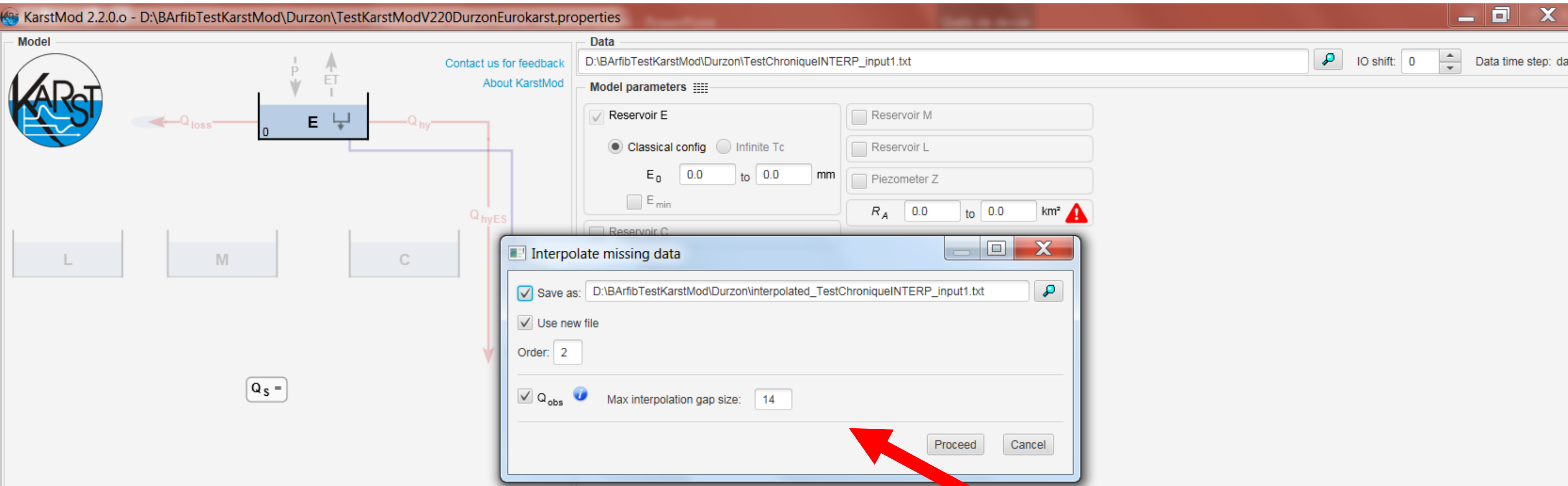
1 : open Data file (.txt or .in)



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)

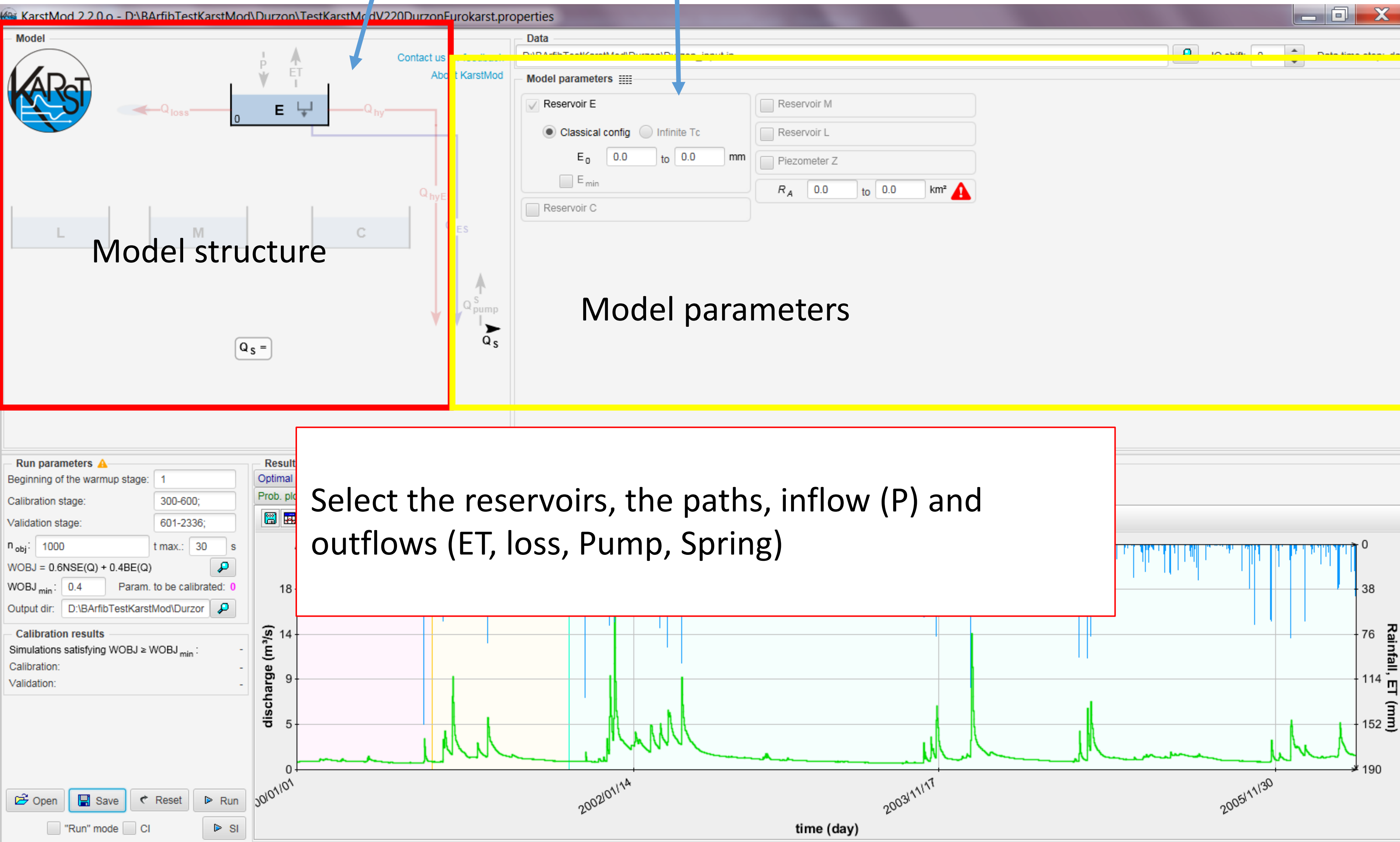
5.2.3 Filling gaps in discharge or piezometric data

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

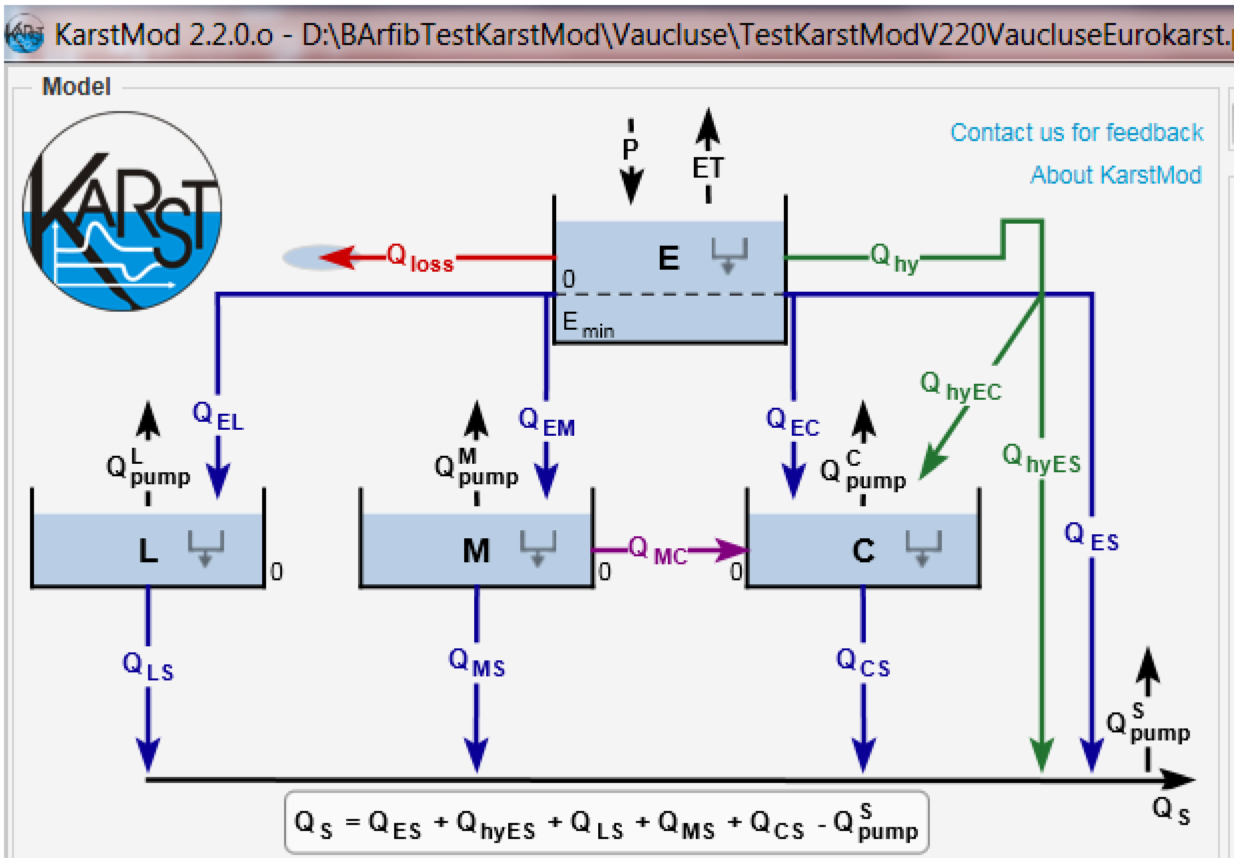


Select the reservoirs, the paths, inflow (P) and outflows (ET, loss, Pump, Spring)

First model | 2 : Model structure and model parameters

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?



"Classical config" modeling

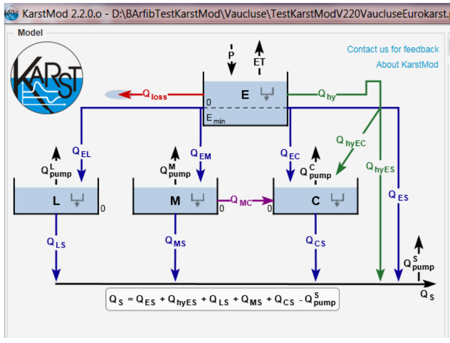
First model | 2 : Model structure and model parameters

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 :

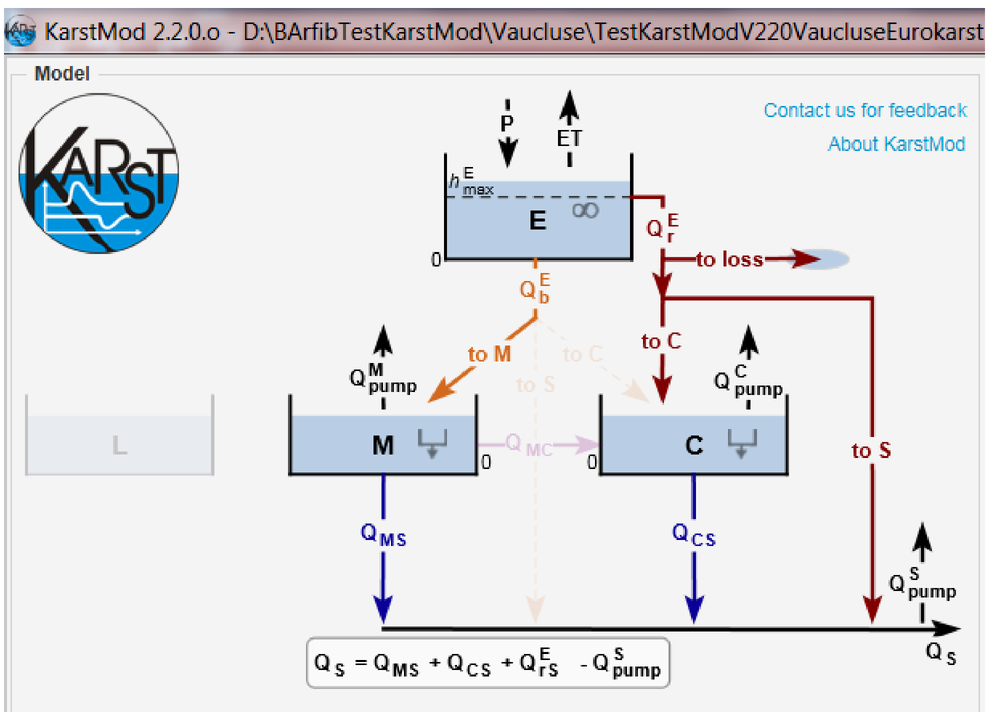
- The functioning of the case study
- Your level of knowledge of the functioning of the case study
- The goal(s) of the modeling



First model | 2 : Model structure and model parameters

2 modeling configuration available for each reservoir

- Classical config. (Maillet's law)
- Infinite characteristic time config.



Infinite Tc :

- Reservoir is partitionning into n sub-reservoirs with linear discharge laws, all running in parallel ➔ Q^E_b

- When the water level Ei becomes larger than hEmax, the ith sub-reservoir is bypassed and the corresponding overflow Q^{Ei}_r is routed directly to the spring (or to the reservoir C or to loss).

