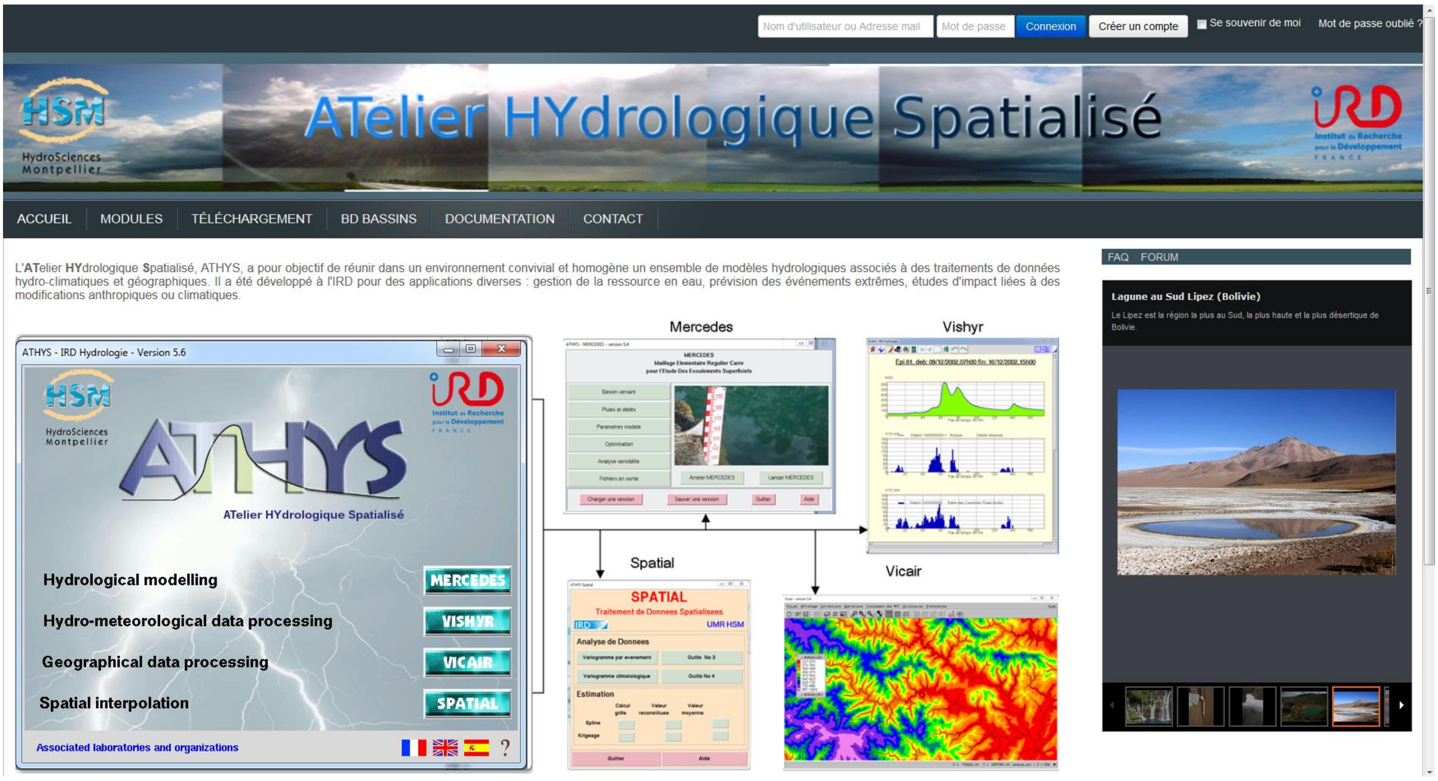
Training Manual – 2020

Distributed rainfall-runoff modelling with ATHYS software

Case of the Gardon catchment at Anduze



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Introduction

This manual is intended as a tutorial for the implementing spatialized hydrological models. ATHYS software provides a homogenous and user-friendly environment for implementing spatialized models over a broad range of watersheds, comparing their efficiency, and making sure they match target applications – resource, risk or impact surveys. ATHYS comprises 4 modules, of which 3 are documented in this manual, the MERCEDES modelling platform, the VISHYR module for the processing of chronological data, the VICAIR module for the processing of spatialized geographical data.

In addition to describing the technical aspects of the software, the other aim of this training manual is to question rainfall-runoff modelling in general and spatialized modelling in particular. For some readers, the manual will be a reminder, while for others, it will introduce modelling and provide a description of different models, and to some extent give the pro and cons. The questions dealing with the usefulness and the limitations of spatialized models – what being spatialized implies and what it does not, is it an advantage? — are illustrated with different examples to enrich the reflection on hydrological modelling.

Note 1: Contributors. The manual was written by Christophe Bouvier (HSM/IRD), (HSM/IRD), Anne Crespy (IRD/HSM), Agnès Crès (HSM/IRD), François-Noël Crès (Polytech'Montpellier), Claudine Dieulin (HSM/IRD) contributed to either developing the software, writing the manual, or translating it into English. The following reference should be cited:

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Note 2: Documentation. A wider technical information is embedded within the software, as HTML pages available after downloading the software. This technical information will give useful help to the users, in complement of the training manual.

Note 3: Acknowledgements. The implementation of ATHYS would not have been possible without the support of the Department of Environment and Sustainable Development and the one of the Central Hydrometeorological (SHAPI), who financially supported the project, participated in the scientific and technical decisions and provided most of the data used in this manual. We are grateful to the people who supported us.

Note 4: The information and results included in this manual are designed for educational purposes only, and the scientific results cited should not be considered as final. The authors cannot be held responsible for any use of this manual other than educational.

1. GENERAL CONSIDERATIONS ABOUT MODELS

1.1 Definitions and objectives

What is a mathematical model?

A set of method of simulating real-life behavior with mathematical equations to understand and forecast the behavior of a complex system and to forecast future behavior under stationary or non-stationnary conditions.

In the case of a rainfall-runoff model, the set of equations links the input variables (or forcing variable, i.e. rainfall, evapotranspiration, elevation, soil, etc.) with the output variables (or forecast, i.e. the stream discharges, water tables, etc.), taking into account the initial state variables (or internal variables, i.e. moisture in the watershed, vegetation growth, level of water in the reservoirs etc.) of the system.

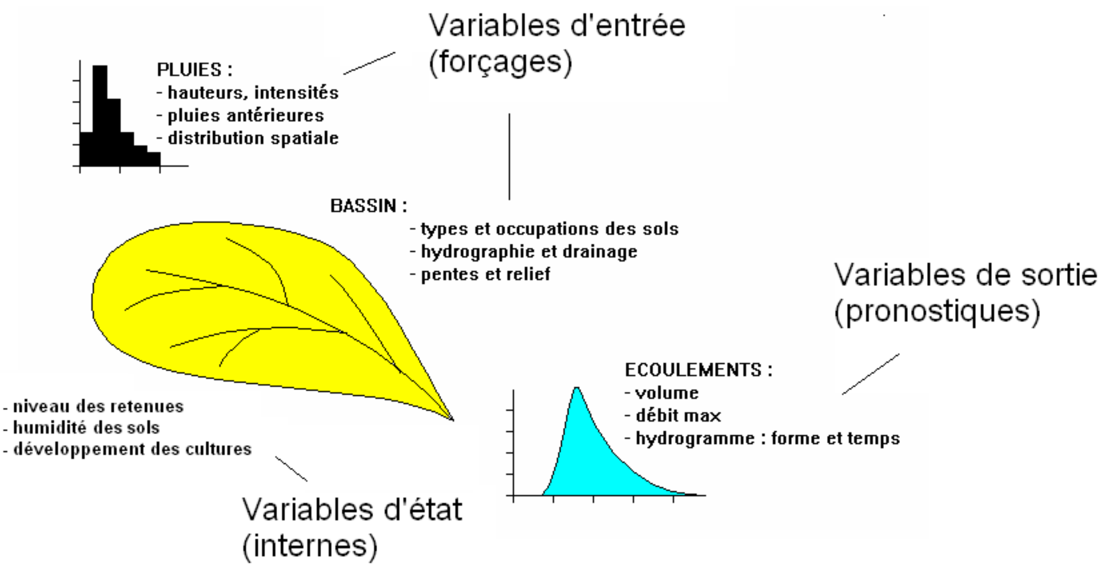

Figure 1-1

A rainfall-runoff model usually comprises a <u>production function</u> (which turns the atmospheric rainfall into efficient rainfall i.e., available for runoff)and of a <u>transfer function</u> (which routes the efficient rainfall to the outlet and reconstitutes flood dynamics).

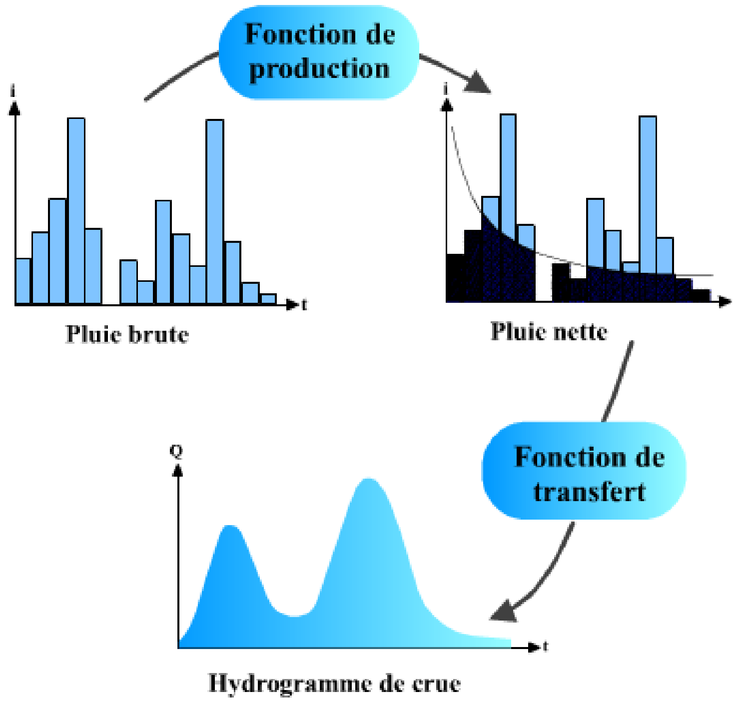

Figure 1-2(From http://hydram.epfl.ch/e-drologie)

From a very schematic point of view, a rainfall-runoff model aims to estimate a runoff coefficient (that may vary in space and over time) and a routing velocity (that may also vary in space and over time).

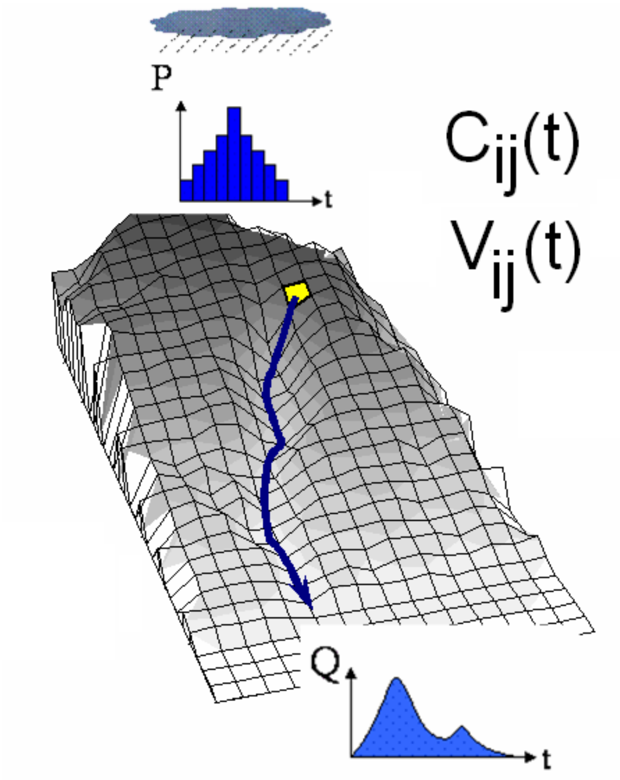

Figure 1-3

Why are rainfall-runoff models useful?

Data concerning river discharges are rare and difficult to measure. Rainfall is more easily measured and acquired, either in real time or post-processed. The primary aim of rainfall-runoff models is thus to simulate discharges from available or estimated rainfall values. By extension, the function of a rainfall-runoff model is to simulate river discharges in any situation that is not monitored by observations (which is most often the case in practice to enable):

- Calculation of rare and extreme discharges;
- Calculation of the discharges of ungauged watersheds;
- Forecasting of discharges at different dates in the future;
- Forecasting of the impact of a change in climate or in the watershed on discharge.

Another aim of a rainfall-runoff model is to test hypotheses concerning hydrological processes. An assumed or designed hydrological behavior can be included in a model, and then tested by comparing it with available rain-discharge observations. Assuming the observations are reliable, if this test fails, the chosen hypothesis will be rejected. If the test succeeds, the chosen hypothesis will be considered as a possible scenario.

1.2. Types of models

Many different rainfall-runoff models exist, but they can be grouped in families in which the model properties are similar:

1) Depending on the nature of the equations used in the model, and the strength of the link with the physics of the processes, i.e. when the link increases, empirical models (regression, neural networks); "conceptual" (analogic reservoir) models; or models physically-based on fluid mechanics equations.