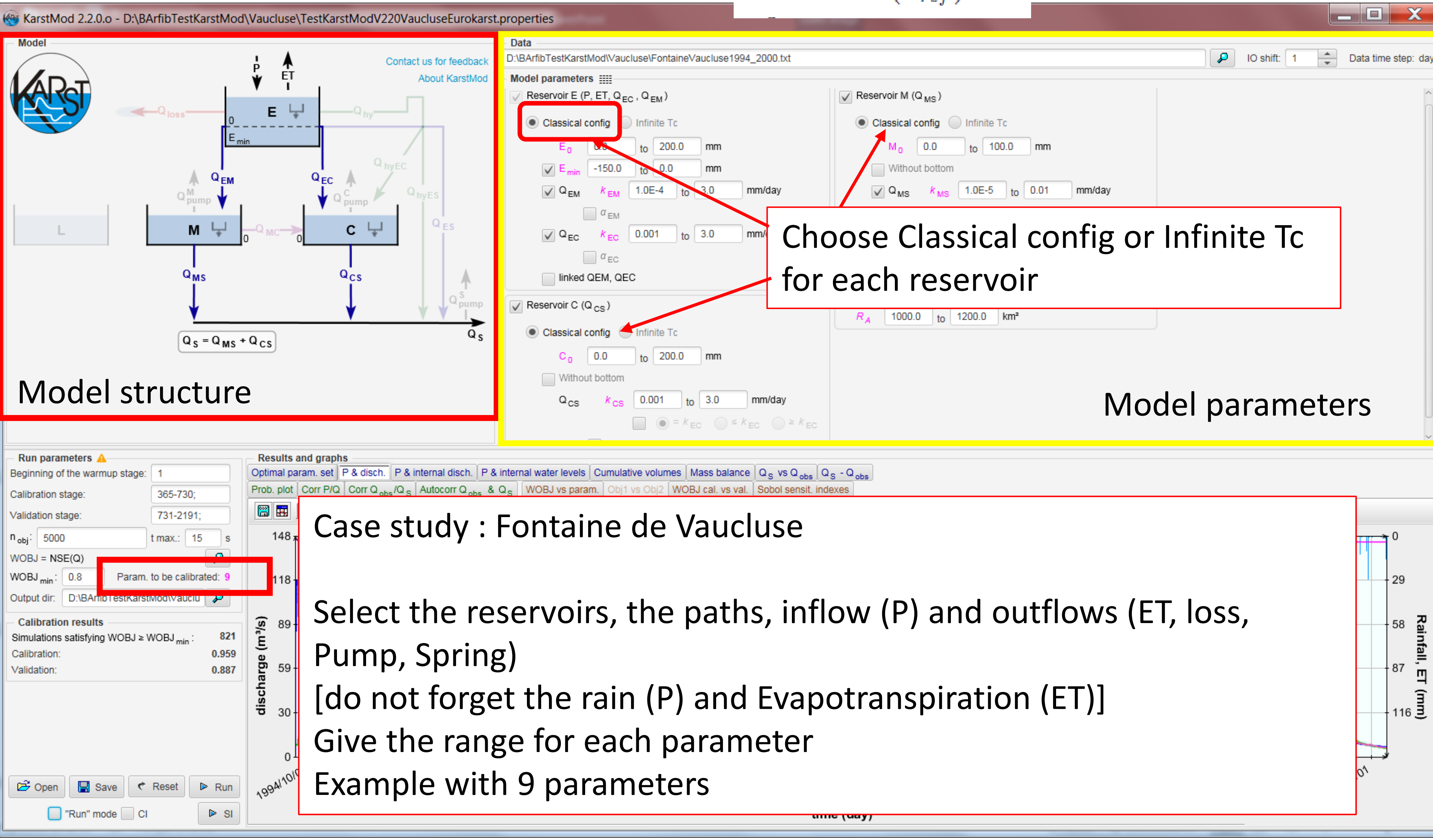
First model 1 | 2 : Model structure and model parameters

Classical configuration. Linear discharge law.

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

A: height of water in reservoir A

α = 1



Case study : Fontaine de Vaucluse

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

[do not forget the rain (P) and Evapotranspiration (ET)]

Give the range for each parameter

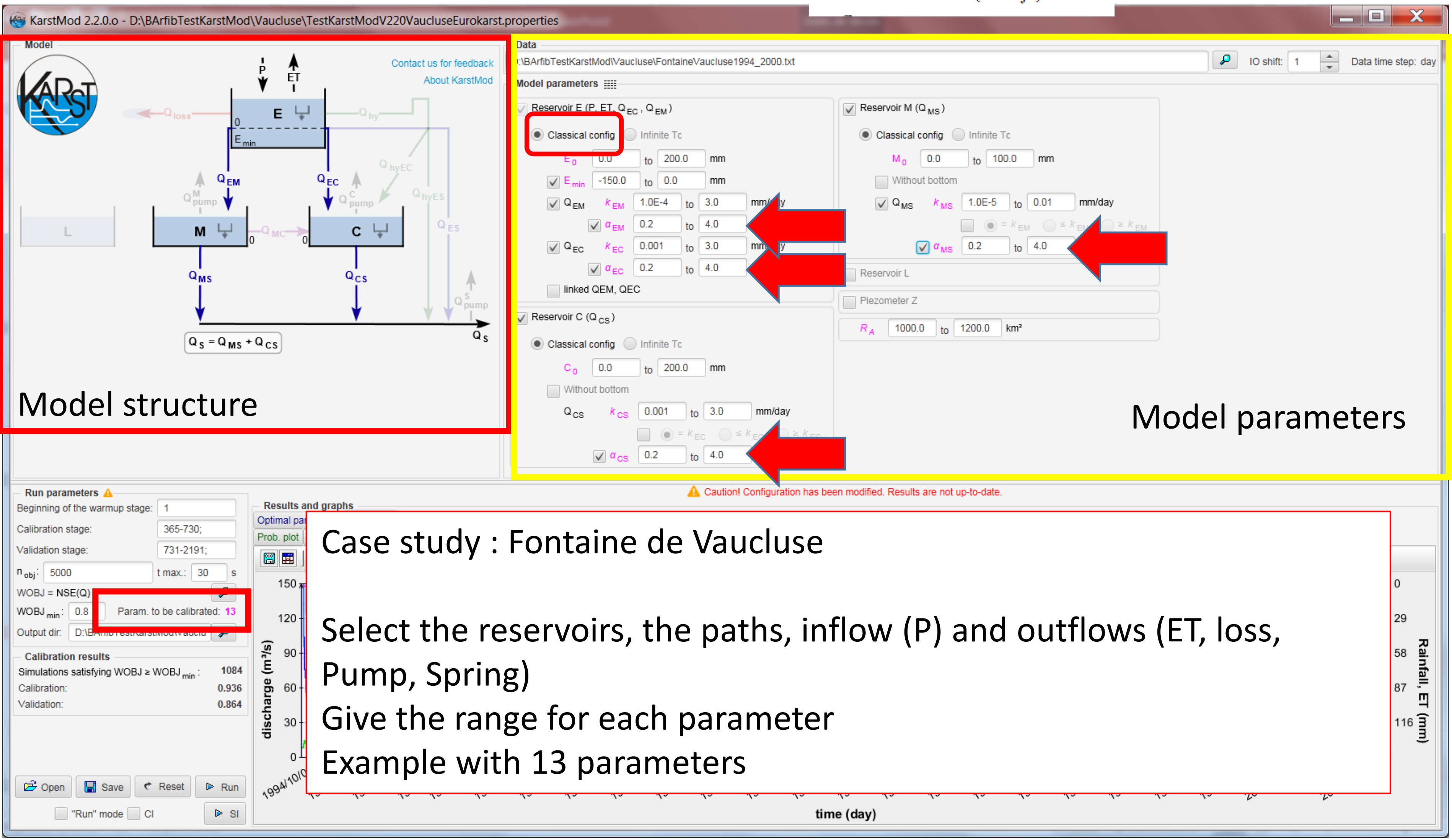
Example with 9 parameters

First model 2 | 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
$\alpha \neq 1$

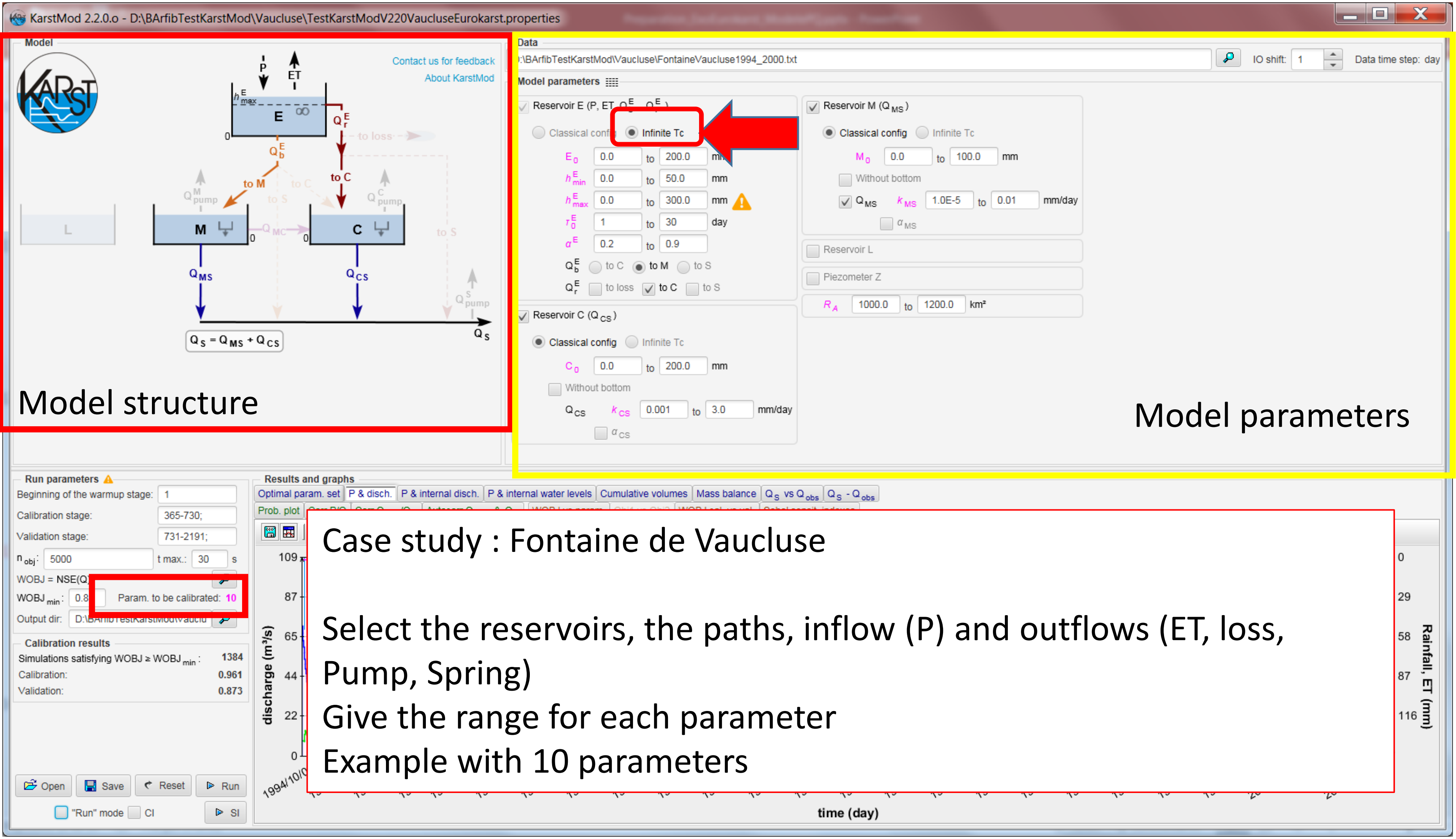


Case study : Fontaine de Vaucluse

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.



Case study : Fontaine de Vaucluse

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

Give the range for each parameter

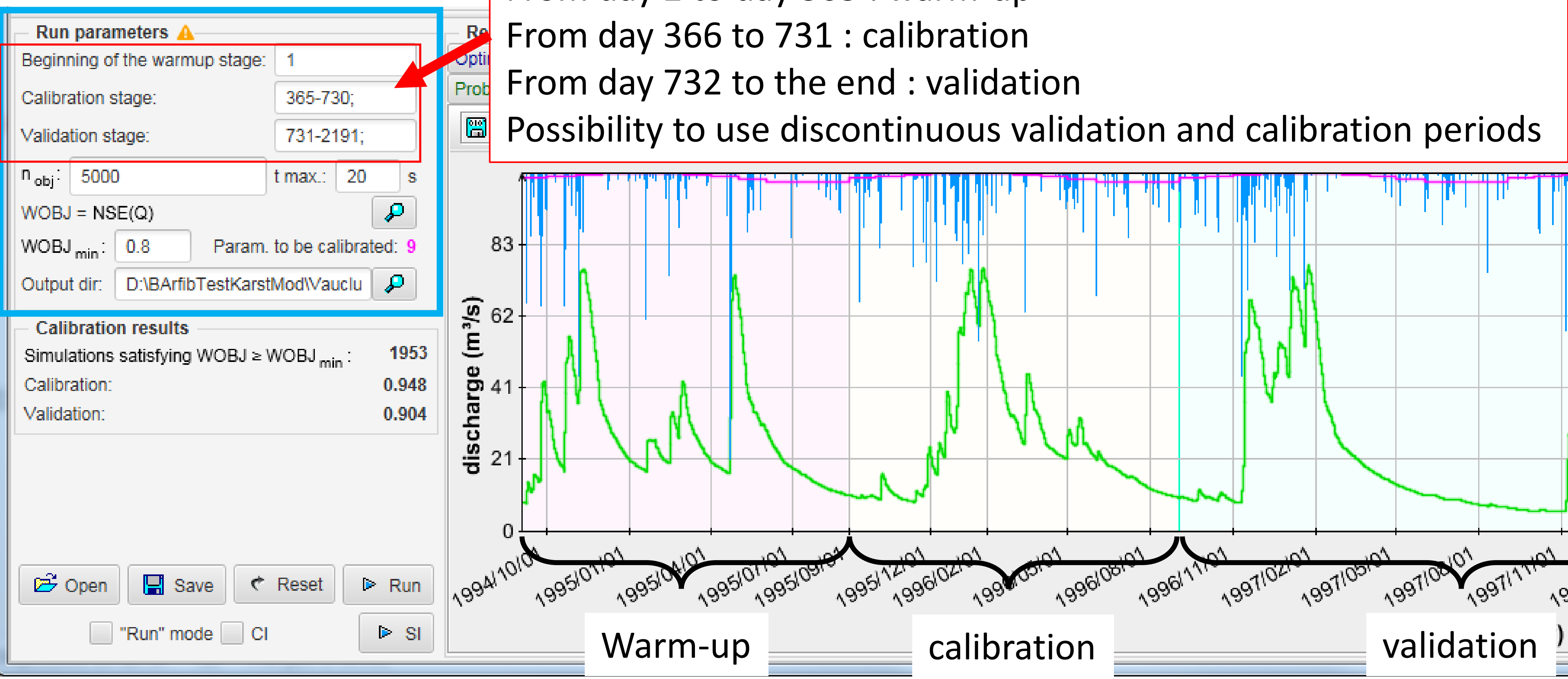
Example with 10 parameters

First model

3 : Run 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.

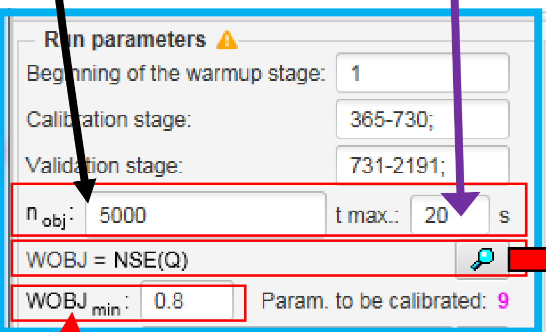
Index starts at 0.
From day 2 to day 365 : warm-up
From day 366 to 731 : calibration
From day 732 to the end : validation
Possibility to use discontinuous validation and calibration periods



Different colors to see the 3 stages on the graph

First model | 3 : Run parameters

- the number n_{obj} of simulations to conduct and requiring verification of the condition $\mathrm{WOBJ} > \mathrm{WOBJ}_{min}$ 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 objective WOBJ function WOBJ, parametrizable via the adjoining button,

Objective function from -∞ to 1 : best performance = 1

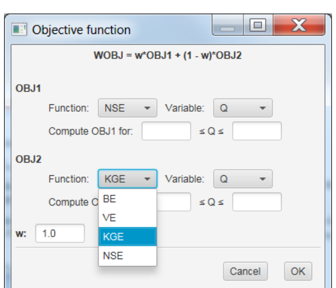
Nash-Sutcliffe efficiency
$$\mathrm{NSE} = 1 - \frac{\sum (U_S - U_{obs})^2}{\sum \left(U_{obs} - \overline{U_{obs}}\right)^2}$$

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

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

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

- the threshold value WOBJ_{min}



WOBJ = w.OBJ1 + (1-w).OBJ2

First model

3 : Run parameters

The directory where the output files are saved.

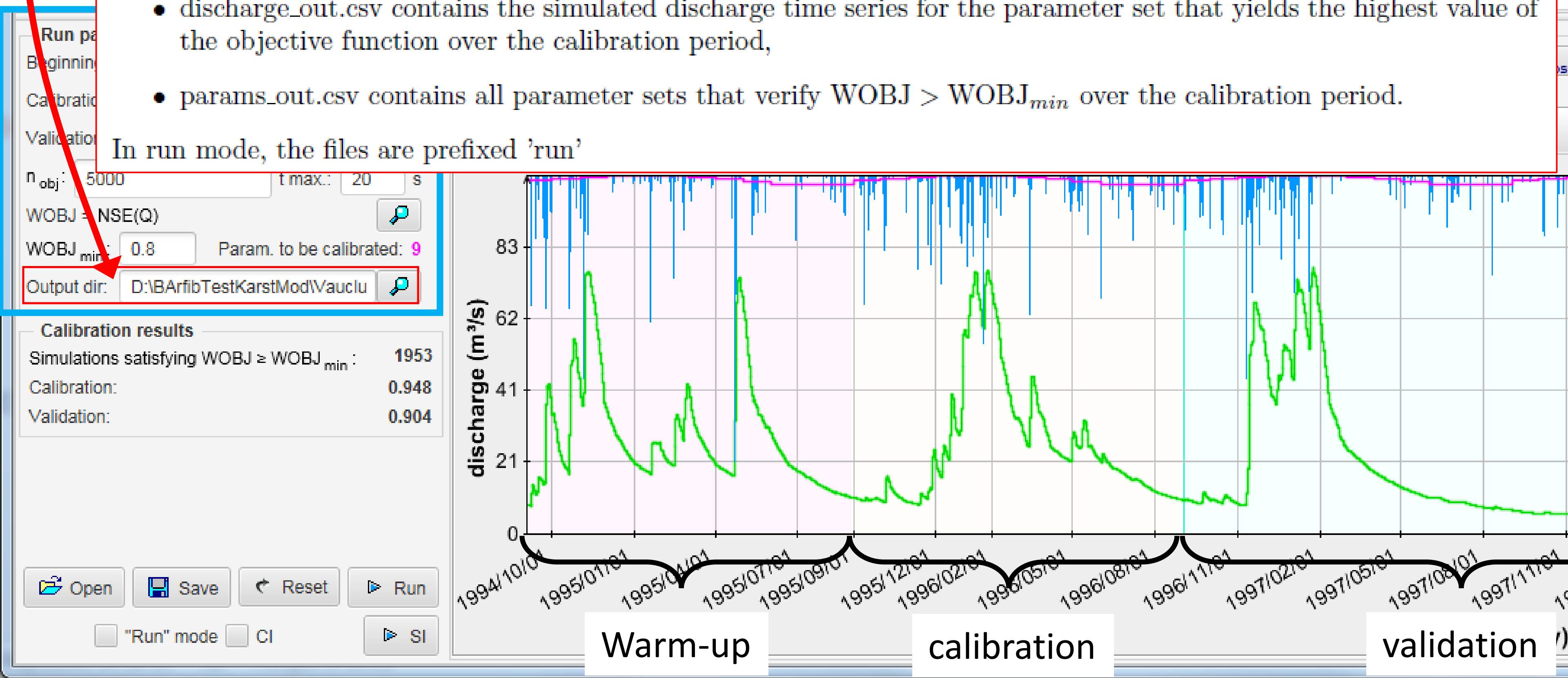
5.3.2 Output files

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

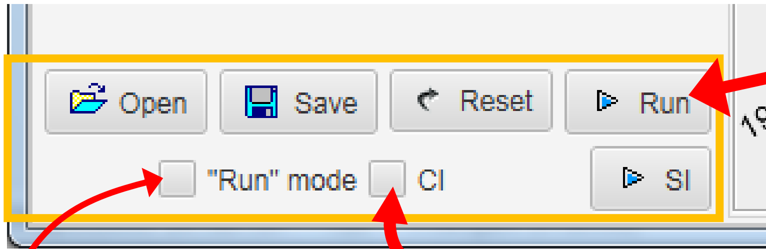
After each run, three output files are generated automatically:

- 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 $WOBJ > WOBJ_{min}$ over the calibration period.

In run mode, the files are prefixed 'run'



First model | 4 : Command bar



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 usefull to test a specific set of parameters, or to test by trial-error the effect of one parameter (usefull in classroom).

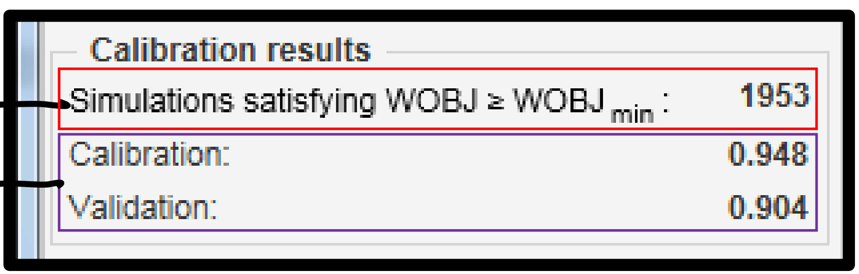
First model

5 : Results

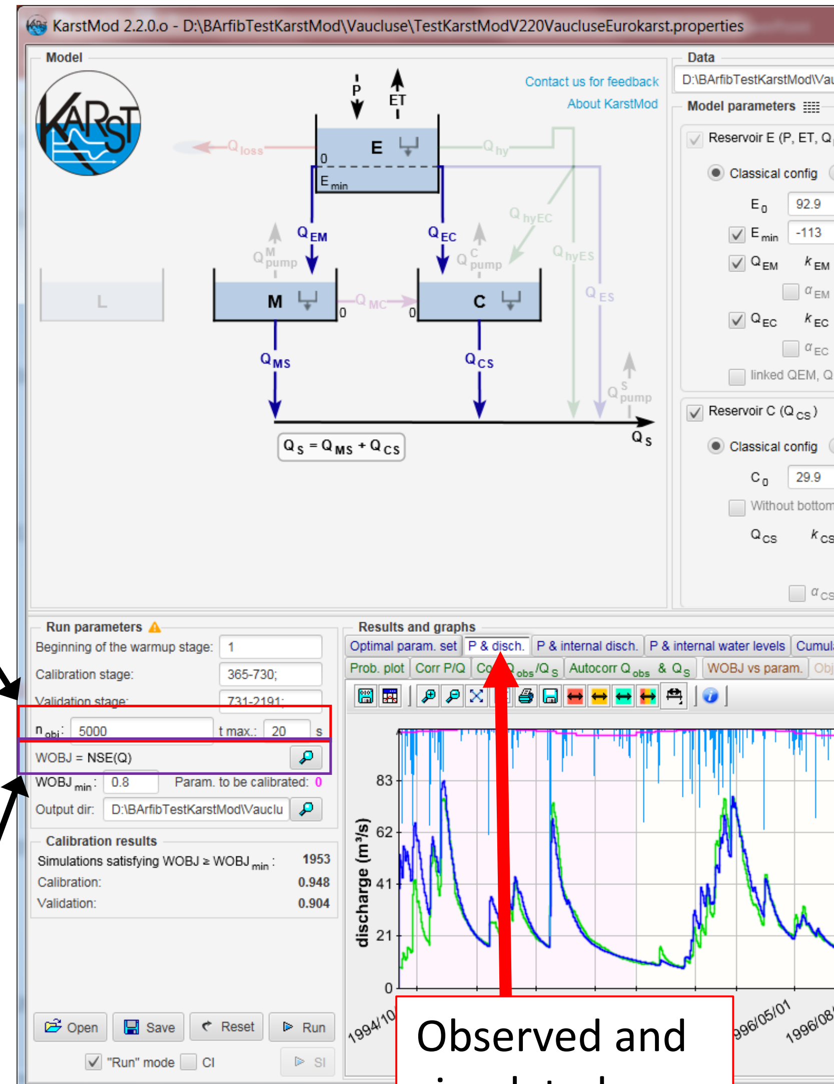
Case study : Fontaine de Vaucluse

Classical configuration. Linear discharge law.

Number of simulations according to n_{obj} and tmax, for WOBJ>WOBJmin



Objective function for the calibration and validation periods



Observed and simulated discharge

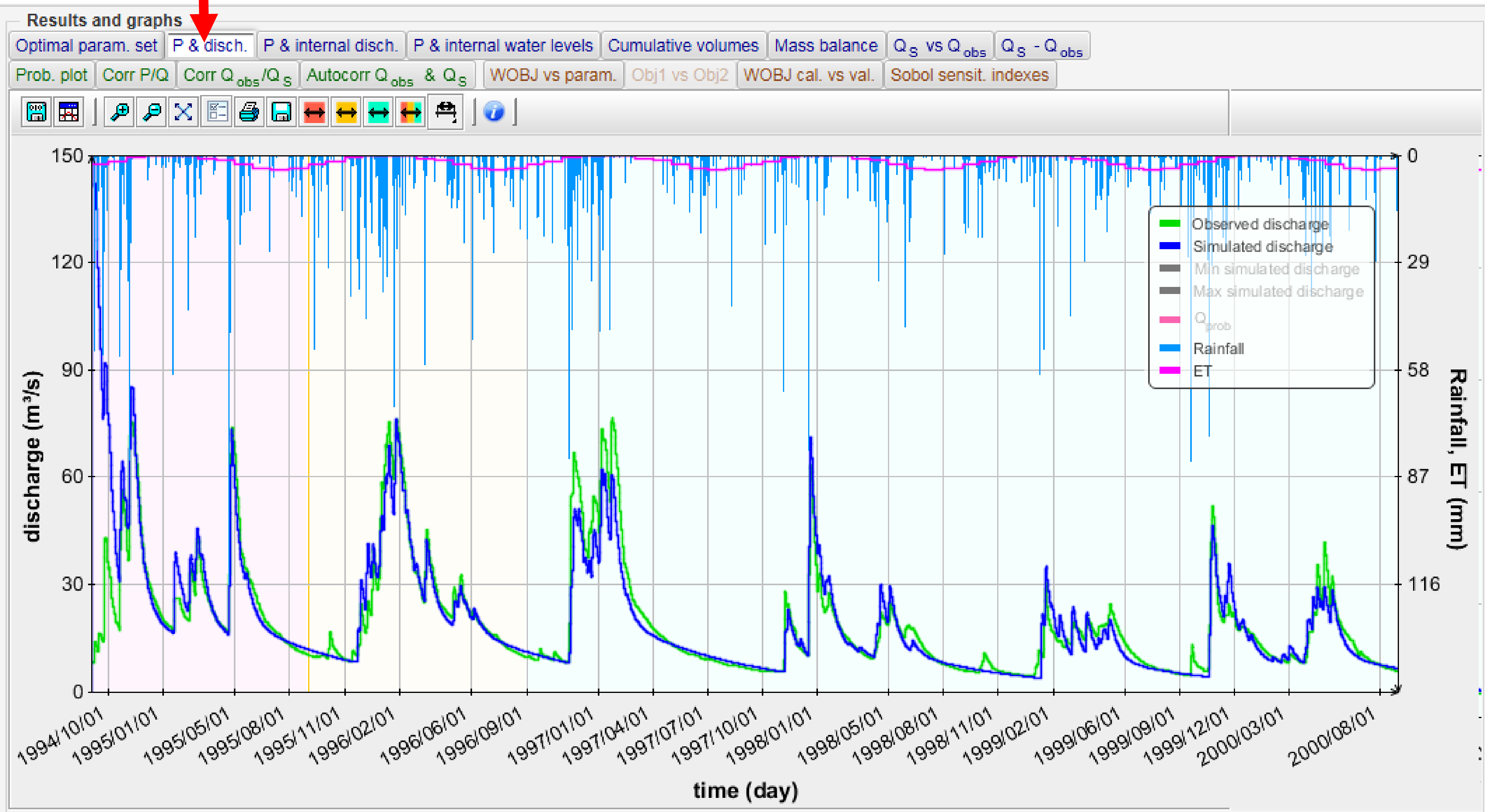
First model

5 : Results and graphs

Case study : Fontaine de Vaucluse

Classical configuration. Linear discharge law.