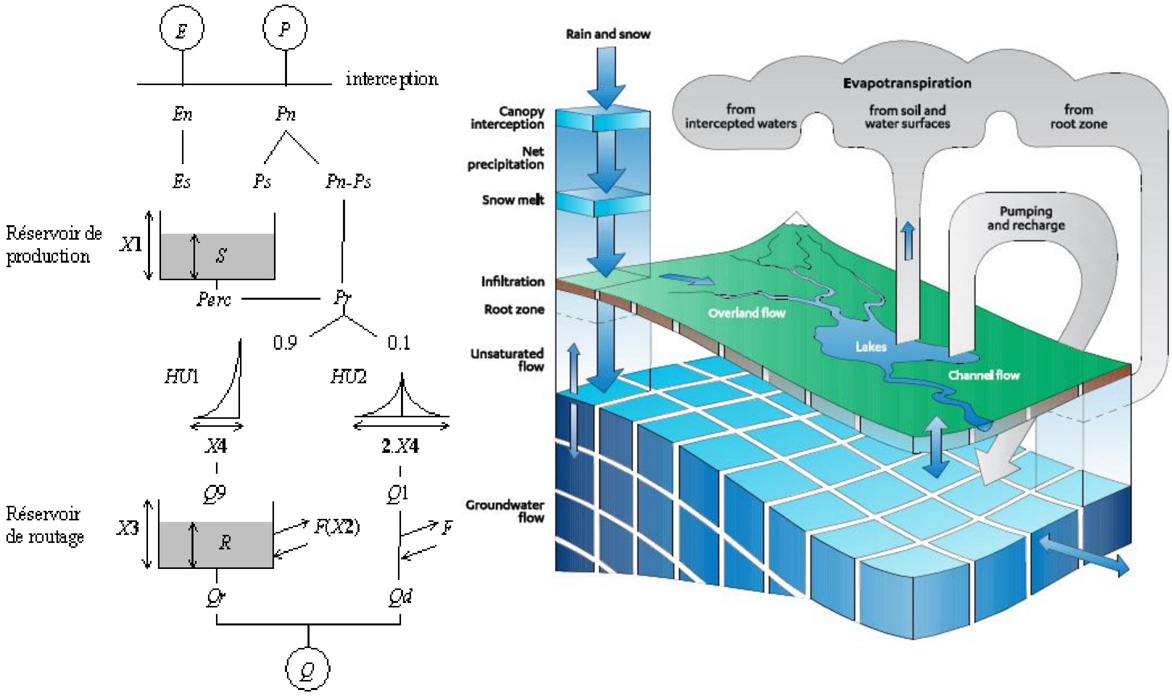

Figure 1-4 On the left, GR4J model (https://webgr.irstea.fr/wp-content/uploads/2013/04/image0021.gif), on the wright, Mike-SHE model (https://www.mikepoweredbydhi.com/products/mike-she)

Physically-based models use for instance Richards' equations (for transfer in the unsaturated zone), Darcy’s equations (for transfer in the saturated zone), Barré de Saint Venant equations (for the free surface flow), Penman-Monteith equations (for evapotranspiration). These equations require many field data that are barely available (e.g. textural and structural soil properties, characteristics of the vegetation, state of the atmosphere), and have to be downscaled at very fine scales for both physical and numerical reasons. Consequently they are rarely suitable tools for operational use, but should be used for impact studies (climate change, modification of the watershed) or to test hypothesis about hydrological processes.

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Empirical models consider the watershed behavior based on observations, at a scale at which the elementary processes are incorporated in simplified concepts . These models involve a limited number of parameters, and are thus more easily set up and calibrated, but extrapolating model results beyond the observed data is not guaranteed.

2) Depending on the range of the simulated discharges, or the different phases: continuous models (the model describes the flood event, but also the inter-event phase and hence the state of the system at the beginning of every event) or event-based models (the model only describes the flood event (or any other characteristic of interest), and the initial conditions must be set up externally) may be used.

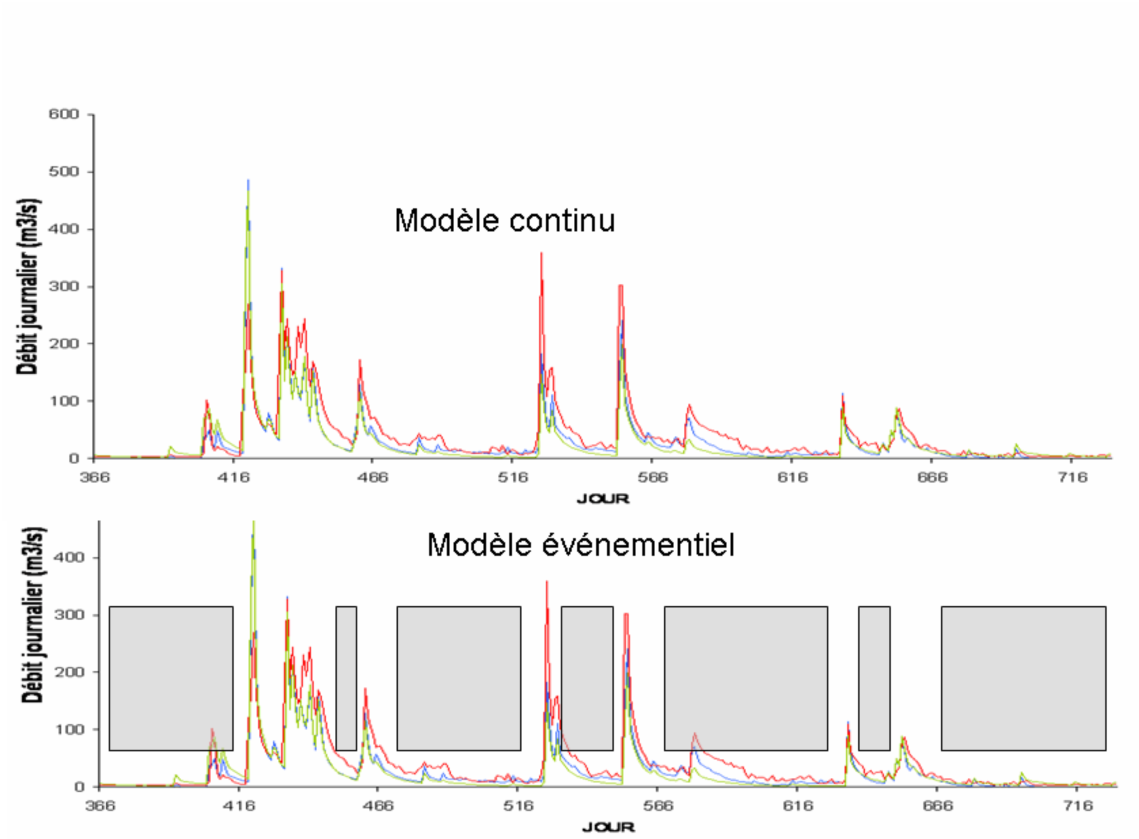


Figure 1-5

The advantage of continuous models is that they simulate a whole set of the discharges, in particular the conditions at the beginning of a flood event. However, these models require a lot of data, and possibly a large number of parameters (because of the complexity of the inter-event phase).Event-based models require fewer data and are usually less complex, but have to be initialized using external variables.

3) Depending on the elementary topology, either lumped models (the variables are in the form of mean values integrating the whole basin: mean rainfall, mean slope etc.) or distributed models (the spatial distribution is taken into account over the catchment).

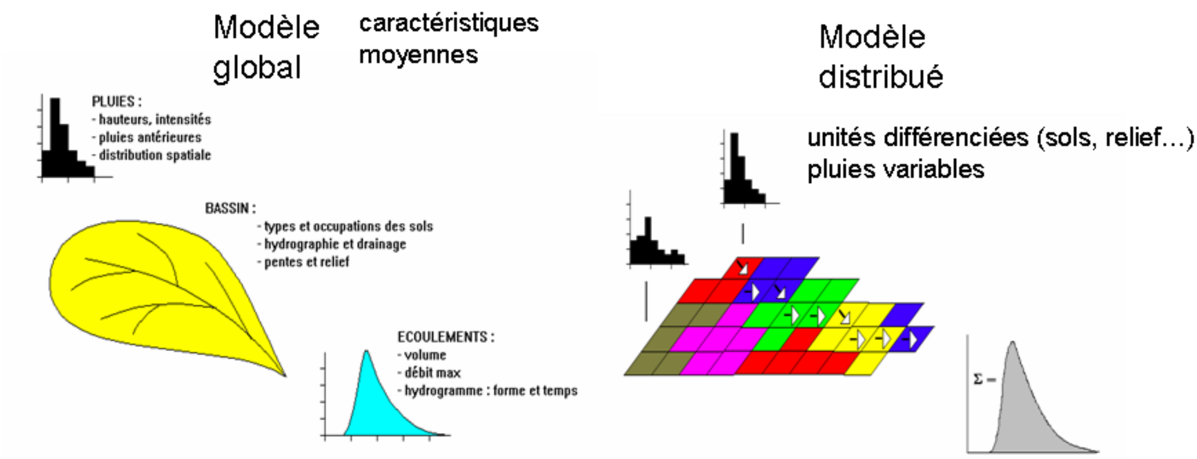


Figure 1-6

The use of a distributed model is not always necessary. In some conditions, e.g. in the case of climatic or geographical homogeneity, a lumped model can produce results that are equivalent to those produced by a distributed model, whereas the structure of distributed models makes it possible to manage available spatial information when there is a lot spatial variability. In this case, distributed models are more powerful than lumped models. However, the complexity of the distributed models should be in agreement with the actual availability of spatial information.

As an example, when rainfall is clearly localized to the upstream or downstream part of the watershed, a distributed model simulates floods that are delayed and shaped differently. In both cases, a lumped model simulates the same flood (dotted line on the graph).

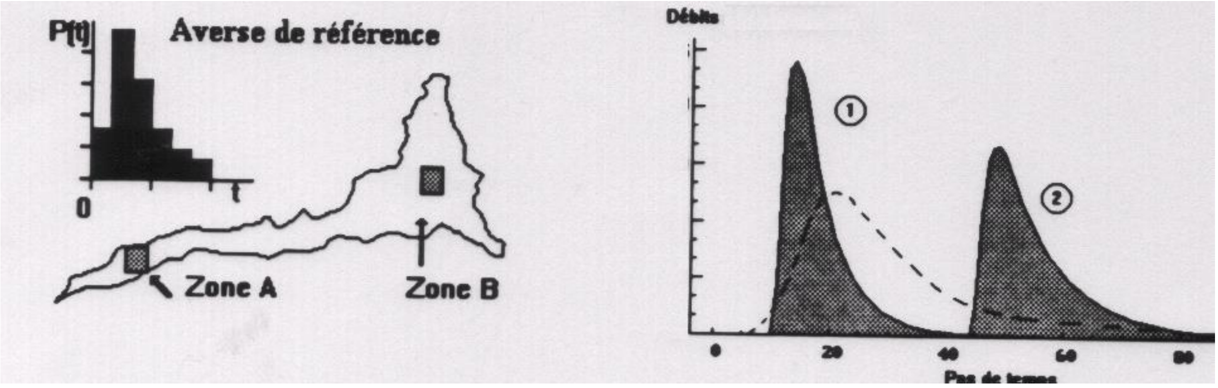


Figure 1-7

1.3. Principles of ATHYS models

ATHYS provides a set of mainly distributed and event-based models. These models can also be processed as lumped (over a larger single cell), and/or continuously.

Principle 1. The models in ATHYS software operate on a regular square cell structure. This structure is suitable for most spatialized data sets (radar rainfall, DEM, SPOT images for land use).

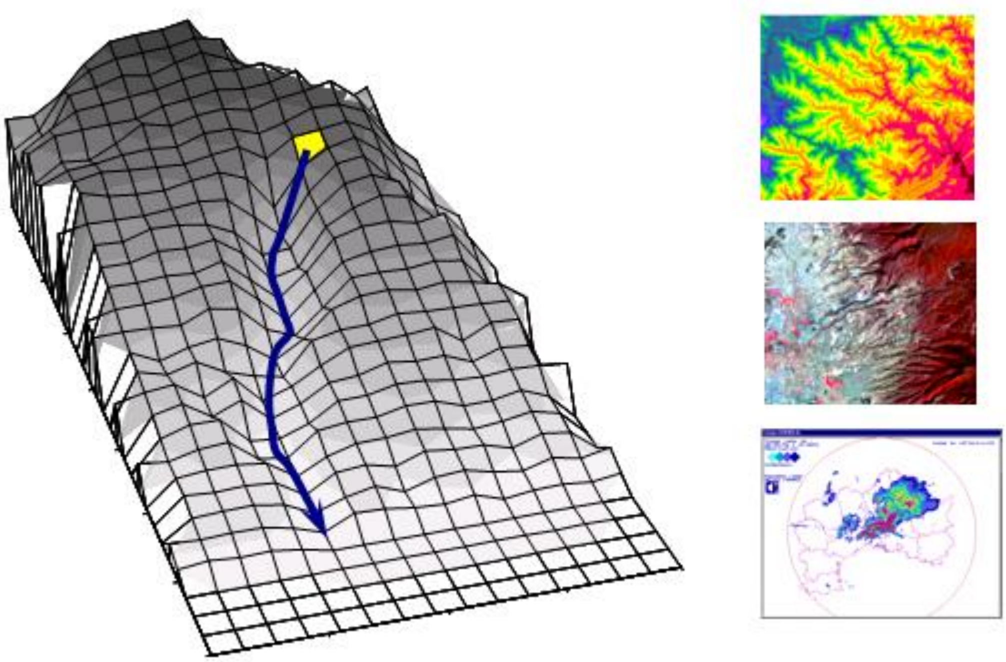
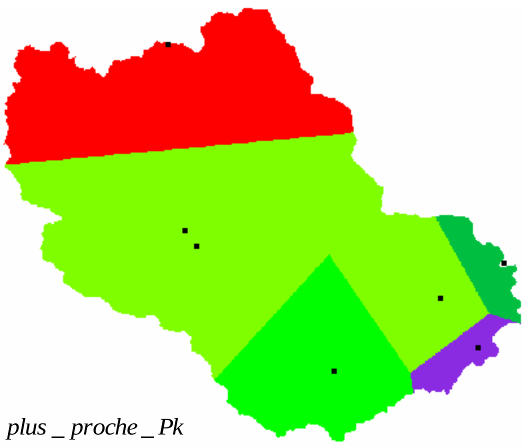
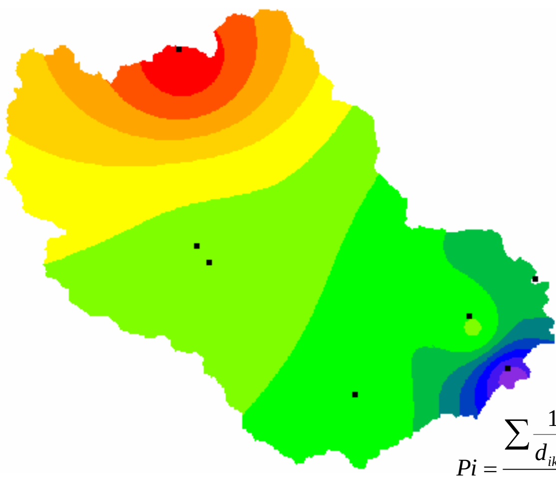


Figure 1-8

Principle 2. Rainfall is interpolated on every cell using the Thiessen method or Inverse Distance Weighed.



$$Pi = plus\_proche\_Pk$$



$$Pi = \frac{\sum \frac{1}{d_{ik}^{\alpha}} Pk}{\sum \frac{1}{d_{ik}^{\alpha}}}$$

Figure 1-9

Principle 3. The efficient rainfall is calculated for every cell. Each cell is associated with a single production function. The production functions may differ from a cell to another.