Observed and simulated discharge



First model

5 : Results and graphs

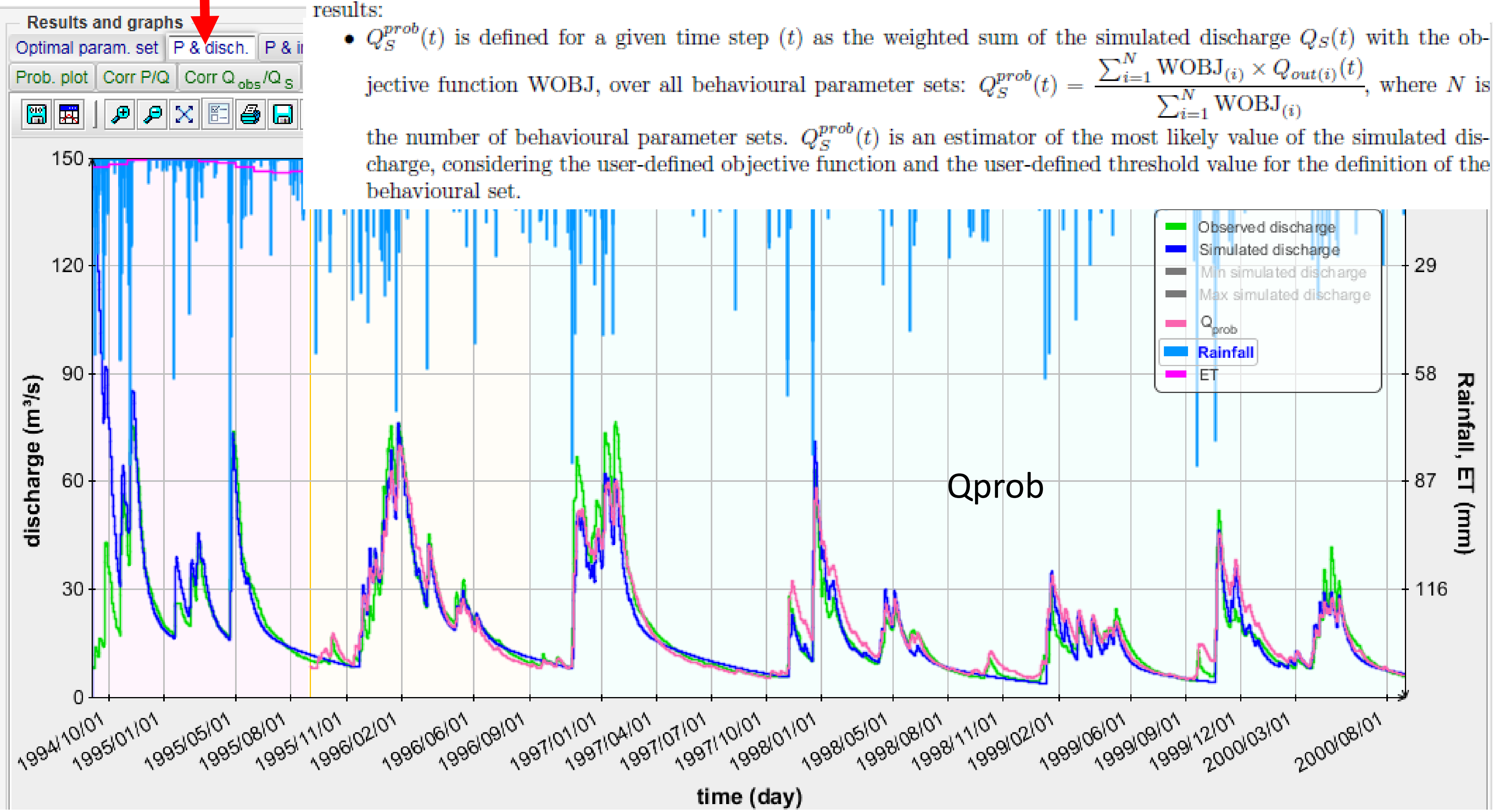
Case study : Fontaine de Vaucluse

Classical configuration. Linear discharge law.

Observed and simulated discharge

Parametric uncertainty of the simulation results KarstMod proposes to use the simulation results from all parameter sets yielding WOBJ > $WOBJ_{min}$ for the evaluation of the uncertainty on the simulation results. The approach is derived from the Regional Sensitivity Analysis (RSA) [9] and the Generalized Likelihood Uncertainty Estimation (GLUE) [1]. Instead of selecting a unique parameter set as the outcome of the calibration process, these methods consider that all parameter sets yielding satisfactory results over the calibration period (behavioural parameter sets) should be considered in the prediction process. The value of WOBJ over the calibration period is used as a likelihood measure for each behavioural parameter set. Based on this assumption, KarstMod proposes the following simulation results:

- $Q_S^{prob}(t)$ is defined for a given time step (t) as the weighted sum of the simulated discharge $Q_S(t)$ with the objective function WOBJ, over all behavioural parameter sets: $Q_S^{prob}(t) = \frac{\sum_{i=1}^{N} \mathrm{WOBJ}_{(i)} \times Q_{out(i)}(t)}{\sum_{i=1}^{N} \mathrm{WOBJ}_{(i)}}$, where N is the number of behavioural parameter sets. $Q_S^{prob}(t)$ is an estimator of the most likely value of the simulated discharge, considering the user-defined objective function and the user-defined threshold value for the definition of the behavioural set.



First model

5 : Results and graphs

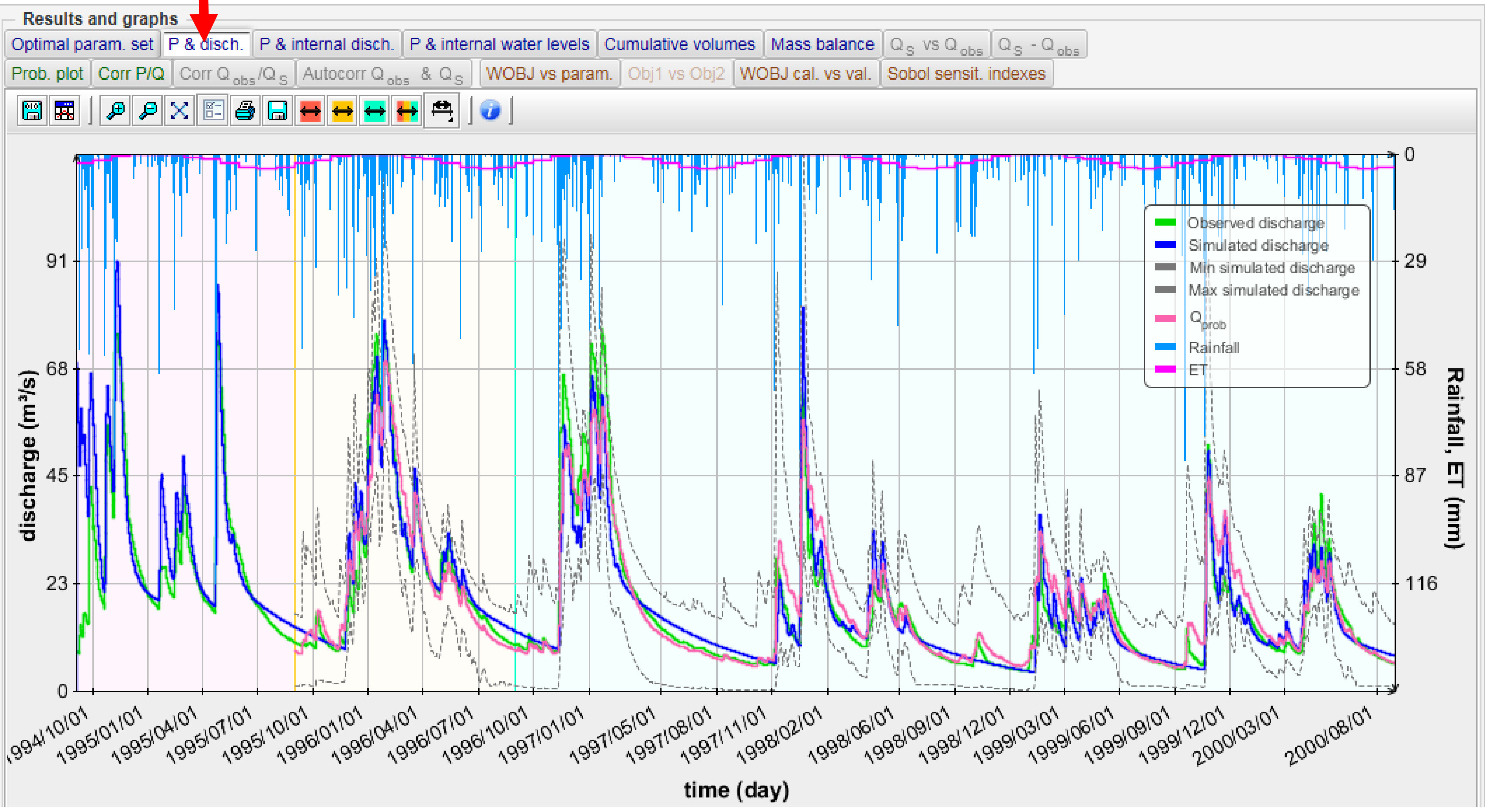
Case study : Fontaine de Vaucluse

Classical configuration. Linear discharge law.

Observed and simulated discharge

Parametric uncertainty of the simulation results

Qprob + Confidence interval plots



First model

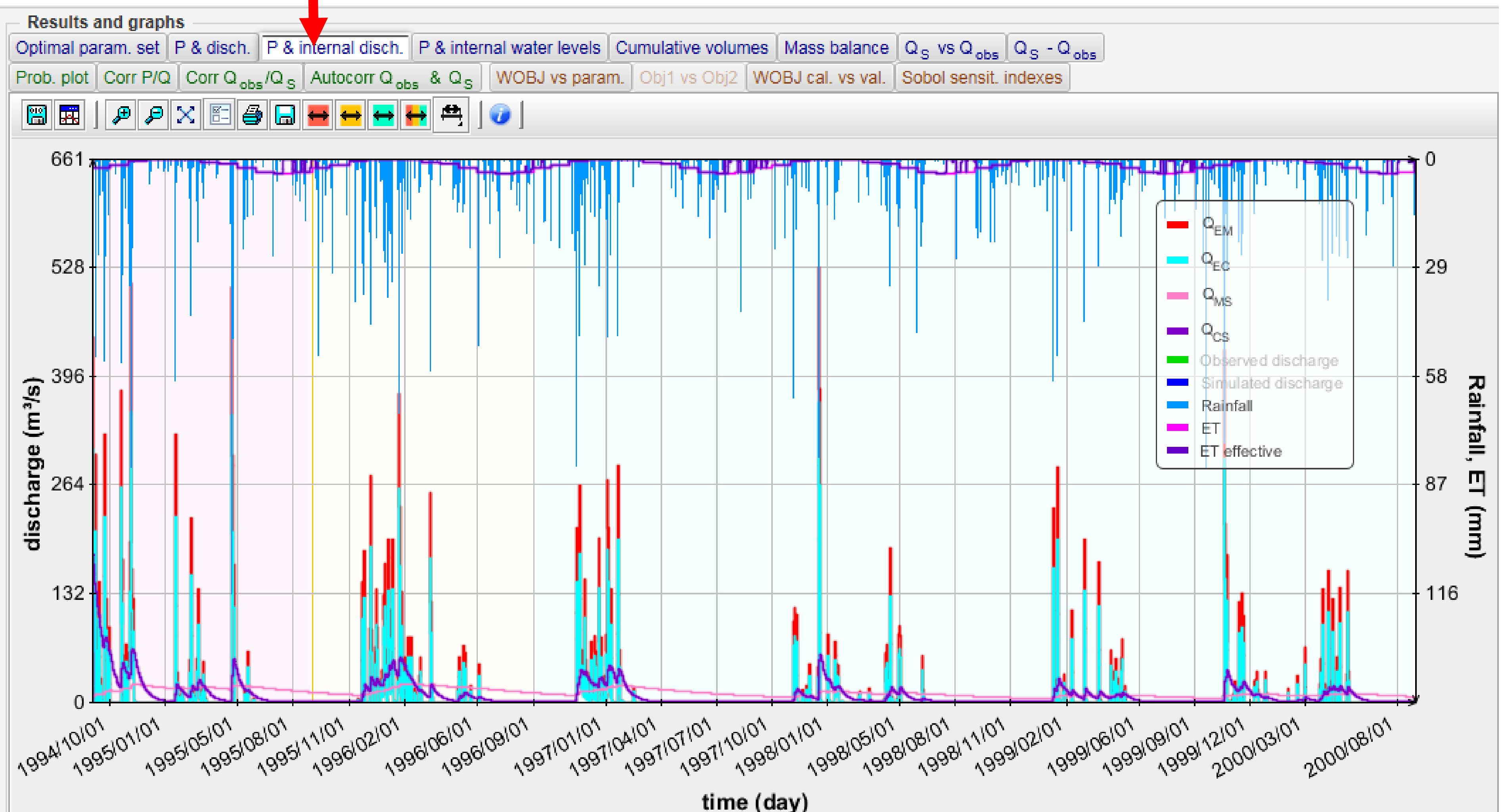
5 : Results and graphs

Case study : Fontaine de Vaucluse

Classical configuration. Linear discharge law.

Rainfall and internal discharge

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



First model

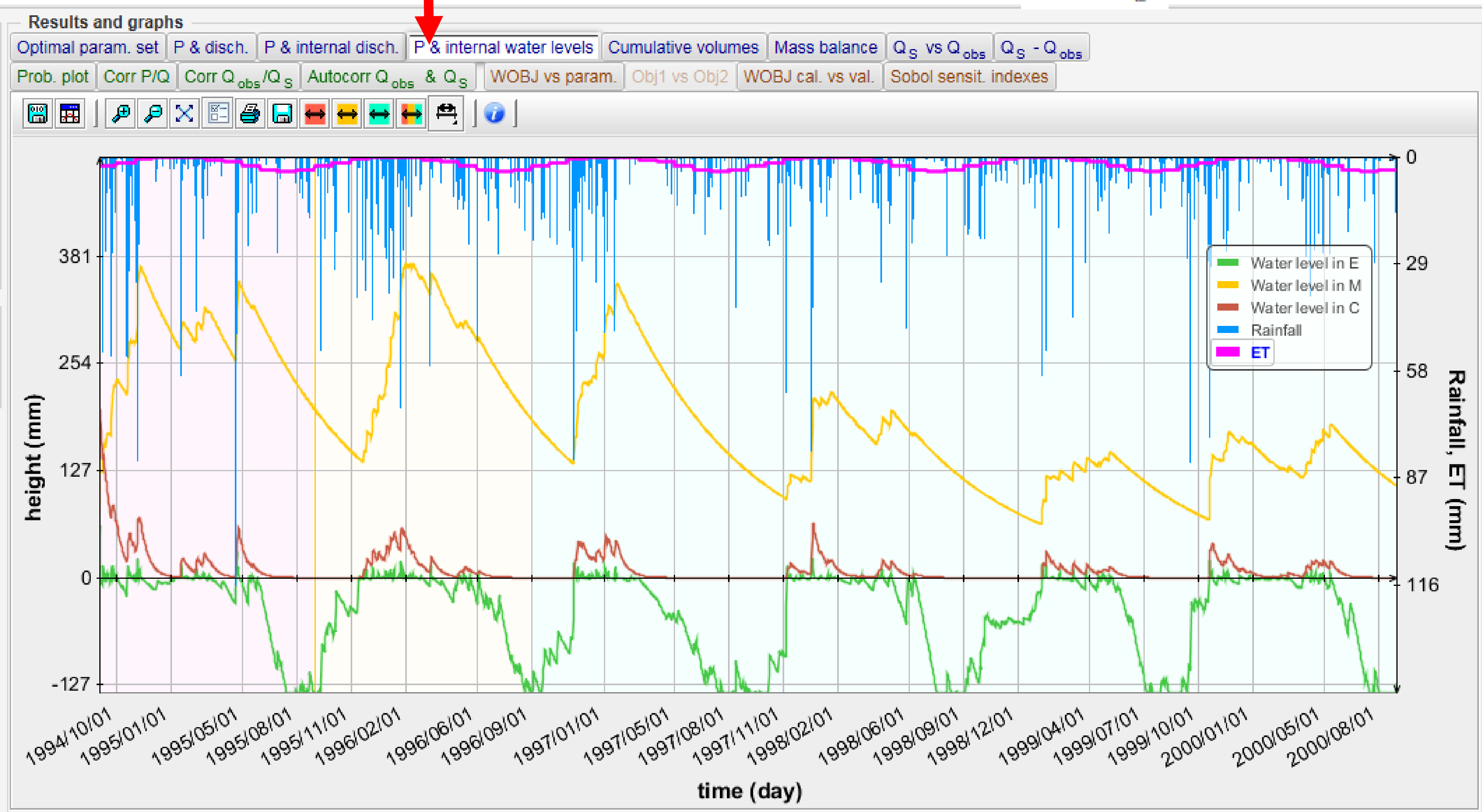
5 : Results and graphs

Case study : Fontaine de Vaucluse

Classical configuration. Linear discharge law.

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 $Z = Z_0 + \frac{A}{w}$



First model

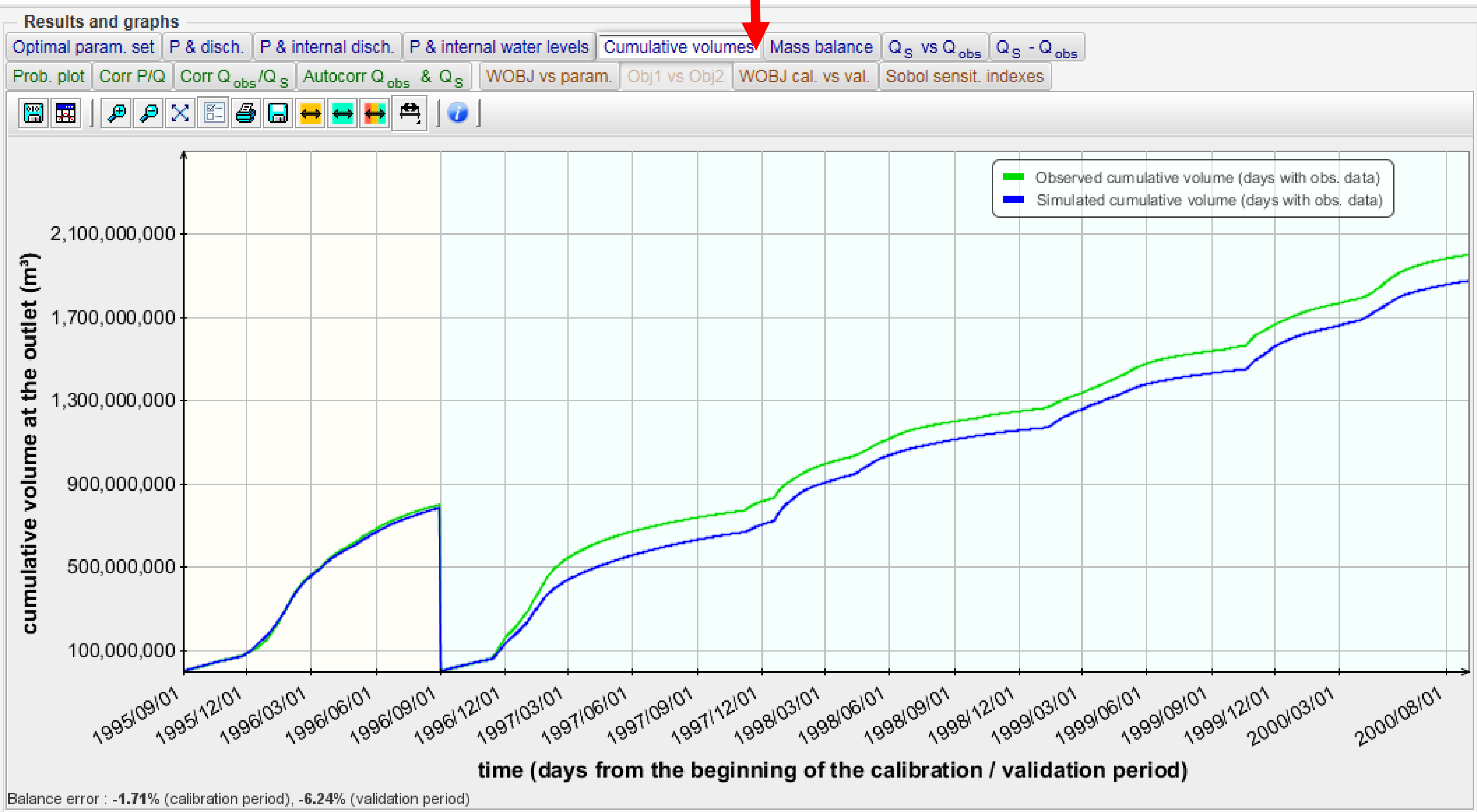
5 : Results and graphs

Case study : Fontaine de Vaucluse

Classical configuration. Linear discharge law.

- To check the balance error

Cumulative volumes



First model

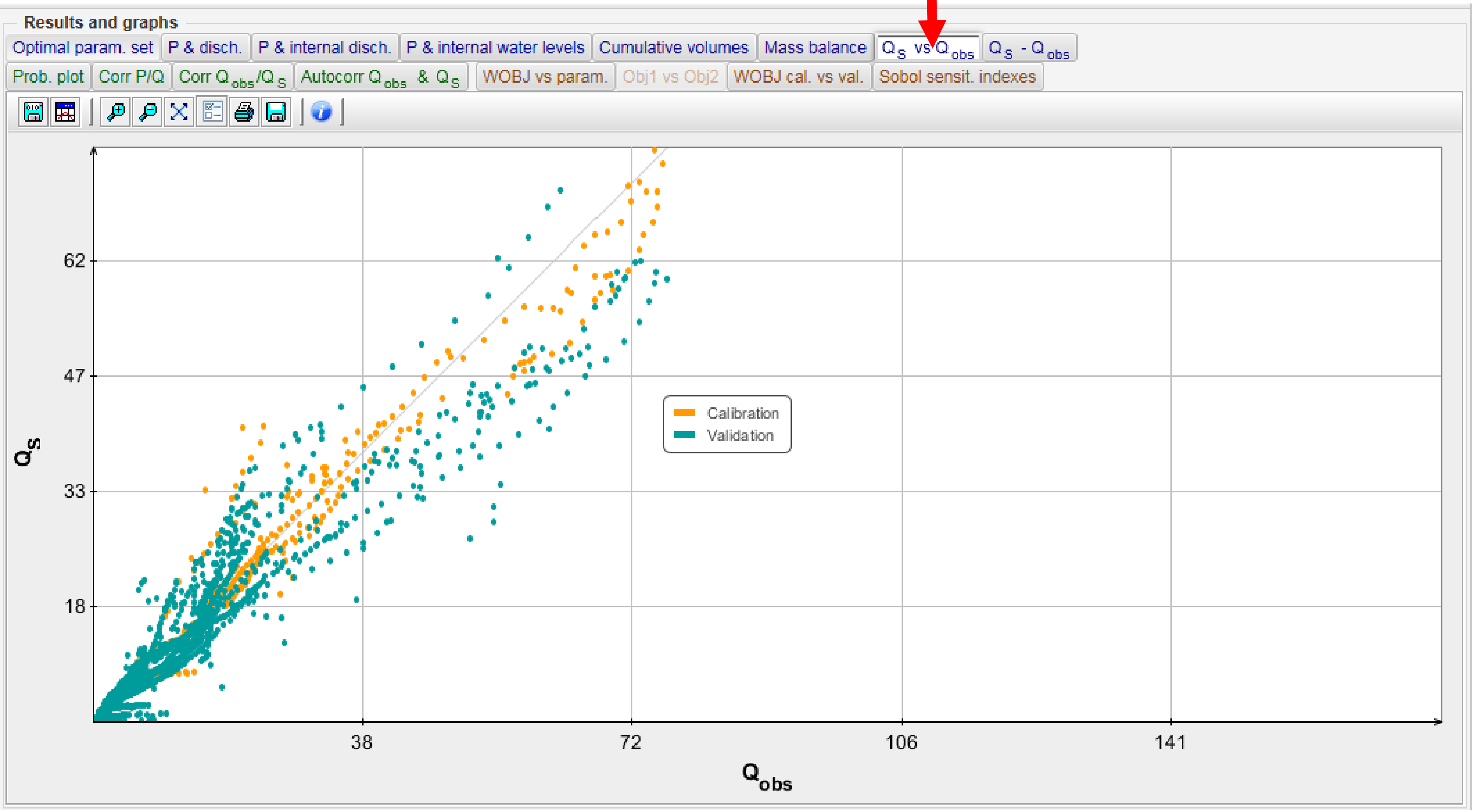
5 : Results and graphs

Case study : Fontaine de Vaucluse

Classical configuration. Linear discharge law.

- To check for systematic drift

Qsimulated VS Qobserved



First model

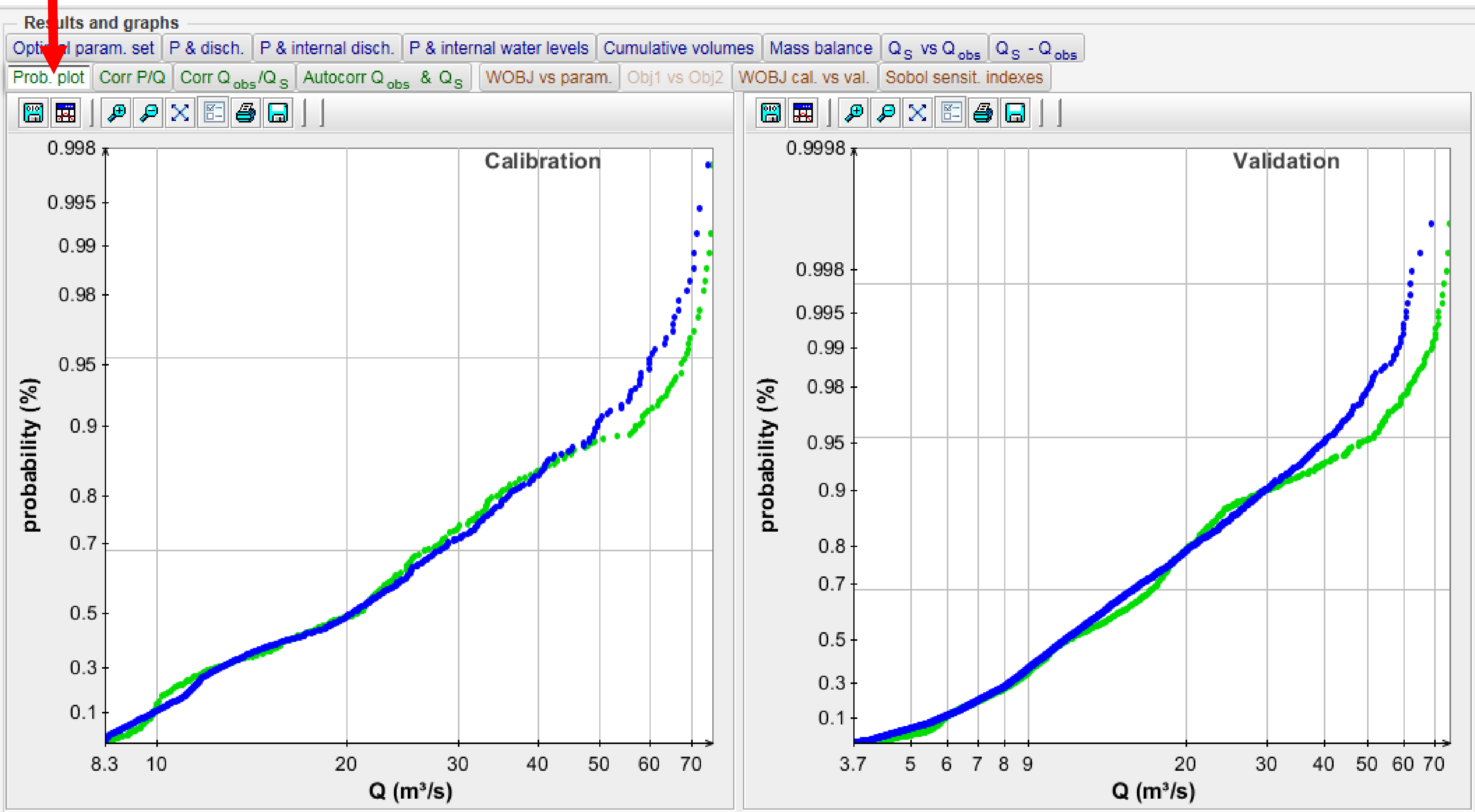
5 : Results and graphs

Case study : Fontaine de Vaucluse

Classical configuration. Linear discharge law.