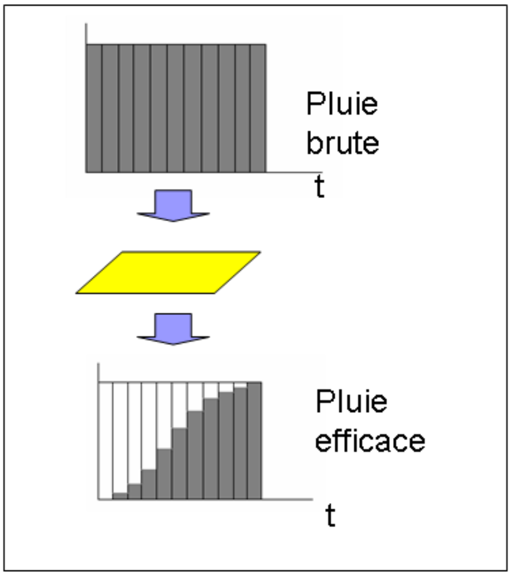


Figure 1-10

Total atmospheric rainfall – Efficient rainfall

Let *Pb(t)* be total rainfall at *t* time and *Pe(t)* efficient rainfall calculated with the production function. Numerous functions are provided, for instance:

Constant infiltration $Pe(t) = Pb(t) - INF$

Constant coefficient $Pe(t) = COEFF.Pb(t)$

Constant threshold $Pe(t)= 0$ *if* $\sum_t Pb(t) > ST0$ *else*
$Pe(t)= Pb(t)$

SCS

$$Pe(t) = Pb(t).\left(\frac{P(t)-0.2S}{P(t)+0.8S}\right)\left(2-\frac{P(t)-0.2S}{P(t)+0.8S}\right)$$

where S is the capacity of a reservoir, Ia is the amount of initial losses and P(t) the cumulated atmospheric rainfall at time t

Green&Ampt $P_b(t)=P_b(t)\text{-}Ks.\left(\frac{\Psi.\Delta\theta}{F(t)}+1\right)$

where Ks is hydraulic conductivity at saturation, $\Delta\theta$ is the difference between moisture at saturation and initial moisture, Ψ is the matrix potential at the moisture front, F(t) is cumulated infiltration from the beginning of the event.

TopModel

$Pe(t) = Pb(t)$ if $\delta_i(t)>0$

$Pe(t) = 0$ else

$\delta_i(t)=\bar{\delta}(t)-\frac{\tau_i-\bar{\tau}}{f}$ et $\tau_i=Ln\left(\frac{a_i}{tg\beta}\right)$ et $K(\delta_i(t))=K_0.exp(-f\delta_i(t))$

where a_i is the surface area drained by cell i, β is the slope of cell i, K is hydraulic conductivity, K_0 and f are adjustment parameters

Principle 4. The efficient rainfall is routed to the outlet. In this case, two modes of transfer are possible: the independent cell mode and the interactive cell mode.

The independent cell mode consists in transferring the contributions of each individual cell to the outlet independently of the other cells. The interactive cell mode takes into account the contribution of cells upstream from the current cell and calculates a balance of the volumes that really flow through each cell at each time step.

Lag and Route model (independent cells mode)

Details are given in section 1.4.2. For a summary, each cell generates an elementary hydrograph at the outlet of the catchment :

$$Q_m(t) = A \cdot \int_{t_0}^{t-T_m} \frac{Pe(\tau)}{K_m} \cdot exp\left(-\frac{t-T_m-\tau}{K_m}\right) d\tau$$

where Pe denotes the efficient rainfall from the cell, A the area of the cell. The travel time Tm is calculated according the flow velocity and the length of the cell. The lag time Km is linearly related to Tm, so that the lag time increases with the propagation time.

The complete flood hydrograph is finally obtained by adding the elementary hydrographs produced by all the cells of the catchment.

Kinematic wave model (interactive cells mode)

More details are given in section 5. For a summary, the Kinematic wave model calculates the discharge at a given time and a given cell from the actual runoff which flows through the cell. The runoff derive from a budget of the inflows and outflows at the cell scale.

The discharges are calculated according the Manning-Strickler formula, where the energy slope is considered as the river bed slope :

$$Q = K\sqrt{S_0}R_h^{0.66}.A$$

where K denotes the Manning-Strickler coefficient, in $m^{1/3}.s^{-1}$ and R_h the hydraulic radius, ratio of the wetted section and the wetted perimeter of the cross-section, in m.

1.4. Detailed presentation of the SCS-LR model

1.4.1. Production function of SCS type

The SCS production function is a very versatile production model and can emulate different types of flood generation processes (Steenhuis et al., 1995). The version used in the model is characterized by:

- An instantaneous runoff coefficient, which is a function of the cumulated rainfall from the beginning of the event;
- A soil reservoir, filled by the fraction of the rain that infiltrates the soil, and is subject to outflow discharge (evapotranspiration, deep infiltration, lateral flow, etc.);
- A delayed runoff, corresponding to a fraction of the outflow discharge of the soil reservoir.

The efficient rainfall Pe(t) is calculated from the rainfall Pb(t):

$$Pe(t) = Pb(t).\left(\frac{P(t)-0.2S}{P(t)+0.8S}\right)\left(2-\frac{P(t)-0.2S}{P(t)+0.8S}\right)$$

where P(t) corresponds to the cumulated rainfall from the beginning of the event, minus an abstracted discharge at each time step. The aim of this abstracted discharge is to simulate the drainage of the soil during the period when it does not rain, and the corresponding decrease in the coefficient of potential runoff.

It can be considered that the amount of rain P(t) corresponds to the level of a virtual reservoir, filled by the atmospheric rainfall Pb(t), and emptied by a quantity that is proportional to the P(t) level. The P(t) level of the reservoir is defined by:

$$\frac{dP(t)}{d(t)} = Pb(t) - ds.P(t)$$

P(0)=0

where ds.P(t) is the abstracted discharge from the reservoir.

To simulate delayed runoff, a soil reservoir is also considered, filled by infiltrated water and emptied by a quantity proportional to the level of the reservoir. The stoc(t) level of this reservoir is determined by:

$$\frac{dstoc(t)}{d(t)} = Pb(t) - Pe(t) - ds.stoc(t)$$

stoc(0) = 0

where ds.stoc(t) stands for an outflow discharge of the soil reservoir by deep percolation, evaporation, sub-surface runoff, etc. For the sake of simplicity, the outflow discharge coefficients of the virtual reservoir of the cumulated rainfall and of the soil reservoir are identical, equal to ds.

Part ω of the outflow discharge of the soil reservoir is routed to the outlet of the watershed as lateral flow. Thus, the runoff quantity generated by the cell at the t time is equal to:

Pe(t) + ω.ds.stoc(t)

The production model has 3 parameters, of which 2 (ds and ω) are constants of the watershed and 1 (S) is influenced by the prior conditions and the state of the system:

S : total storage capacity of the soil reservoir, in mm;
ds : outflow discharge coefficient, corresponding to the drainage potential the soils require to dry out, in d^{-1}
ω : fraction of the outflow discharge as lateral flow, adimensional.

N.B.: for flood peaks, the *S* reservoir capacity is the most sensitive parameter of the model, the other parameters do not vary much. For the Mediterranean catchments, *ds* and *w* could be for example : *ds = 1 d^{-1}, ω = 0.2*

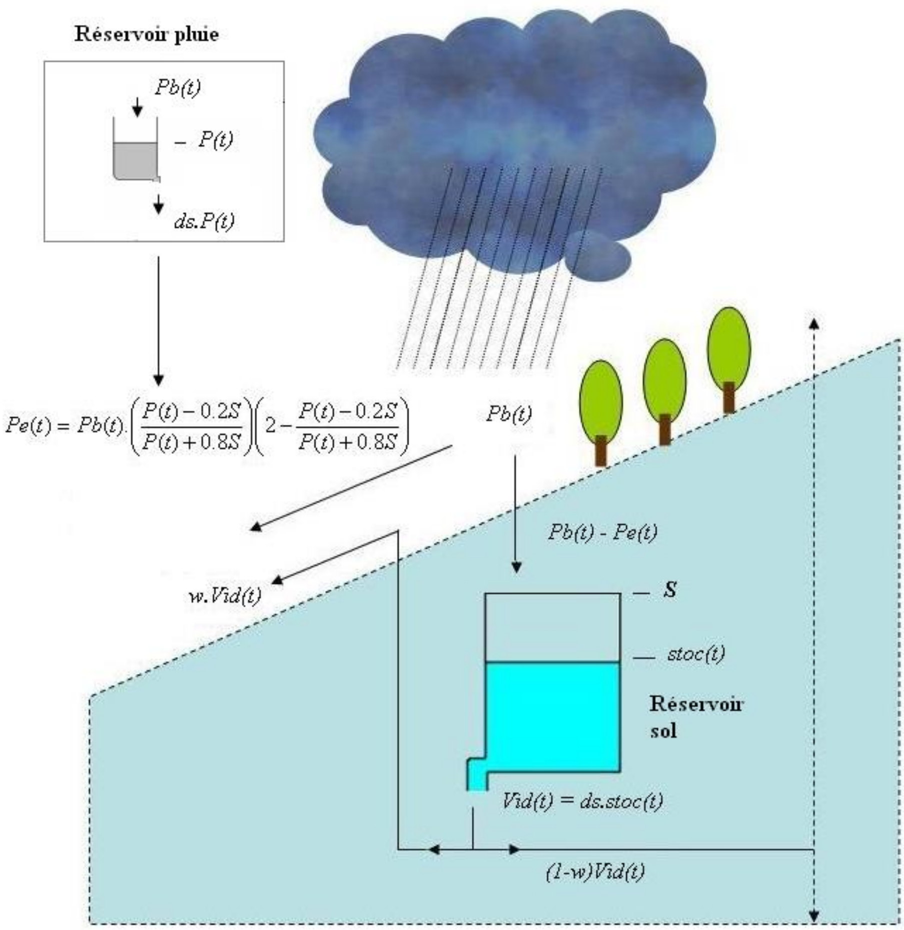


Figure 1-11

N.B.: for the first approximation, the *S* parameter can be estimated from the SCS tables found in the existing literature.

1.4.2 Lag and route transfer functions

The lag and route transfer function routes the volumes generated by each cell to the outlet. Each cell generates an elementary hydrograph at the outlet of the catchment, which depends on :

- the propagation time Tm (route) between the cell and the outlet of the catchment, depending on the flow velocities on the length between the cell and the outlet of the catchment, $T_m = \sum \frac{l_k}{V_k}$

- the lag time Km (lag) between the cell and the outlet of the catchment, calculated by using a linear storage model, of capacity Km.

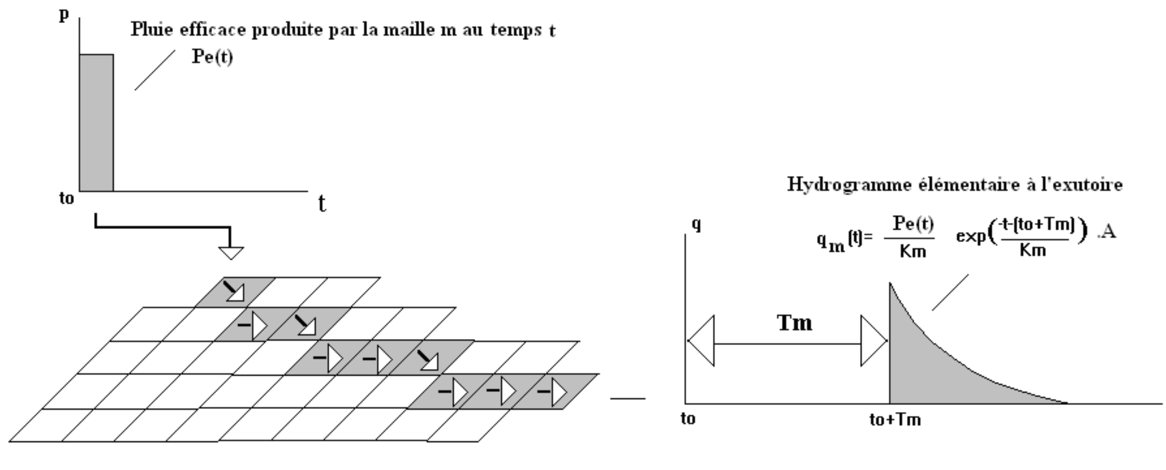


Figure 1-112

The efficient rainfall at time t_0, $Pe(t_0)$, generates an elementary hydrograph :

$$q_m(t) = 0 \qquad \text{if } t < t_0 + T_m$$

$$q_m(t) = \frac{P_e(t_0)}{K_m} \exp\left(-\frac{t-(t_0+T_m)}{K_m}\right).A \qquad \text{if not}$$

where A denotes the area of the catchment, l_k and V_k length and velocity of the cells k between the cell and the outlet of the catchment

By integrating all the efficient rainfall between t_0 et le temps $t\text{-}T_m$, the elementary discharge at time t can be written as:

$$Q_m(t) = A \cdot \int_{t_0}^{t-T_m} \frac{Pe(\tau)}{K_m} \cdot exp\left(-\frac{t - T_m - \tau}{K_m}\right) d\tau$$

The complete flood hydrograph is finally obtained by adding the elementary hydrographs produced by all the cells of the catchment.

In Mercedes, the Lag and Route model has 5 parameters :

- 3 parameters μ, α, β related to the flow velocity V_k over cell k : $V_k = \mu.I_k^{\alpha}.S_k^{\beta}$, where I_k and S_k denote the slope and the upstream area of the cell k. The recommended values are $\alpha = 0.5$ and $\beta = 0.2$, the slopes being in m/m and the upstream areas in km^2.

The flow velocity can be set in a simplest way, with $\alpha = 0$ and $\beta = 0$. In this case, the velocity flow $Vo = \mu$ appears as a constant over the catchment, or part of the catchment, μ being a velocity, in m/s. This parameter can be derived from concentration time formulas.

- 2 parameters k_0 et k_1 related to the lag time Km :

$$K_m(t) = k_0.T_m+k_1$$

The lag time thus increases with the propagation time (ko parameter). The k_1 parameter is mainly used in case of a single cell catchment, emulating a lumped model ; in this case should be used : Vm = 10000 m/s, Km = k_1. In the other cases, it is recommended to use $k_1 = 0$ and Km = k_0.Tm, so that the lag time Km is linearly related to the propagation time Tm.

The travel times are calculated according to:
- The transfer velocity on every cell, *Vm*;
- The diffusion of the flood wave, via a linear reservoir, of *Km* capacity. The diffusion increases with an increase in the distance between the cell and the outlet.

2. ATHYS SOFTWARE

The aim of ATHYS (*ATelier HYdrologique Spatialisé*, Spatialised hydrological workshop) is to provide a a friendly and homogenous framework for hydrological modeling as well as numerical/graphical processing of hydro-climatological and geographical data in . The software was developed at IRD for different applications: management of water resources, forecasting extreme events, impact of anthropogenic or climatic modifications on floods or flow regimes (Bouvier et Delclaux, 1996 ; Bouvier et al., 2010 ; Bouvier et al., 2012).

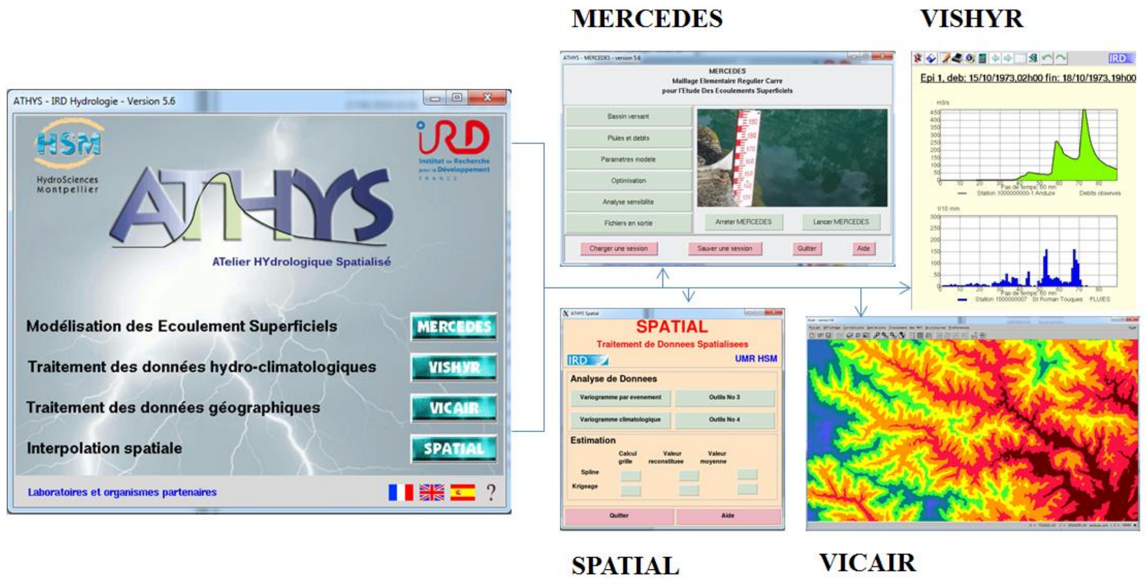


Figure 0-1

ATHYS comprises 4 modules:

MERCEDES: distributed model platform
VISHYR: numerical/graphical processing of local hydro-climatological data
VICAIR: numerical/graphical processing of geographically spatialized data
SPATIAL: spatial interpolation platform

In this chapter we give a brief introduction to the VICAIR and VISHYR modules, whereas the MERCEDES model platform is more detailed.

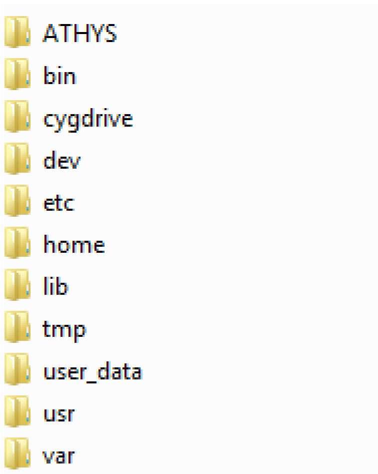
2.1. Installing ATHYS

ATHYS can be downloaded from the site: www.athys-soft.org, in either Windows or Linux versions. The Linux emulator CYGWIN is required to run the Windows version, and is also installed when ATHYS is downloaded.

Installation on Windows involves the following steps:

- Downloading and running the setup.exe;
- Creating a storage directory (ex: C:\ATHYS);
- Copying the files in the storage directory;
- Installing the Cygwin emulator;
- Installing ATHYS;
- Creating shortcuts and icons;
- Installing the Acotools compiler in the ATHYS folder in the « All programs » of Windows

At the end of the installation process, the ATHYS directory contains the following sub-directories:



ATHYS directory stores all the programs required by the software.

home stands for the user account where the demonstration data set of the Gardon at Anduze is initially stored

All the other sub-directories are required by the Cygwin Linux emulator, but don't have to be managed by the user.

At the end of the installation, an icon is created on the desktop:

Figure 0-2

Double clicking this icon launches the program:

Figure 2-3

A window is opened in which all the processes and their progress are displayed (calculations, results of the different requests, etc.).

To exit this window click on the  button

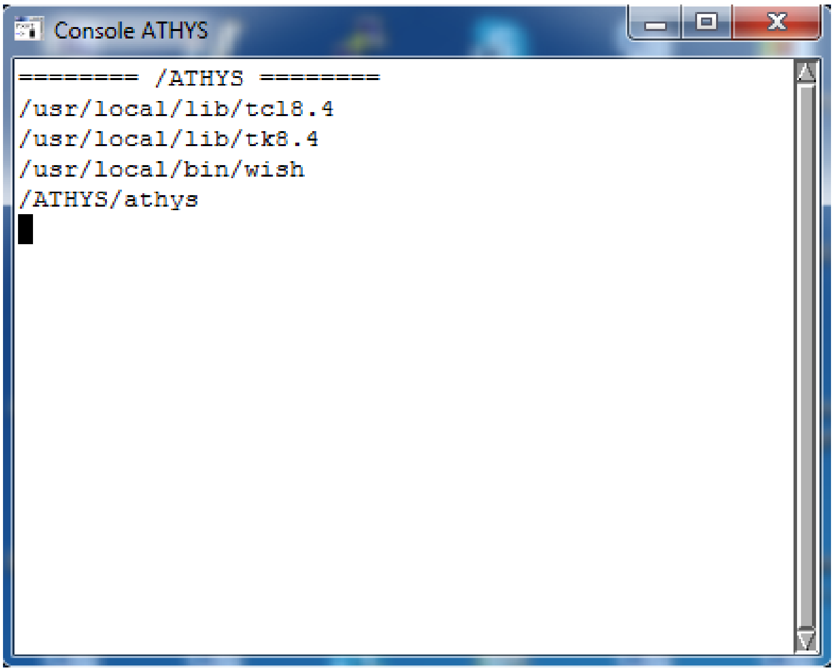
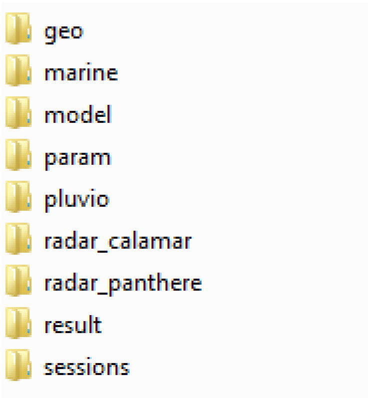


Figure 0-3

The demonstration data set of the Gardon at Anduze is stored in the /home/anduze sub-directory that contains:



Geo contains the spatialized geographical data files: DEM and derived (slopes, drainage …), soil map, etc.

Pluvio contains the hydro-rainfall data files: rainfall, discharge, etc.

Sessions contains different examples of modelling options : model, parameters, input and output data

2.2. Introducing the data

The Gardon watershed at Anduze is located in the southern Cevennes, about 70 km north-east of Montpellier. It drains a surface area of 545 km².

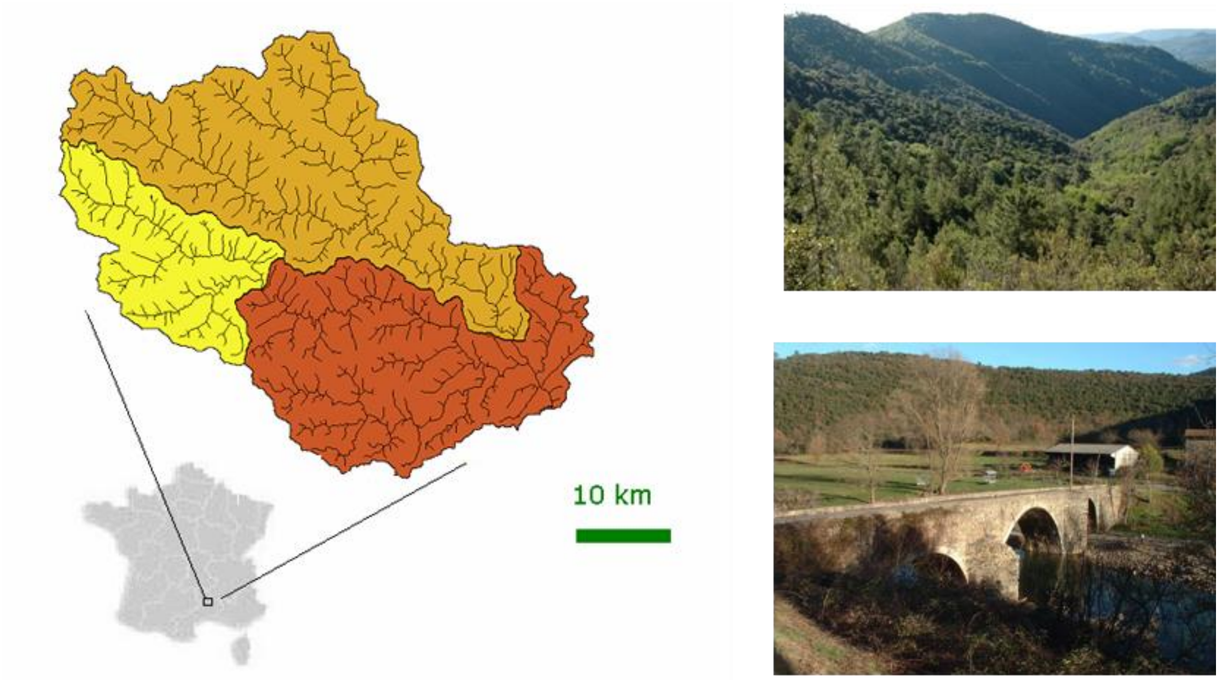


Figure 2-5

At Anduze, the Gardon watershed is subject to flash floods caused by rainfall amounts that can reach several hundred millimeters in 24 hours, especially during the fall. Estimated maximum discharge during the flood that occurred on September 8-9, 2002, reached more than 3,000 m3/s, corresponding to an estimated 50 year return period.

Figure 2-6

Figure 2-7

The watershed is made up of 3 main geological units: shale (yellow), granite (blue), limestone (grey).