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

Cumulative probability plot



First model

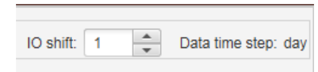
5 : Results and graphs

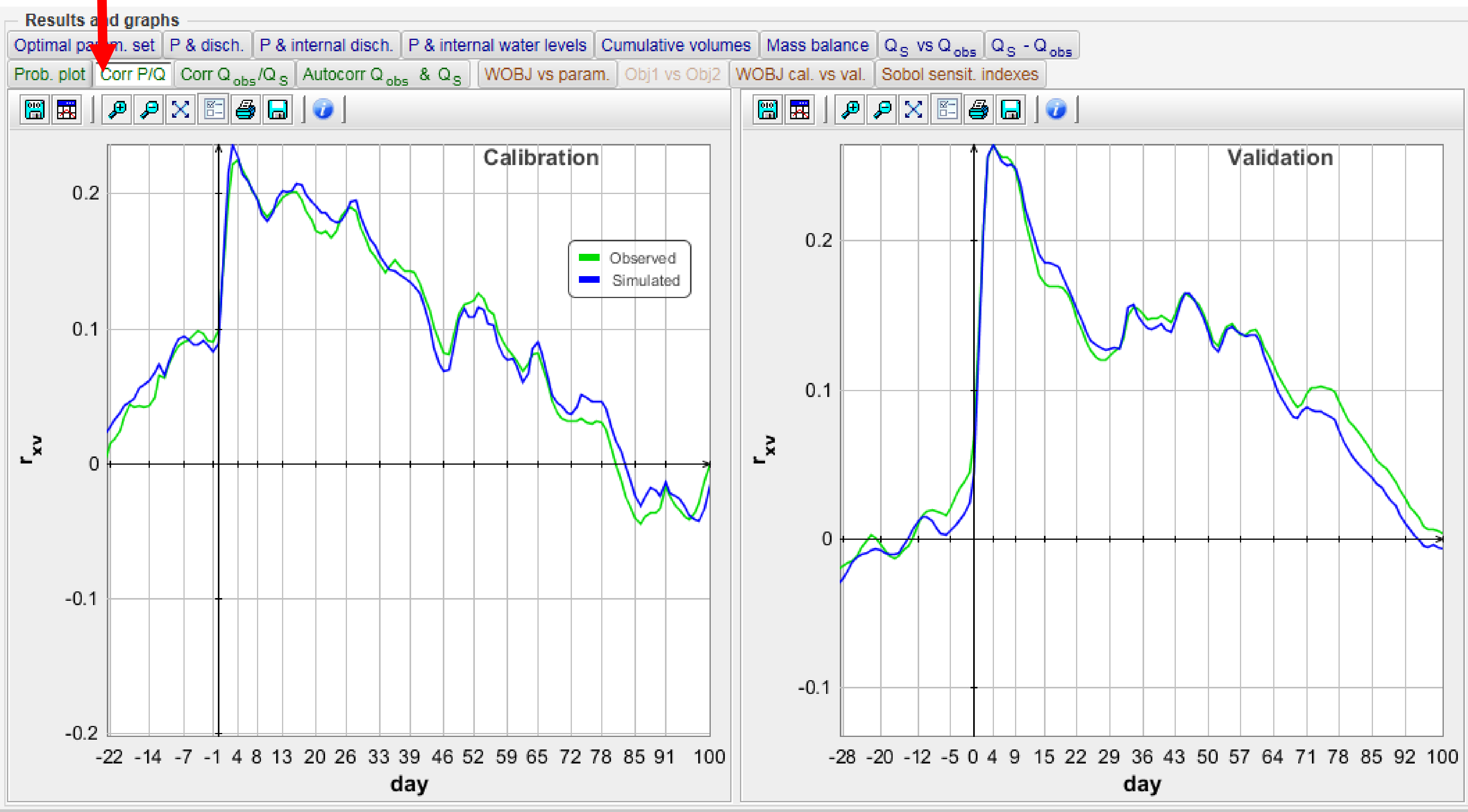
Case study : Fontaine de Vaucluse

Classical configuration. Linear discharge law.

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

Cross correlogram Rain-Discharge





First model

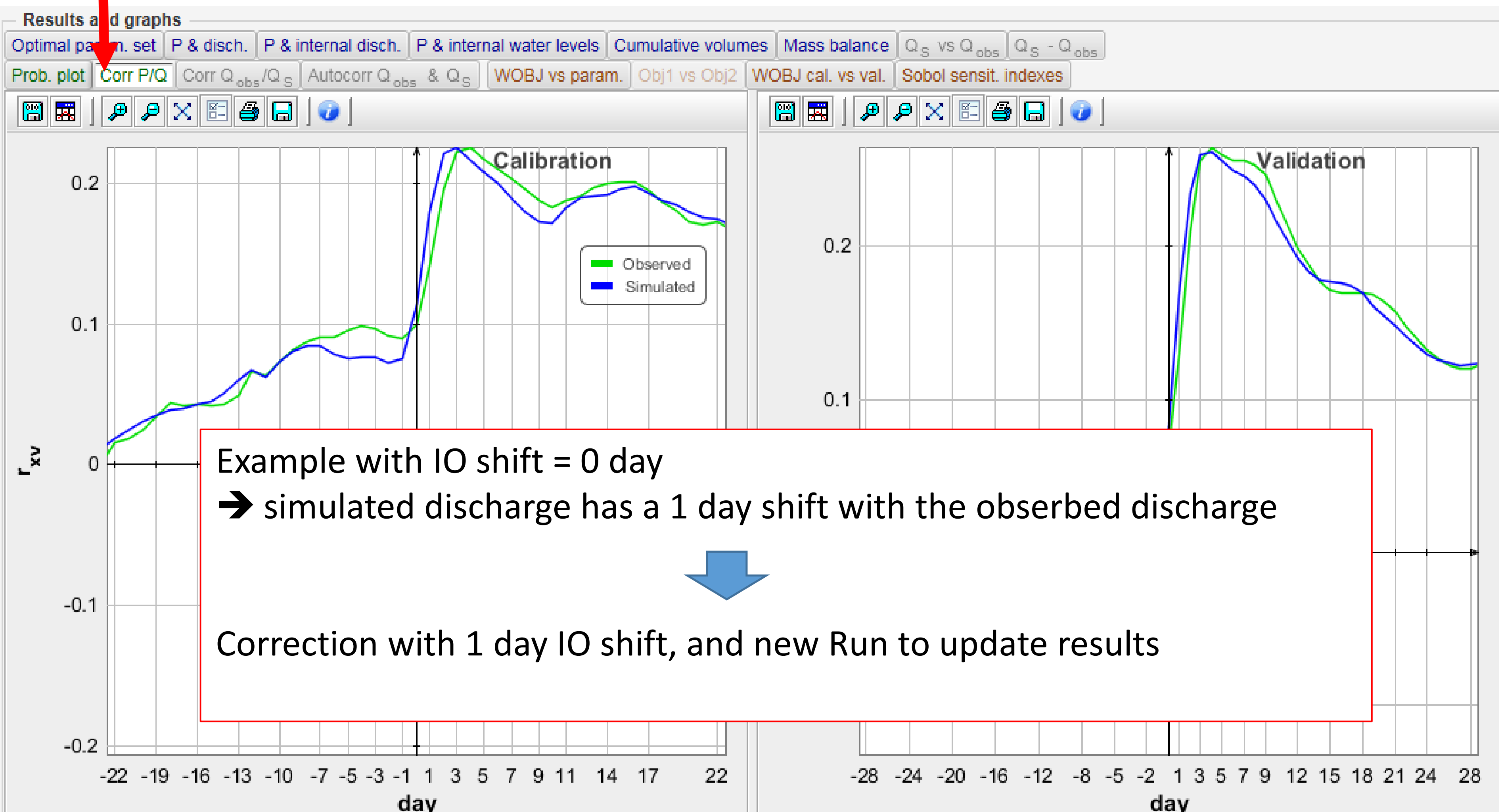
5 : Results and graphs

Case study : Fontaine de Vaucluse

Classical configuration. Linear discharge law.

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

Cross correlogram Rain-Discharge



Example with IO shift = 0 day

➔ simulated discharge has a 1 day shift with the obserbed discharge

Correction with 1 day IO shift, and new Run to update results

First model

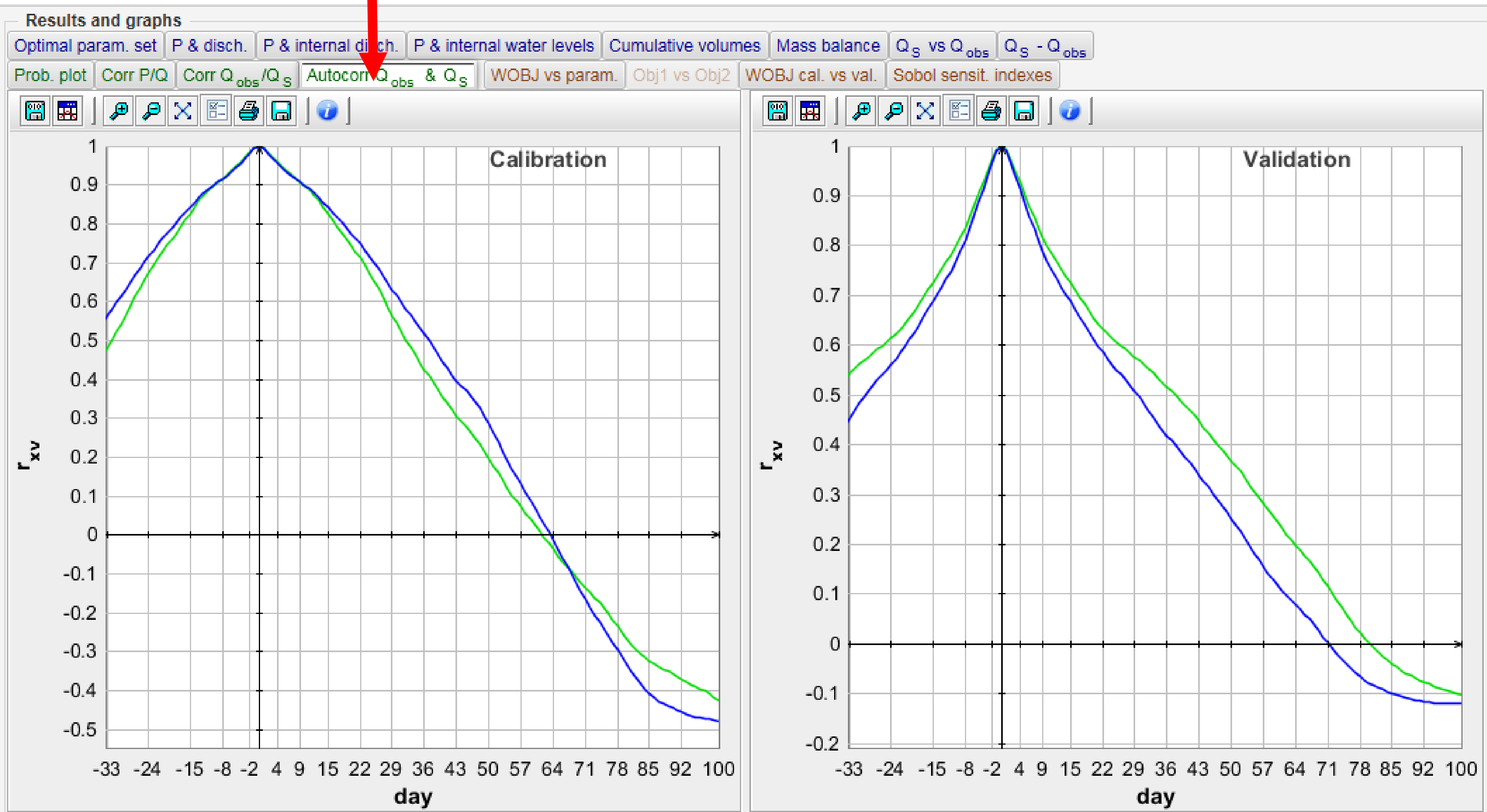
5 : Results and graphs

Case study : Fontaine de Vaucluse

Classical configuration. Linear discharge law.

- A tool for karst hydrogram characterization and aquifer functionning rating
- To compare observed and simulated discharge

Discharge correlogram



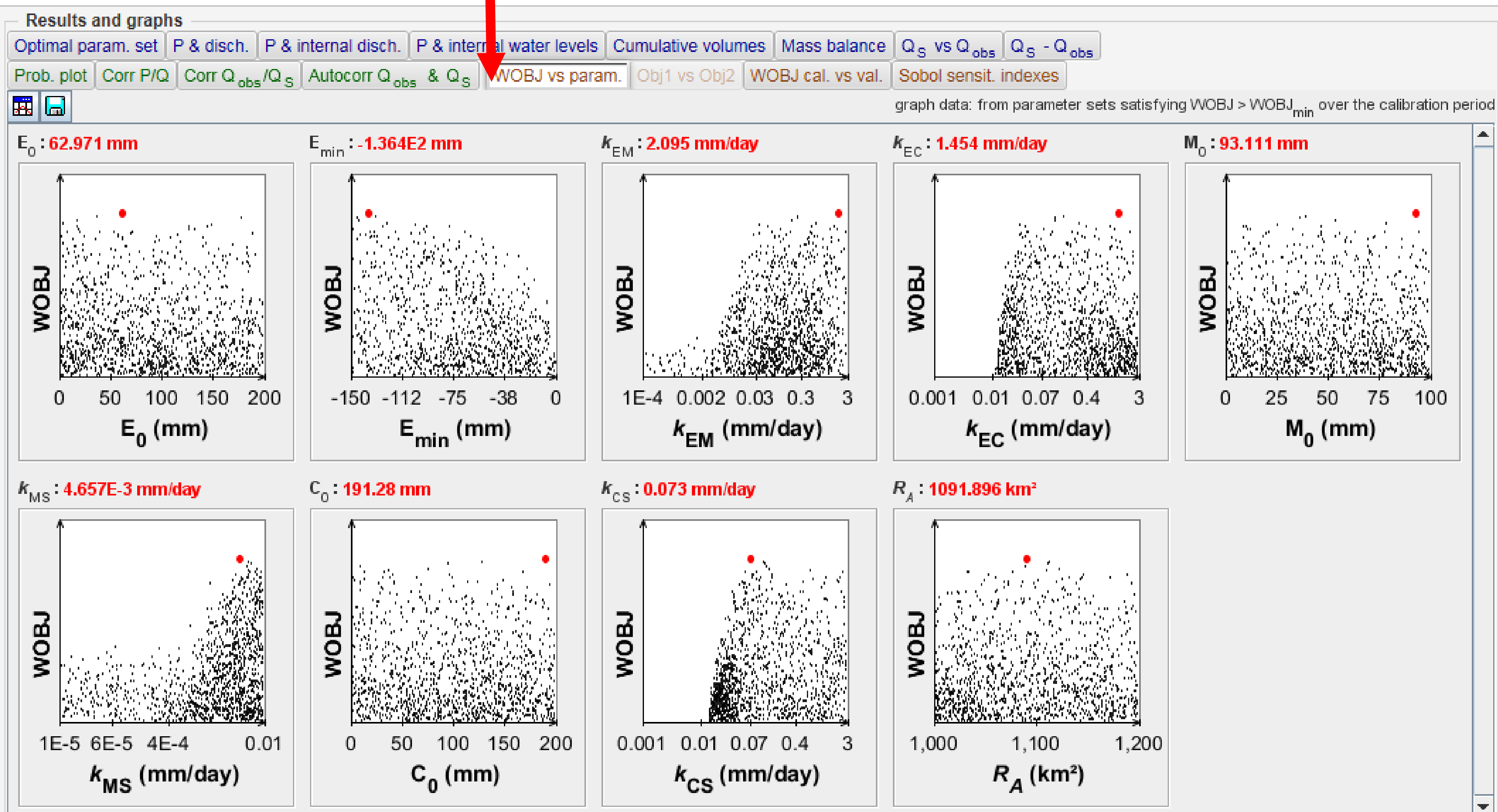
First model

6 : Equifinality analysis

Case study : Fontaine de Vaucluse

Classical configuration. Linear discharge law.