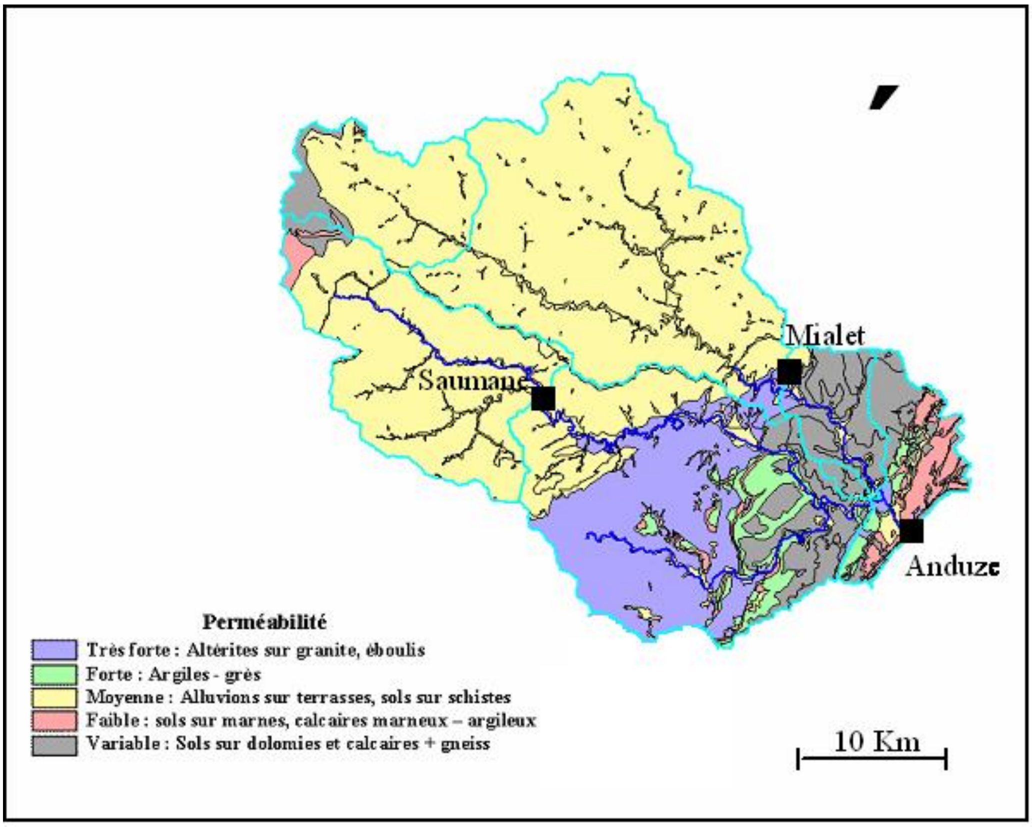


Figure 2-8 (source Ayral, 2005)

The soils are shallow, rarely more than one meter deep (mean depth 30-50 cm). The mean permeabilities are generally rather high, and the soils may store several tenths, even hundreds of millimeters of rainfall before surface flow occurs.

Geographical data

The basic geographical data are:

The DEM at a 50 m step : *Anduze.mnt*;

The drainage pathflow grid mesh, calculated from the DEM : *Anduze.dr1.*

These files are stored in the geo subdirectory geo (see section 8.2 for obtaining these files):

Anduze.mnt: digital elevation model with a 50 m step = elevation of the cell nodes of a 700 X 600 grid mesh, coordinates of the lower left point X0 = 699 837 ; Y0 = 1 890 630 in the projection Lambert2 étendu, DEM unit: 1 meter.

Anduze.dr1 : drainage model with a 50 m step = pathflow coded from 0 to 8 for every cell of a 700 X 600 grid, coordinates of the lower left point X0 = 699 837 ; Y0 = 1 890 630 in the projection Lambert2 étendu.

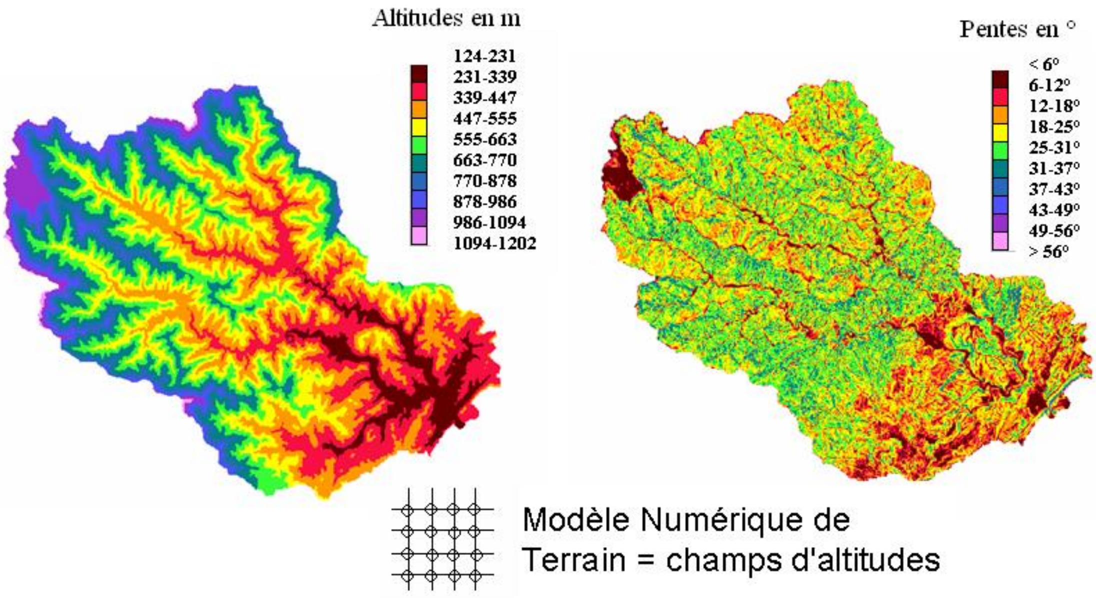


Figure 2-9

The elevations range from 124 to 1202 m and the slopes are steep, average 40%. The digital elevation model (DEM) with a 50 m step makes it possible to obtain a lot of information concerning the topography and the morphology of the watershed (Fig. 2.10).

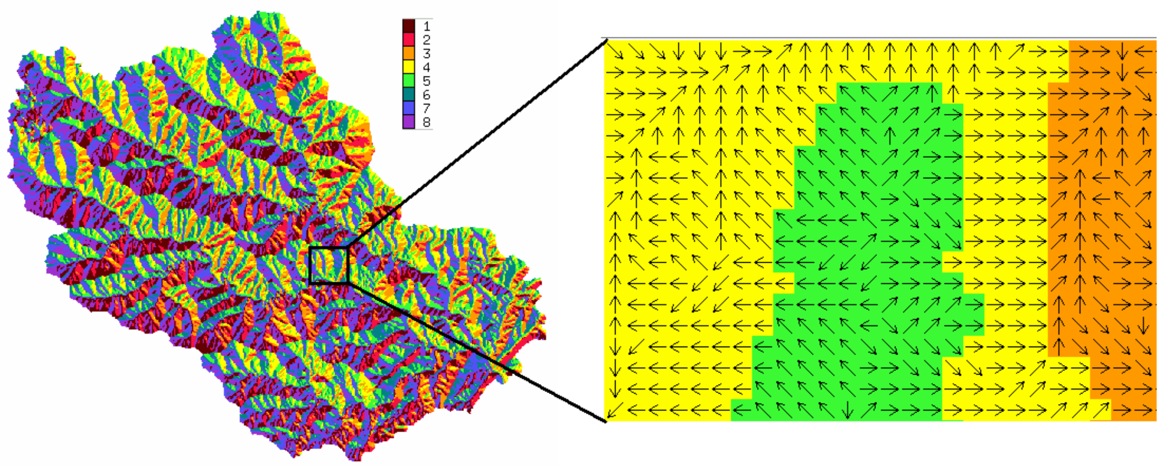


Figure 2-10 : Drainage pathways of each cell of the catchment. A given cell flows towards the neighboring cell which has the lowest elevation

Other files are also provided:
Anduze.sol : soil map, the pixel size is 50 m. Each pixel is coded from 1 to 9, according to the associated soil class.

Hydro-rainfall data

The basic hydro-rainfall data are stored in this file

Base28.txt : rainfall-runoff data at an hourly time step, 28 flood events from 1973 to 2003, including one discharge station (Anduze), 6 rain gauge stations + mean rainfall (calculated using the Thiessen polygon method)

Line 1	Code related to the txt format (here 5000)
Line 2	Type of gauges (observed discharge Q-obs ; input discharge Q-inj ; rainfall P ; temperature T0 ; evapotranspiration Ev ; concentration C%) (5 characters max)
Line 3	Number of the gauge (10 characters max for P, T0, Ev, C%, and 12 characters max for Q-obs et Q-inj)
Line 4	Name of the gauges
Line 5	Longitude of the gauges, in the geographical projection (Lambert, UTM ...)
Line 6	Latitude of the gauges, in the geographical projection (Lambert, UTM ...)
Line 7	Blank line for separating 2 events
Line 8 and other	date (jj/mm/aaaa) hour (hh:mm), then values at the gauges

	1	2	3	4	5	6	7	8	9
1	5000								
2		Q-obs	P	P	P	P	P	P	P
3		1000000000-1	1000000005	1000000006	1000000007	1000000008	1000000009	1000000004	1000000000
4		Anduze	Barre-des-Cévennes	Mialet	Saint-Roman-de-Tousq	Saumane	Soudorgues	Anduze	Pmoy
5		732087	705562	726074	714690	714232	719440	738043	700000
6		1896930	1916178	1903962	1906295	1903081	1896440	1907177	1900000
7									
8	15/10/1973 03:00	1.80	-10.00	0.00	0.00	-10.00	0.00	0.00	0.00
9	15/10/1973 04:00	1.80	-10.00	0.00	5.00	-10.00	5.00	0.00	4.00
10	15/10/1973 05:00	1.80	-10.00	5.00	5.00	-10.00	10.00	5.00	6.00
11	15/10/1973 06:00	1.80	-10.00	10.00	5.00	-10.00	10.00	5.00	7.00
12	15/10/1973 07:00	1.80	-10.00	10.00	5.00	-10.00	15.00	15.00	8.00
13	15/10/1973 08:00	1.80	-10.00	15.00	10.00	-10.00	25.00	5.00	14.00
14	15/10/1973 09:00	1.80	-10.00	15.00	5.00	-10.00	5.00	20.00	7.00
15	15/10/1973 10:00	1.80	-10.00	20.00	10.00	-10.00	15.00	10.00	13.00
16	15/10/1973 11:00	1.80	-10.00	10.00	5.00	-10.00	5.00	10.00	6.00
17	15/10/1973 12:00	1.80	-10.00	5.00	5.00	-10.00	5.00	0.00	5.00
18	15/10/1973 13:00	1.80	-10.00	10.00	5.00	-10.00	5.00	10.00	6.00
19	15/10/1973 14:00	1.80	-10.00	5.00	5.00	-10.00	5.00	0.00	5.00
20	15/10/1973 15:00	1.80	-10.00	15.00	5.00	-10.00	5.00	0.00	7.00
21	15/10/1973 16:00	2.01	-10.00	5.00	10.00	-10.00	15.00	10.00	10.00
22									
23	18/10/1973 14:00	100.00	0.00	0.00	0.00	-10.00	0.00	0.00	0.00
24	18/10/1973 15:00	97.00	0.00	0.00	0.00	-10.00	0.00	0.00	0.00
25	18/10/1973 16:00	91.00	0.00	0.00	0.00	-10.00	0.00	0.00	0.00
26	18/10/1973 17:00	85.00	0.00	0.00	0.00	-10.00	0.00	0.00	0.00
27	18/10/1973 18:00	80.00	0.00	0.00	0.00	-10.00	0.00	0.00	0.00
28	18/10/1973 19:00	77.00	0.00	0.00	0.00	-10.00	0.00	0.00	0.00
29									
30	11/09/1976 16:00	15.60	0.00	0.00	0.00	-10.00	0.00	0.00	0.00

- default units : m3/s for Q, 1/10mm for P, Ev, °C for T0, % for C%

- missing data are -10 for P, Ev, To, C%, -100 for Q

- date and hour must be separated by a space. All other data must be separated by tabulation.

- decimal values must be separated by a . (point)

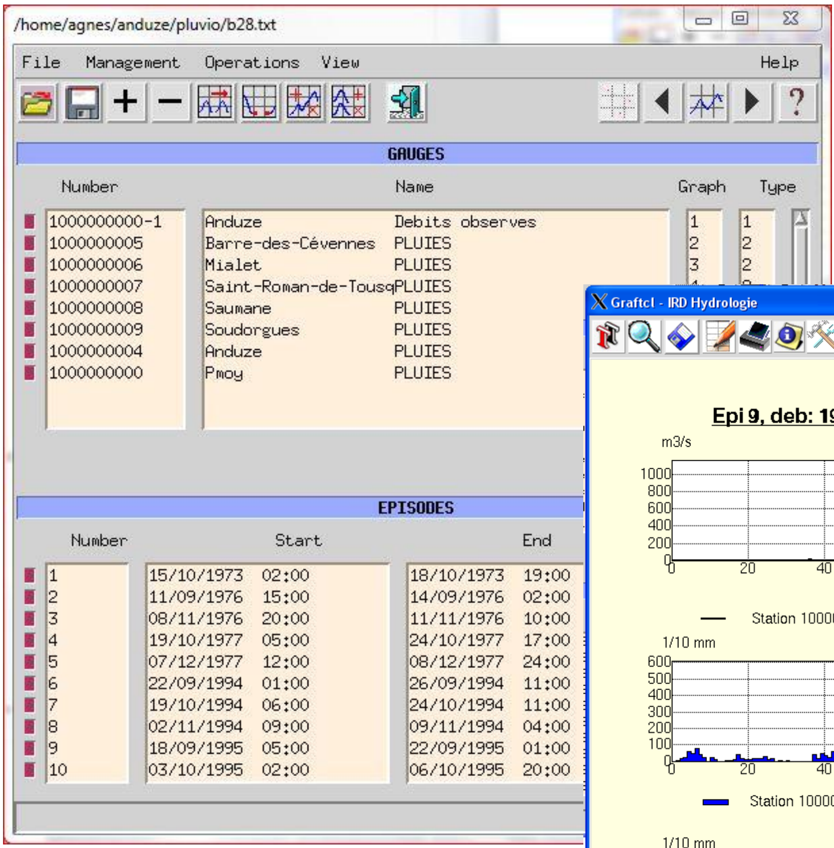
- the date refers to the end of the time step Δt. The corresponding P, Ev data are the cumulated P, Ev between date $-\Delta t$ and date. The corresponding Q, T0, C% data are mean Q, T0, C% between date $-\Delta t$ and date.

Radar rainfall data, which provide rainfall at a 5 min time step and every 1 km^2 cell are also available (see section 8.2).

2.3. Introducing VISHYR

VISHYR offers various facilities for correcting, calculating, managing and displaying local hydro-climatological data:

VISHYR main menu



VISHYR graphical window

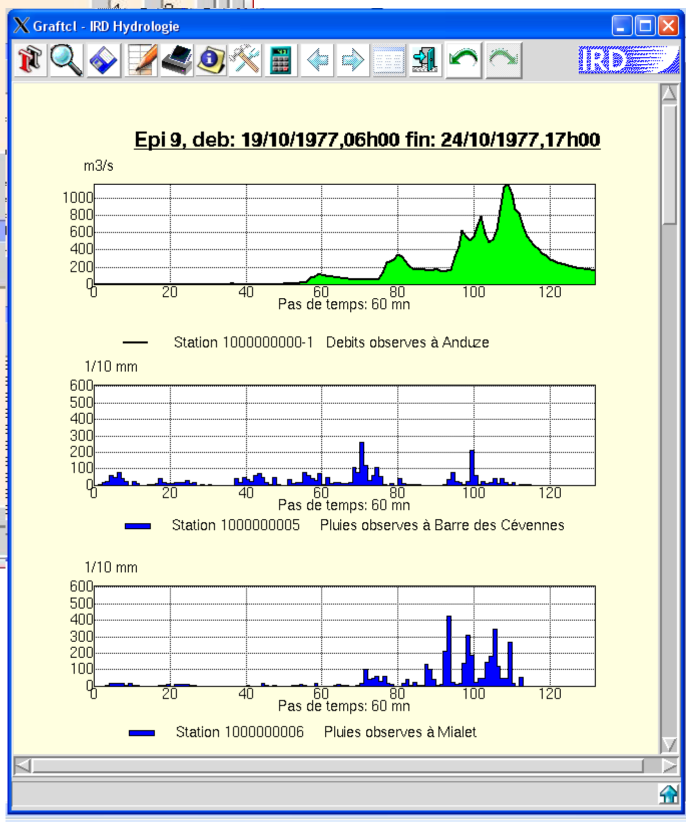


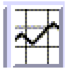
Figure 2-12

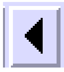
The accepted file formats supported by VISHYR are Asci TXT files, , which can be obtained from (see section 4.4):

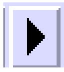
- Export from Excel, with txt format (using tabulation for separating data)
- Export from radar images CALAMAR or PANTHERE/ANTILOPE type;
- Export from PLUVIOM and/or HYDROM.

The first step is to open the hydro-meteorological data file. 

The hydro-meteorological stations and events the data file contains are displayed in the corresponding lists. The different events can be displayed chronologically, using the following keys:

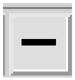
 Display the current event

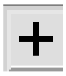
 Display the previous event

 Display the next event

The  keys turn the display of the corresponding hydro-meteorological station or event on or off.

One hydro-meteorological station or event in the data file can be deleted, or one station or one event can be added from another file.

 Delete one station or one event;

 Add one station or one event.

Once the file is loaded, several processes are available:

- Display the event,
- Modify the rainfall or discharge by algebraic computation, change dates or time steps;
- Calculate the event characteristics;
- Manage the lists of the stations and the events.

Please refer to the help pages in the software to obtain a more detailed description of the VISHYR functions and their use.

<u>Applications:</u>

1/ open the file base28.txt hydro-meteorological events, this file contains the hands-on data concerning the Gardon at Anduze;

2/ display the hydro-meteorological events;

3/ calculate the characteristics of these events;

4/ modify the list of the stations and the events.

2.4. Introducing VICAIR

VICAIR offers various facilities for correcting, calculating, managing and displaying geographical data or hydro-meteorological spatialized data:

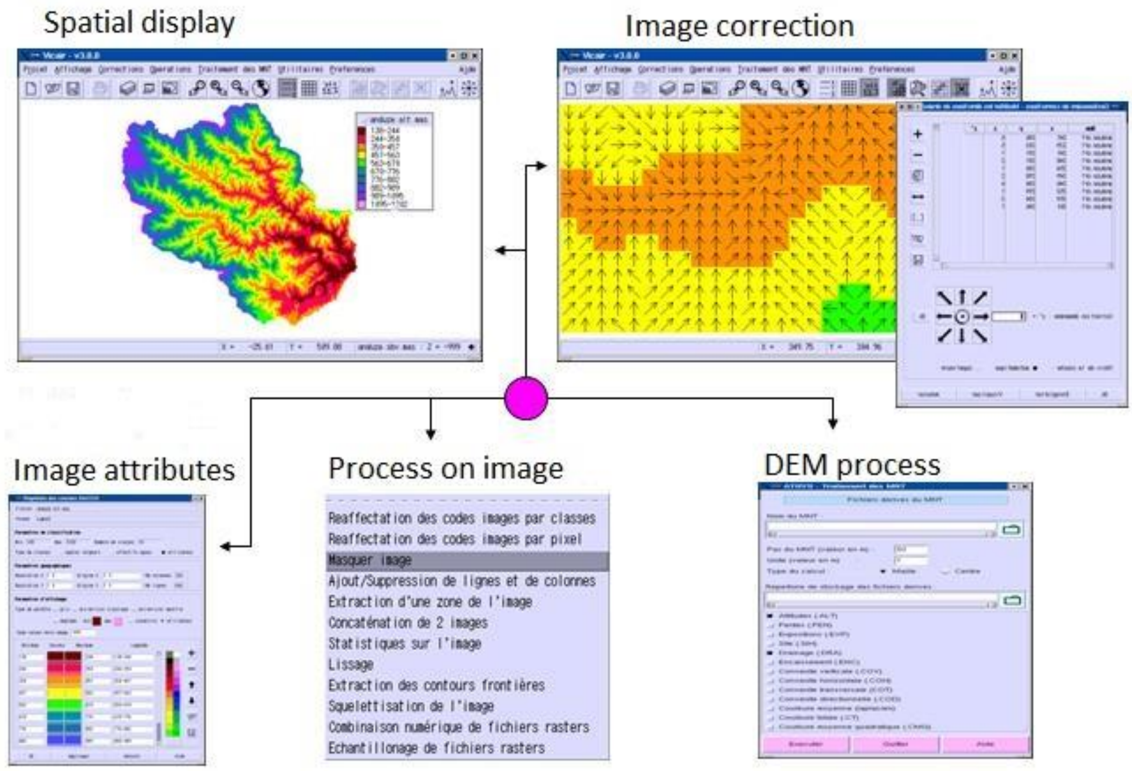


Figure 2-13

The accepted file formats supported by VICAIR are :

- ArcInfo or MapInfo ASCII export files;
- Grass binary or ASCII export files;
- Surfer ASCII export files.

Viewing/correcting a file in Vicair consists in :

- Open a project:
  Choose *Project/New*, or *Project/Open* (if the project already exists)

- This function opens the layer manager, in which the different files which define the project are stored (superimposition of different images or geographical maps).

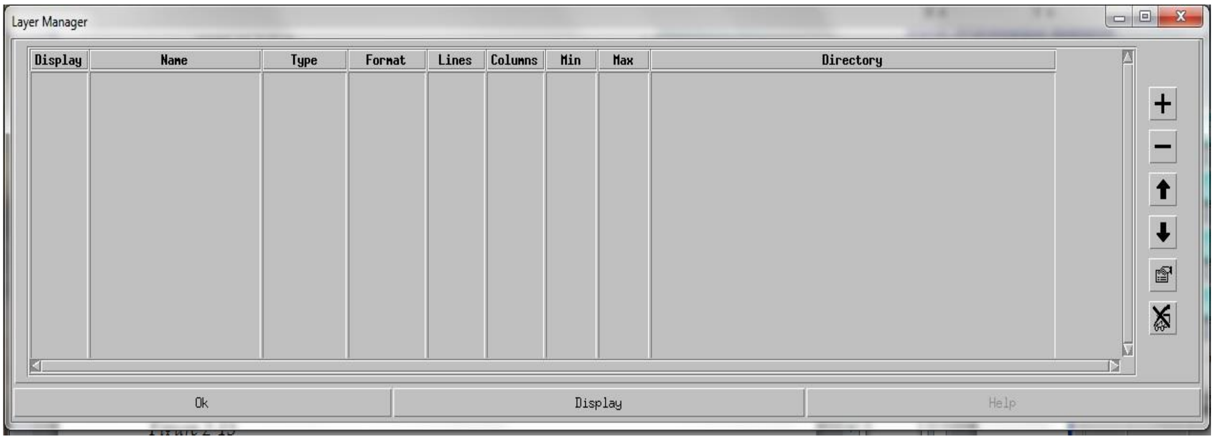
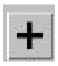


Figure 2-14

- Open a file:

Icon  in the layer manager

This icon (widget) activates a browser that makes it possible to choose the file. The file is then displayed in the layer manager

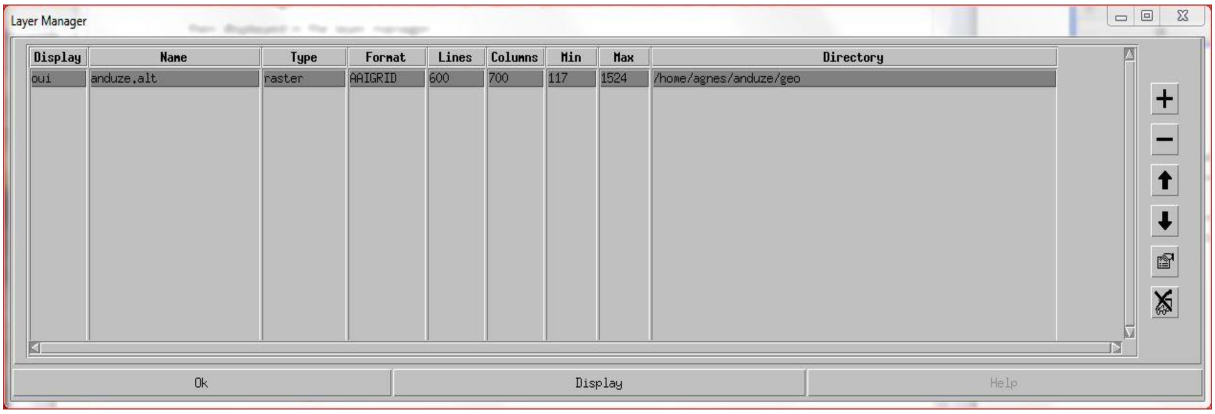


Figure 2-15

- Activate the display :

Display button of the layer manager;

This key activate the view of the picture associated with the file, with numerical and graphical attributes with default values (here 10 classes of color).

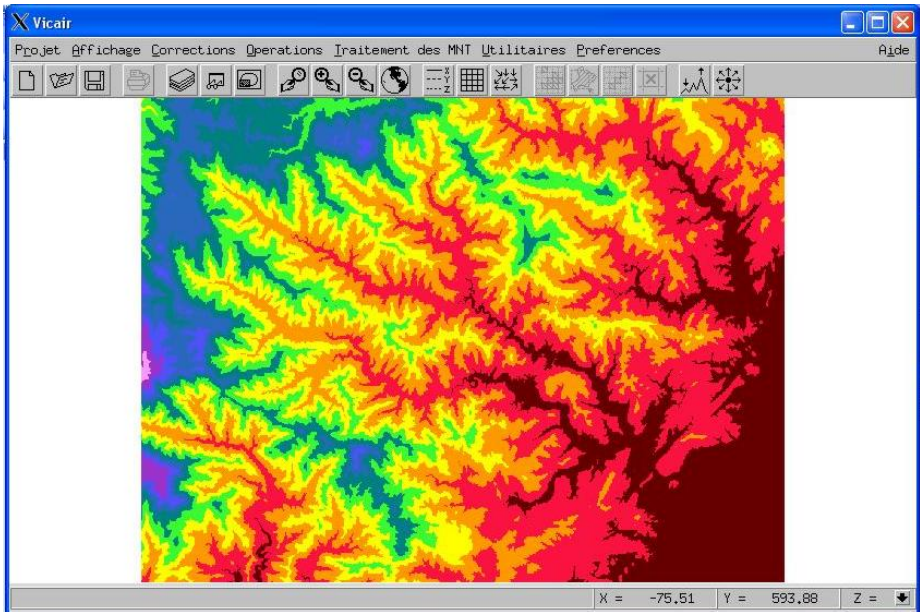
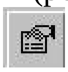


Figure 2-16

- (possibly) modify the file properties:

Icon  of the layer manager opens the <u>property manager</u>, associated with the picture:

* Number of classes;
* Georeferencing in the geographical projection to locate the pictures on the map;
* Choice of the range of colors, etc.