Objective function VS parameter value



First model

6 : Equifinality analysis

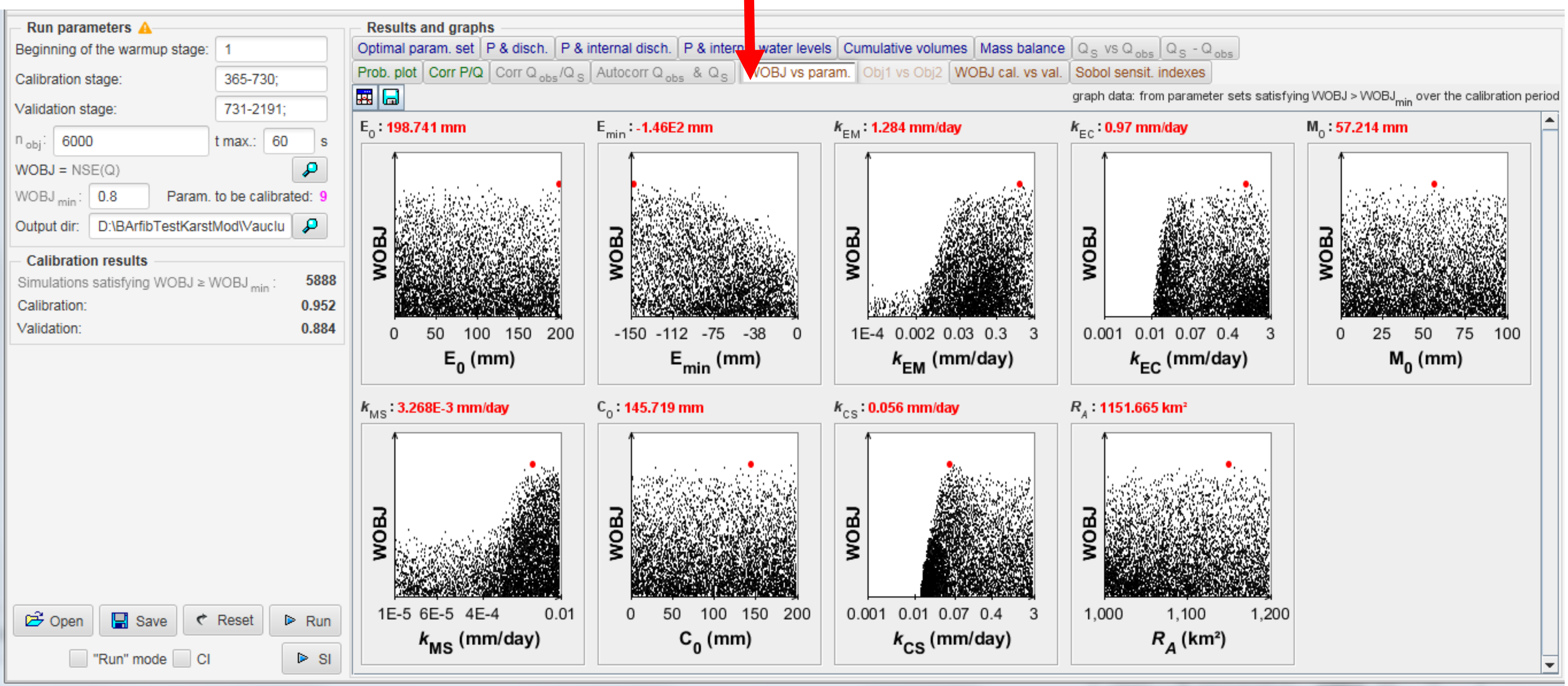
Case study : Fontaine de Vaucluse

Classical configuration. Linear discharge law.

New example with more results (parameter sets satisfying WOBJ>WOBJmin)

At the end of the equifinality analysis, a new Run can be perform.
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



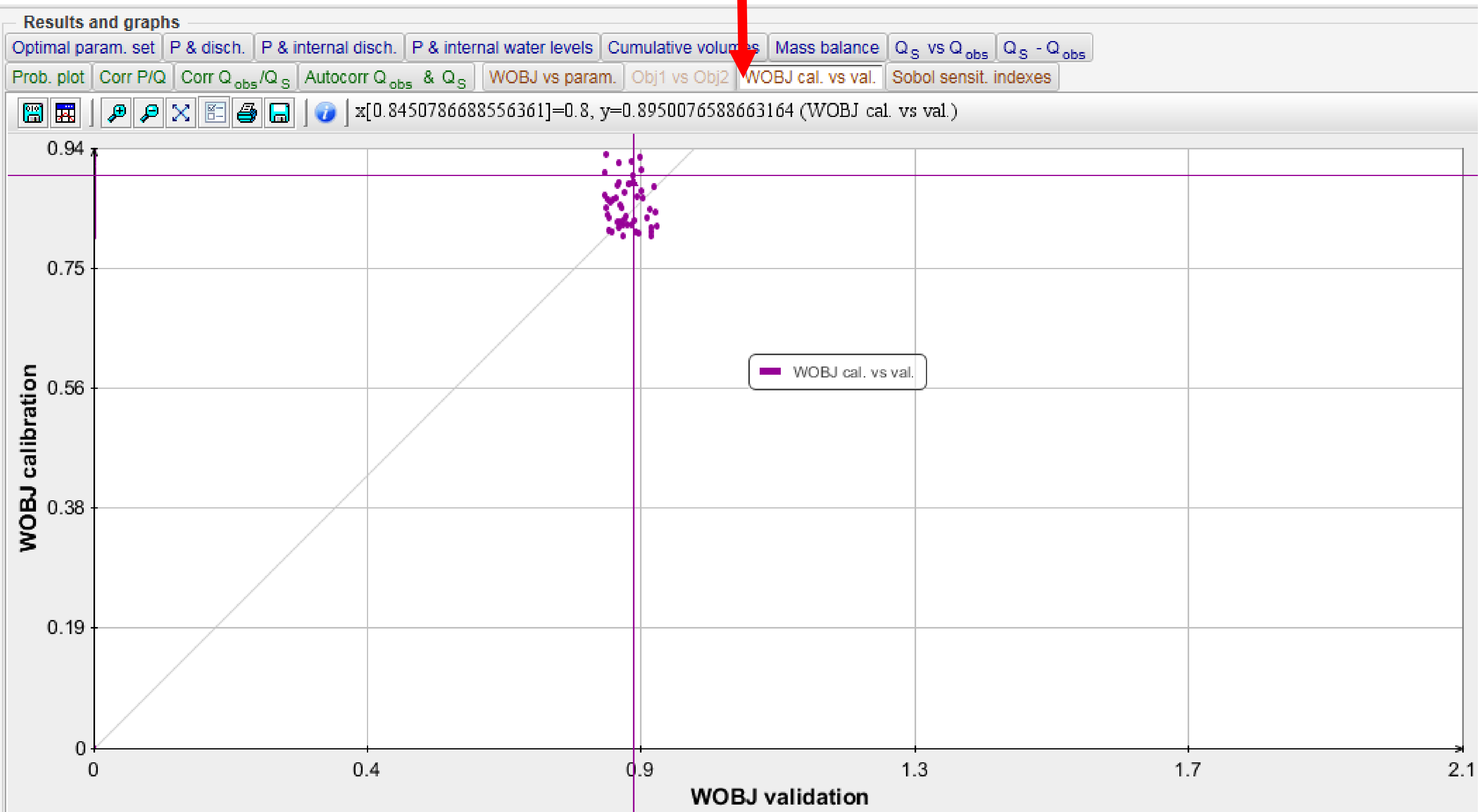
First model

6 : Equifinality analysis

Case study : Fontaine de Vaucluse

Classical configuration. Linear discharge law.

Objective function calibration VS validation



First model

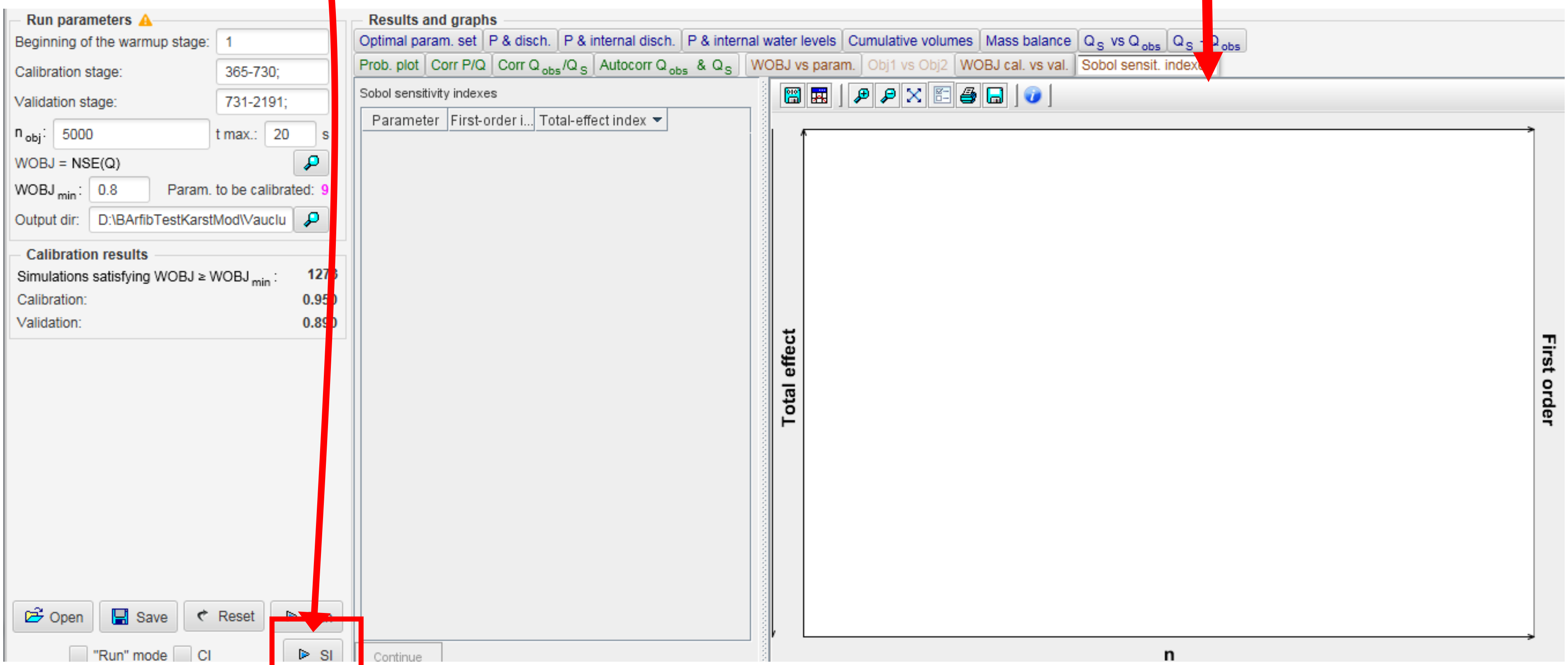
6 : Equifinality analysis

Case study : Fontaine de Vaucluse

Classical configuration. Linear discharge law.

Run the « SI » tool

Sobol sensitivity index



First model

6 : Equifinality analysis

Case study : Fontaine de Vaucluse

Classical configuration. Linear discharge law.