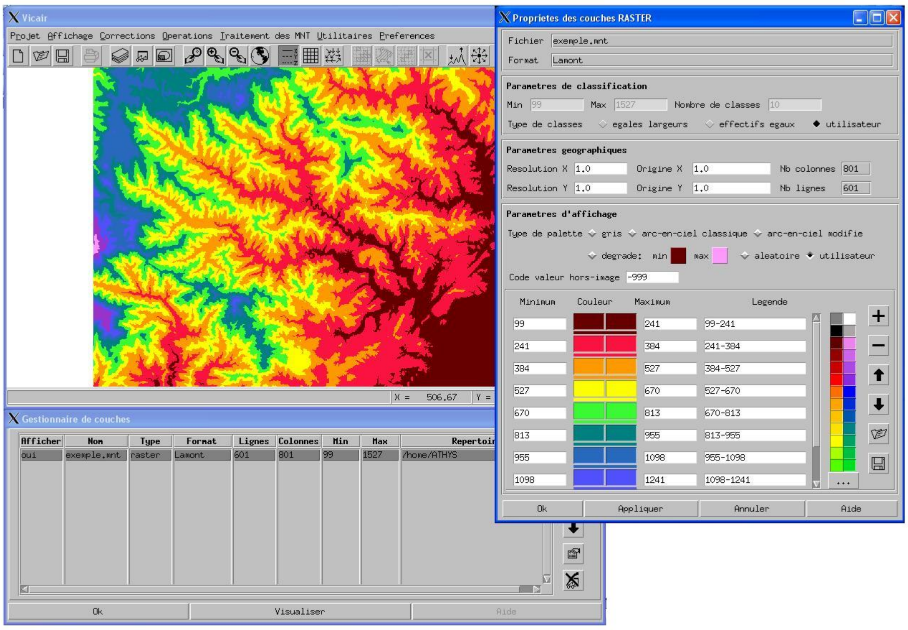
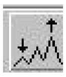


Figure 2-17

- (possibly) modify the pixel values :

  Function *Correction / Correction of pixel* or icon  of VICAIR, which allows modifying one or several pixel values in interactive screenplay mode. For a better view, a zoom of the image is activated before correcting. This function also opens the correction manager, which summarizes the required corrections

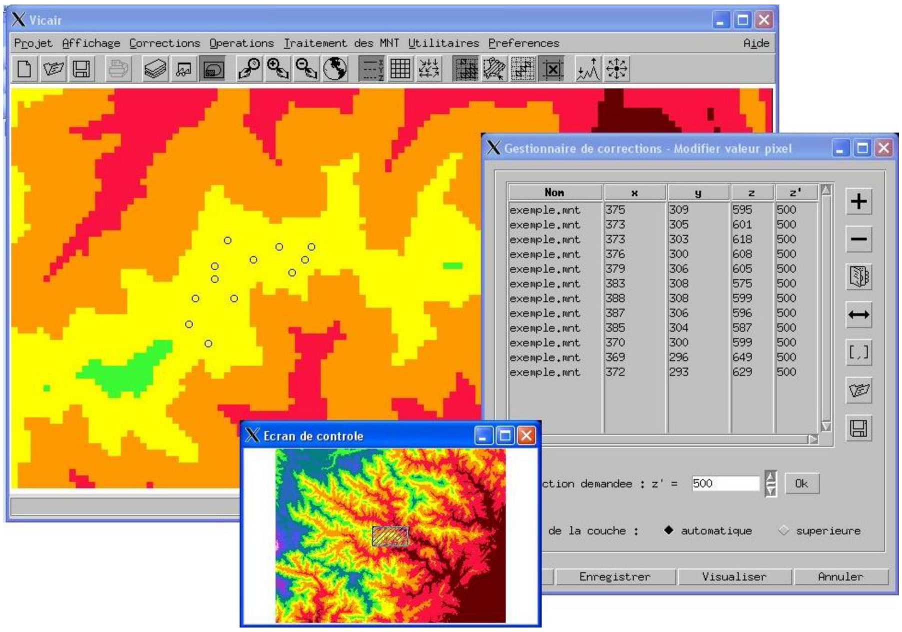
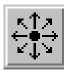


Figure 2-18

- (possibly) modify the drainage pathways :

  Function *Correction / Correction of drainage* or icon  of VICAIR, which allows modifying one or several drainage pathways in interactive screenplay mode. The drainage pathways are displayed as arrows. For a better view, a zoom of the image is activated before correcting. This function also opens the correction manager, which summarizes the required corrections

Applications:

1/ Display the spatialized data files provided in the geo directory;

2/ Modify the properties of the displayed maps;

3/ Display the hydrographical network at different levels of detail using the .sbv file.

2.5. Introducing MERCEDES

The MERCEDES module is made up of 6 menus that enable management of a modelling session

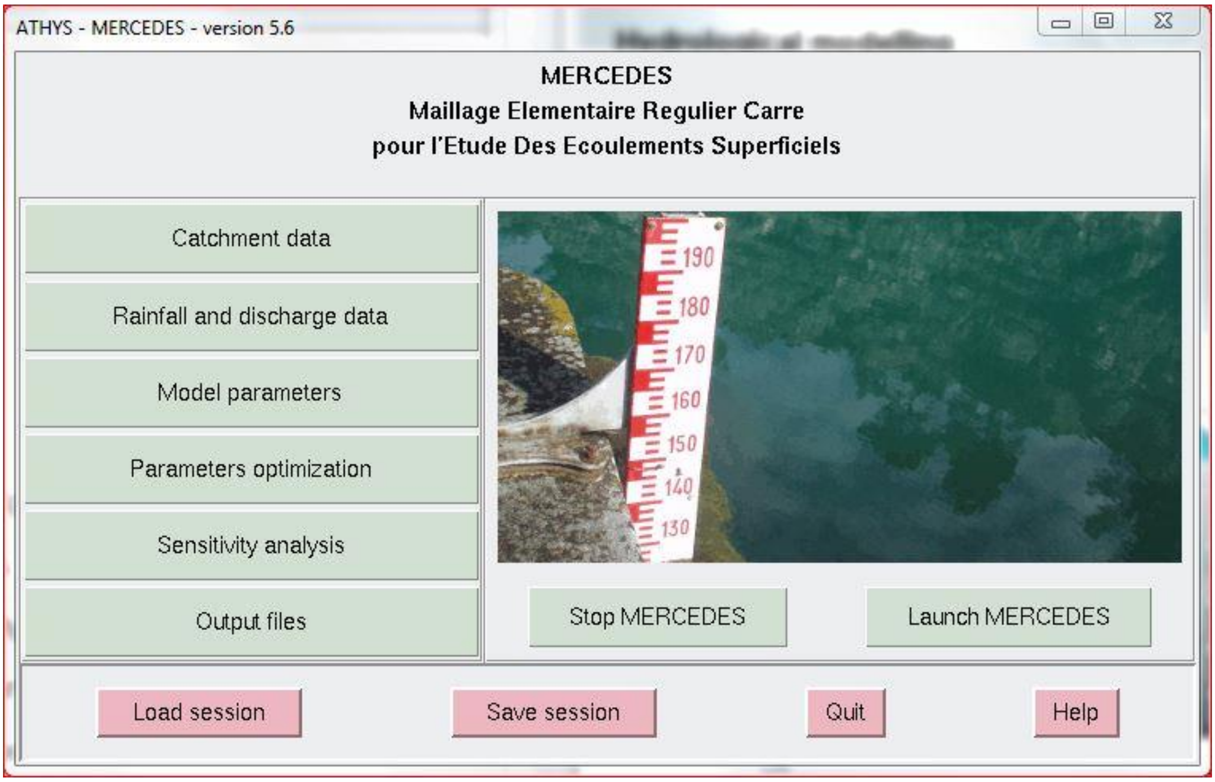


Figure 2-19

- **Catchment data :** description of the catchment to be processed;
- **Hydro-meteorological data :** hydro-meteorological characteristics of the events to be simulated;
- **Model parameters :** definition of the models to be used;
- **Parameters optimization :** automatic calculation of the model parameters;
- **Sensitivity analysis :** sensitivity of the error function according the estimation of the parameters;
- **Output files :** access to the files containing the results.

It is also possible to **Load** or **Save** a **session**. A "session" is made of all the pieces of information to be filled in in the different menus that creates a given model for a given watershed (or group of watersheds).

2.5.1. Menu 1 : Catchment data

This menu is used to describe the catchment(s) to be processed.

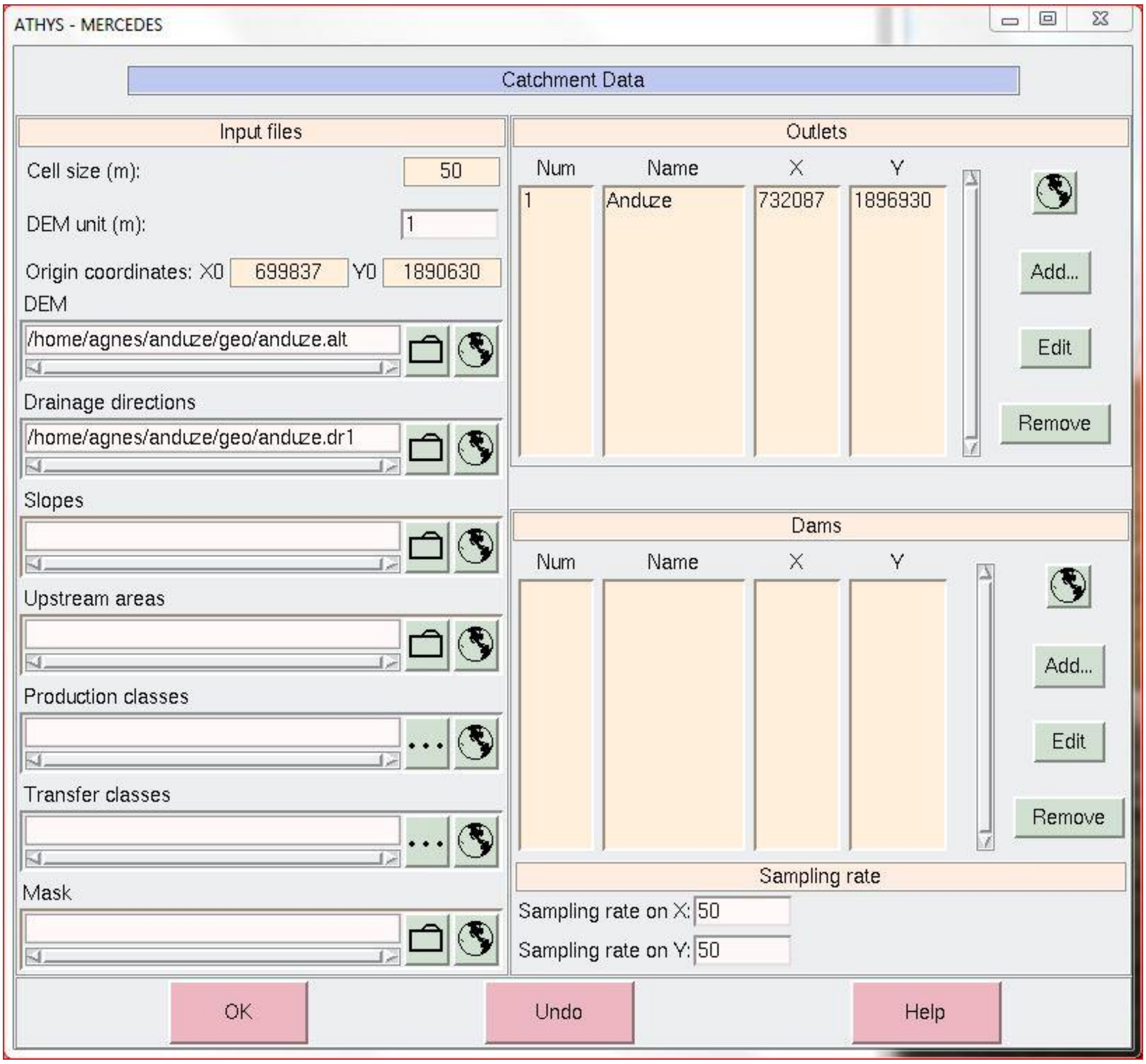


Figure 2-20

The **pixel size** is the length of a DEM cell (in meters), whereas the **DEM unit** expresses the unit of the elevations (1 for meter, 10 for decameter, 0.1 for decimeter). The **coordinates of the X0 and Y0** origins correspond to the the coordinates in the lower left corner in the geographical projection used. <u>The pixel size and X0 and Y0 origin coordinates fields are automatically filled in when the DEM is loaded.</u>

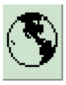
Two files are required for all simulations:

The **Digital Elevation Model (DEM) file**: this is a raster type file. Different formats can be used including the ArcMap or MapInfo export formats. This file size is M by N (M lines and N columns) and a Z value giving the elevation of each node of the grid mesh.

The **pathflow file** stores the direction the water will flow in each cell (i.e. which other cell the water flows into) with a value ranging from 1 to 8 (1=North, 2=North-East, and so on until 8, clockwise). Code 0 refers to a sink that MERCEDES will not process process (i.e. the catchment area will be incomplete), and the sink will have to be filled within the area delimited by the different sub-watersheds defined by the outlet coordinates. The creation of the drainage file and its process (filling the sinks) are computed with the VICAIR program. The size of the file is M by N.

The other files are optional, and will be defined hereafter.