Sobol sensitivity index

Results and graphs

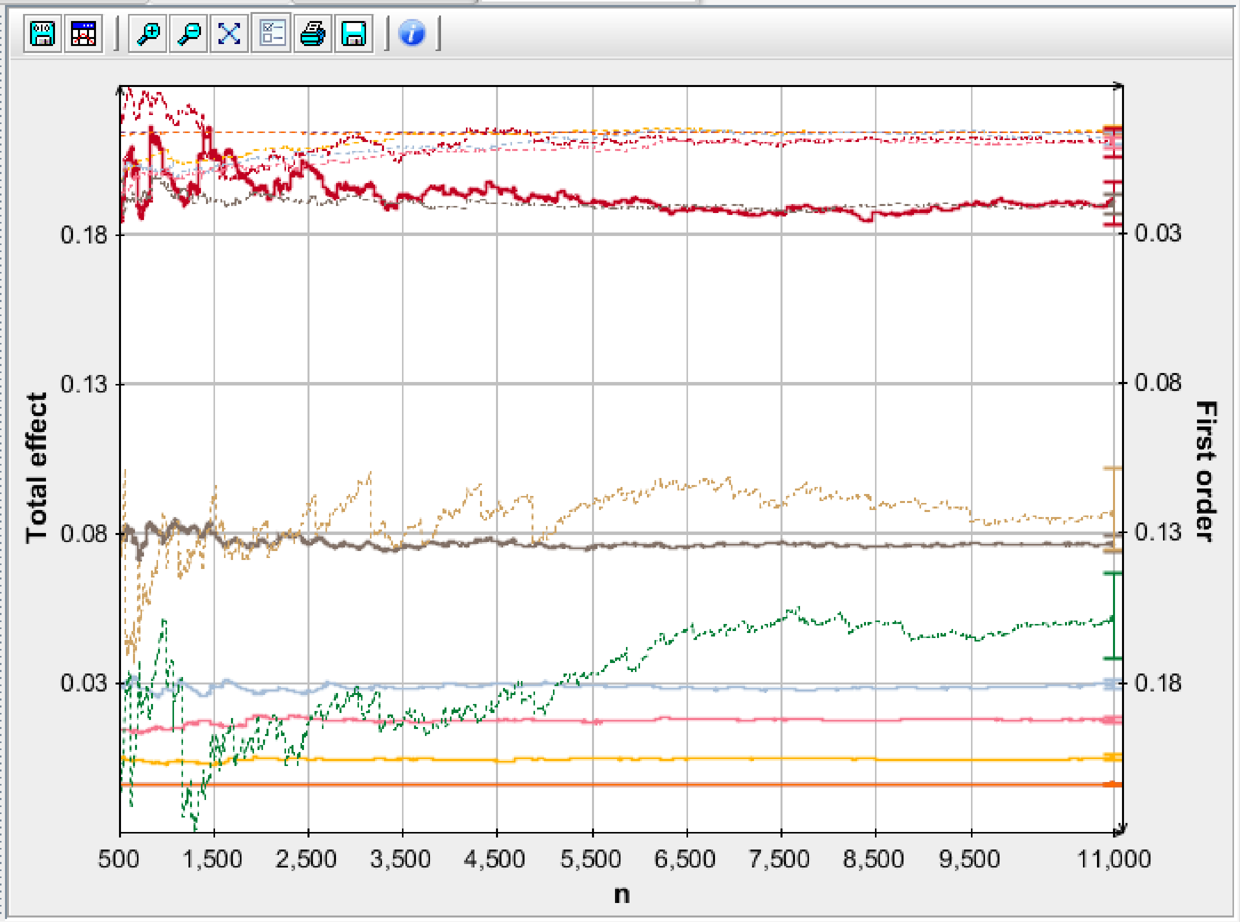
Optimal param. set | P & disch. | P & internal disch. | P & internal water levels | Cumulative volumes | Mass balance | Q_S vs Q_{obs} | Q_S - Q_{obs}

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. | Sobol sensit. indexes

Sobol sensitivity indexes

Parameter	First-order index	Total-effect index
k_{EC}	0.122	0.734
k_{CS}	0.156	0.723
k_{BM}	0.003	0.187
k_{MS}	0.023	0.077
E_{min}	0.001	0.032
R_A	0.003	0.021
E_0	-7.869E-4	0.008
C_0	-1.381E-4	9.209E-5
M_0	5.47E-5	1.729E-5

Continue



First model | 2 : Model structure and model parameters

You need a conceptual scheme of hydrogeological functionning 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 :

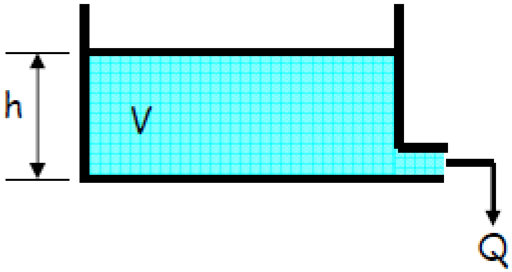
- The functioning of the case study
- Your level of knowledge of the functioning of the case study
- The goal(s) of the modeling

Your first model is fine?

↓

Start a new model or explore the output files

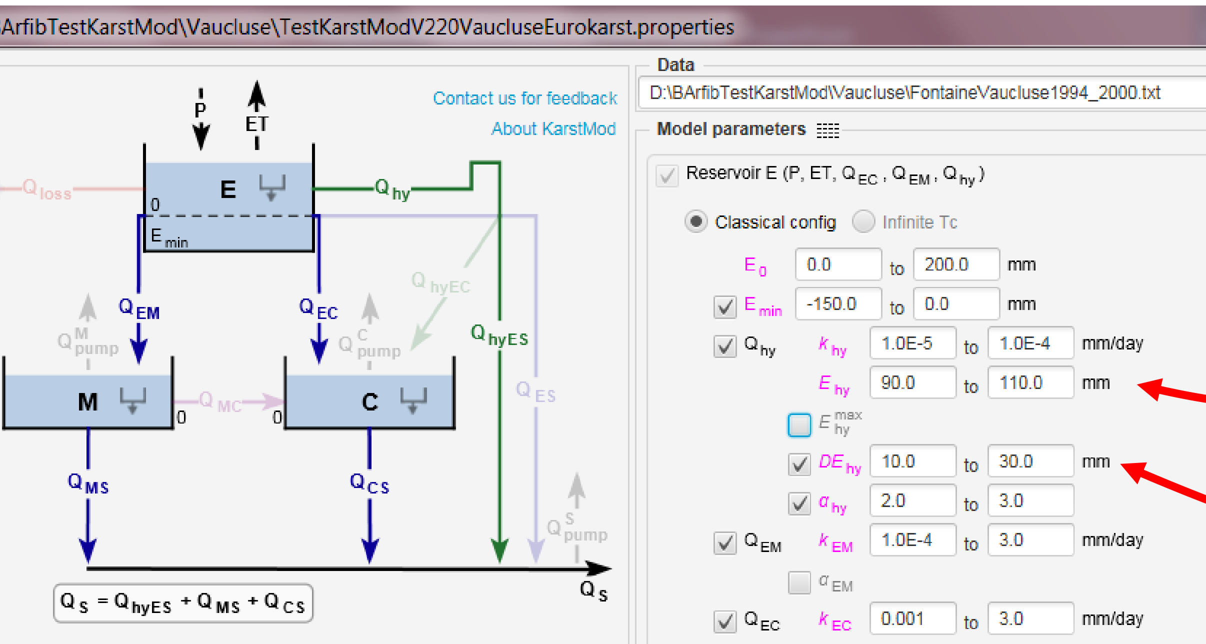
Supplementary material : Hysteretic function



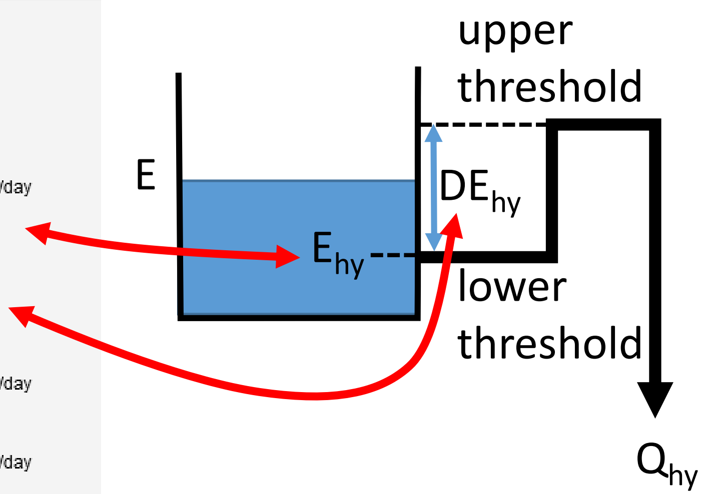
Linear function between height of water and specific discharge (Qt: L/T) $Q_t = K \cdot h$

Non linear function $Q_t = K \cdot h^{\alpha}$

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



Hysteretic function

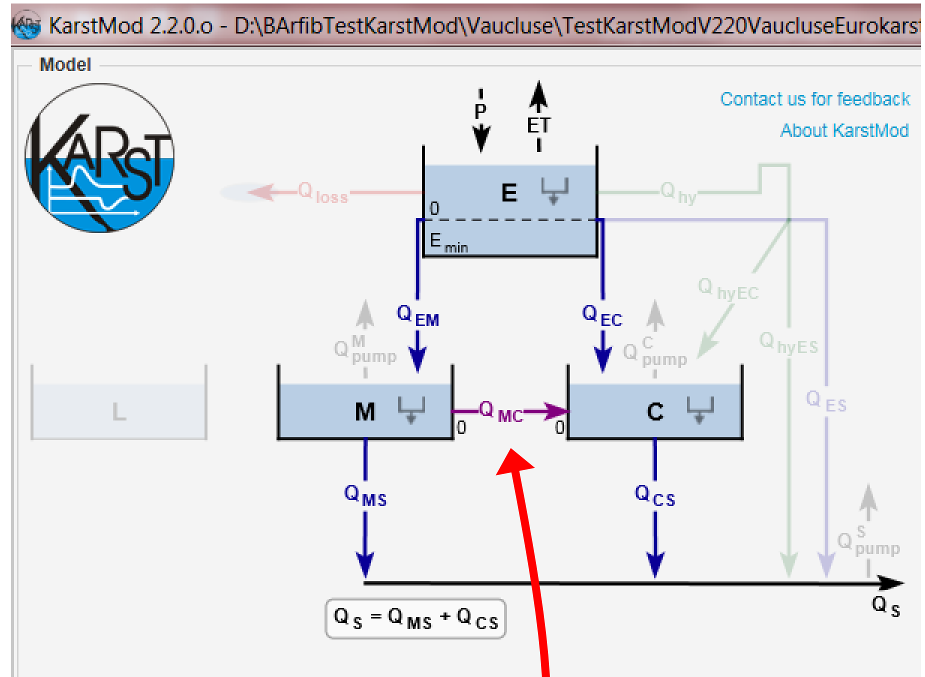


If DE_{hy}=0 (also named ΔE_{hy}), the hysteretic function simplifies to a threshold discharge function

$$Q_{hy} = \varepsilon_{HY} \times k_{hy} \left(\frac{E - E_{hy}}{L_{ref}} \right)^{\alpha_{hy}}$$
$$Q_{hyEC} = x_{hy} \times Q_{hy}$$
$$Q_{hyES} = (1 - x_{hy}) \times Q_{hy}$$

$$\left.\begin{aligned} \varepsilon_{HY} &= 0 \\ E &= E_{hy} + \Delta E_{hy} \end{aligned}\right\} \Rightarrow \varepsilon_{HY} = 1$$
$$\left.\begin{aligned} \varepsilon_{HY} &= 1 \\ E &= E_{hy} \end{aligned}\right\} \Rightarrow \varepsilon_{HY} = 0$$

Supplementary material : Exchange function Q_{MC}



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

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

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

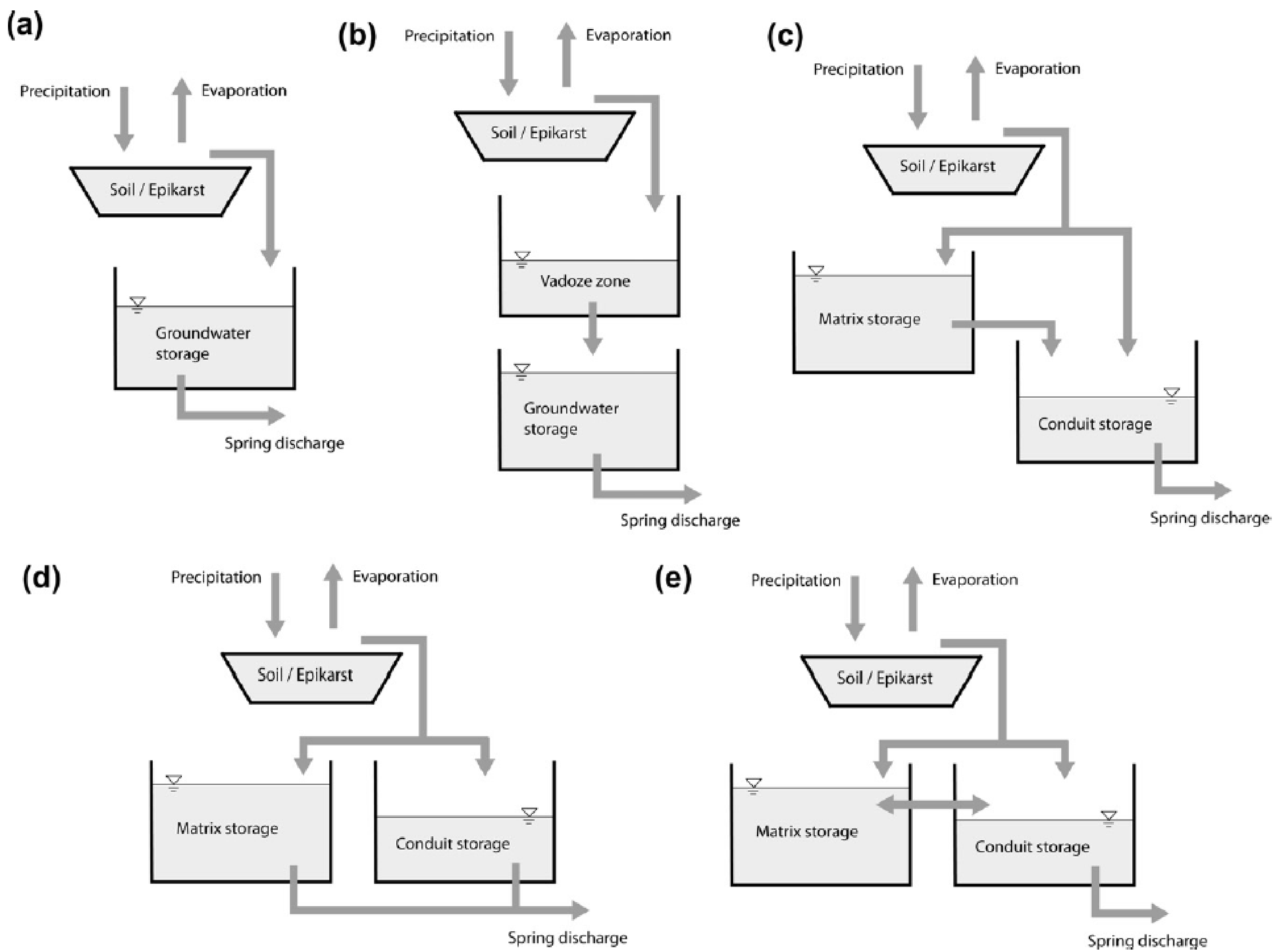


Fig. 3. The hydrological model ensemble: (a) simple model, (b) serial model, (c) combined model, (d) parallel model, and (e) exchange model.