In the right part of the menu, the **outlet coordinates** define the cells where the simulated discharges will be calculated. These coordinates are in the geographical projection units used for the X0 and Y0 previous coordinates.

The  button makes it possible to rebuild the sub-watersheds upstream from these outlets (for control purposes).

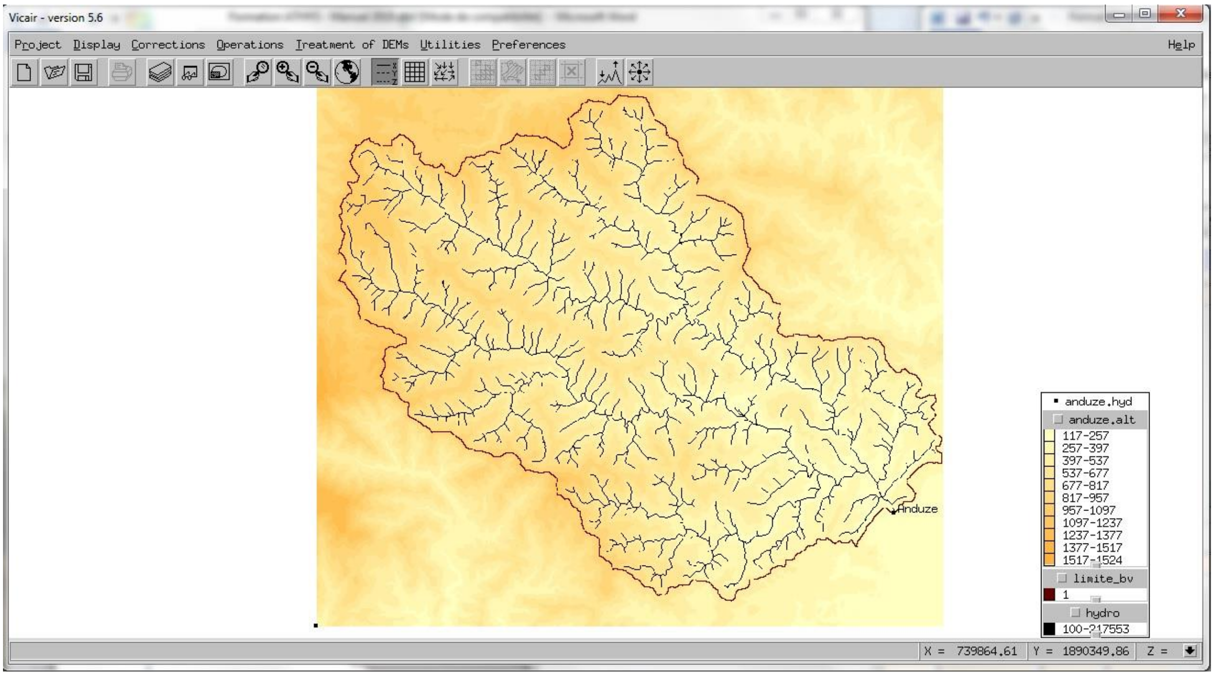


Figure 2-21

Finally, the X and Y **sampling rate** makes it possible to shorten the calculation time while limiting the number of cells to be taken into account. For instance, for a sampling rate of 10 in X and Y, only one cell out of 100 will be taken into account in the calculations (but its surface area will be multiplied by 100).

NB: a high sampling rate can considerably modify the hydrographs and the user will need to compare the results with those obtained with the finest spatial resolution.

2.5.2. Menu 2 : Hydro-meteorological data

This menu describes the the hydro-meteorological characteristics of the events that will be simulated..

One Hydro-Meteo file is required for any simulation.
The Hydro-Meteo file contains all the hydrological and meteorological data to be used for modelling a set of events. Hydrological data can be discharges, water levels, chemical concentrations, etc., meteorological data consist in precipitation, temperatures, evapotranspiration, etc.

This file has to be either in TXT file format. Once this file is validated, the data are displayed in the lists (stations and events).

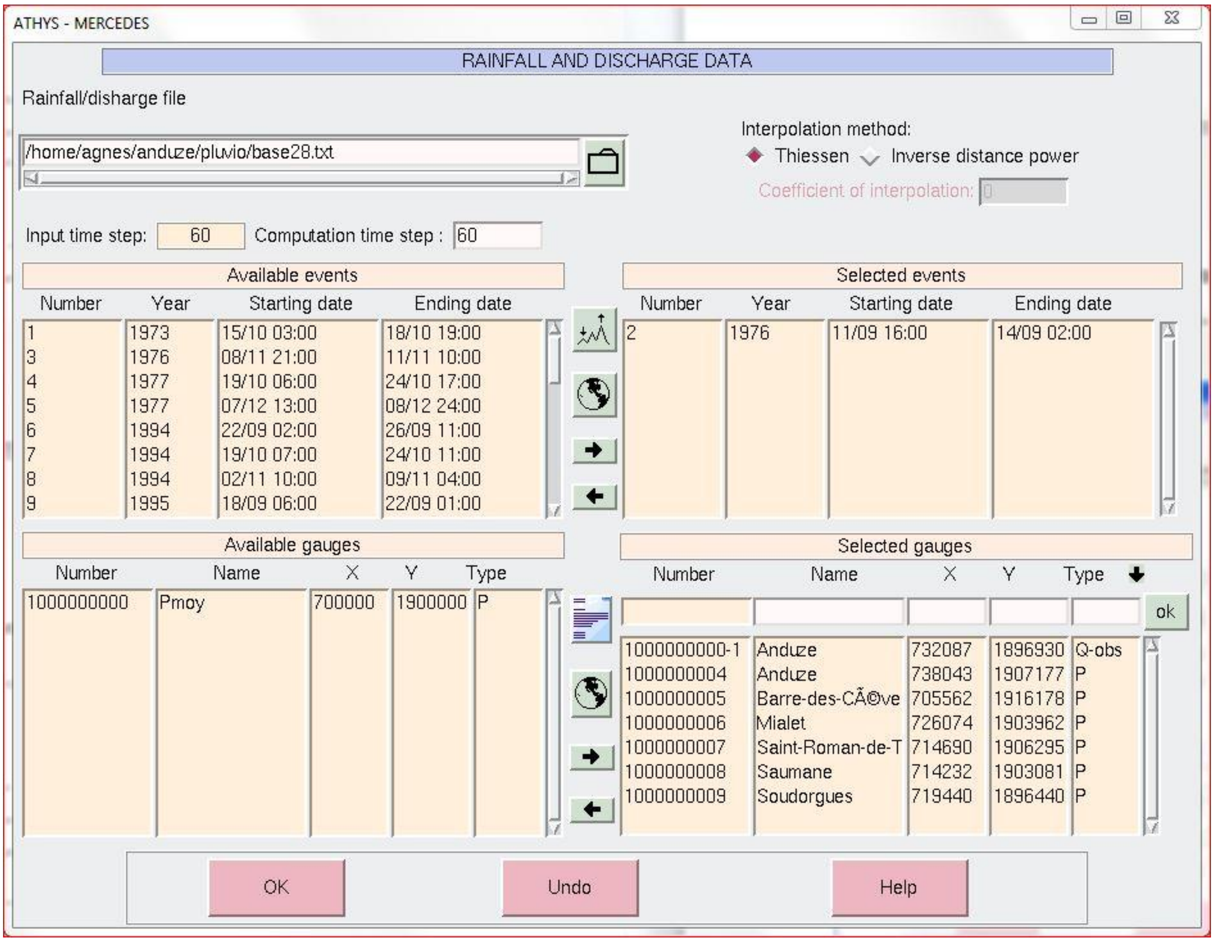


Figure 2-4

The example in figure 2-21 (base28.txt) contains 28 **flood events**. The user can choose to simulate from 1 to 28 events by:

- Clicking on the event in the upper left or right window;
- Clicking  to select the event (the event moves from the left to the right window);

- Or clicking  to deselect the event (the event moves from the right to the left window).

A double-click on one event moves it from one window to the other. It is possible to click on several events using the Shift key of the keyboard (continuous extended selection) or the Ctrl key (discontinuous extended selection).

The events can be displayed <u>one by one</u> using the  button once the event has been selected.

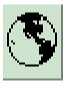
The **initial time step** is the time step used to create the archive of the hydro-meteorological data. This initial time step cannot be modified.

The **initial time step** is the time step used to create the archive of the hydro-meteorological data. This initial time step cannot be modified.

The **time calculation step** that will be used in the process of the models is in minutes, and must be a divisor or a multiple of the initial time step. Initially, the time calculation step is equal to the initial time step.

The **rainfall and hydrometrical reference stations** are displayed on the second level of the window. The rainfall stations that will be used for the spatial interpolation of rainfall are validated while moving them to the window on the right (and conversely). The X and Y coordinates of the selected stations can be modified by clicking on the corresponding station, and validated with the OK button. Selecting hydrometrical stations makes it possible to write the corresponding observations in the result output files of the model.

The  button corresponds to the input of the coordinates from a test file (was useful for older format than the txt).

The  button is used to display the location of the rain gauges.

In the upper right part of the screen, the buttons "**Interpolation methods — Thiessen or Inverse Distance Weighed**" make it possible to choose the rainfall interpolation method on every cell of the ctchment. Only the selected rain gauges (those in the right-side list of the stations) are used to perform the interpolation method.

2.5.3. Menu 3 : Model parameters

This menu lets the user define the models that will be used for the production function and the transfer function, and the corresponding parameters.

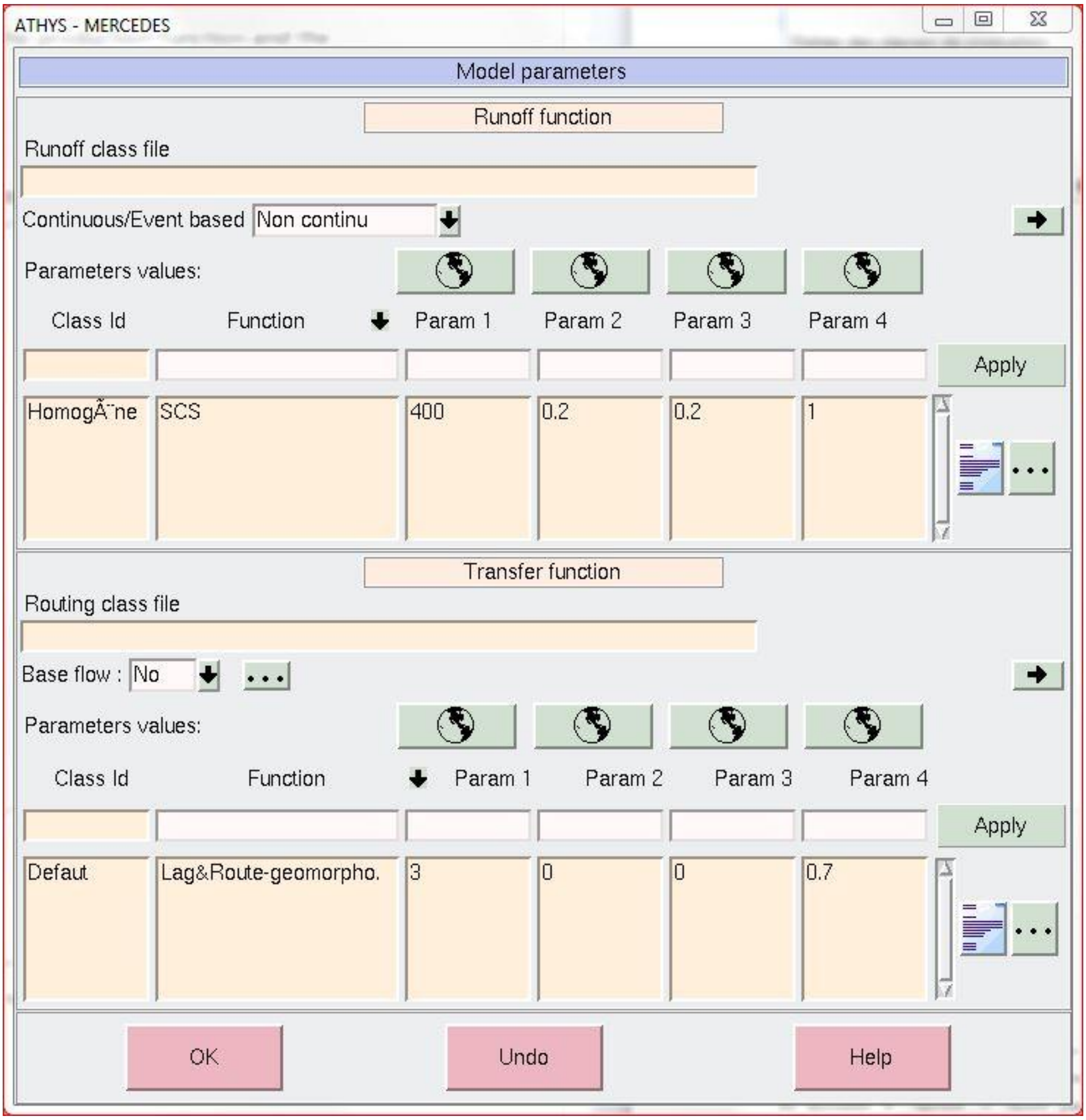


Figure 2-5

Production function

The "**continuous**" or "**non-continuous**" modes define the behavior of the soil reservoir, especially the initial state of this reservoir when rainfall events are sequential. The continuous mode means that the sequence of rainfall events is taken into account to define the initial state. In this case, between 2 rainfall events, the level in the soil reservoir decreases according to the following scheme: $H(t_1) = H(t_0)exp(-ds.(t_1-t_0))$, where $H(t_0)$ is the level f the reservoir at the end of the previous event, $H(t_1)$ the level of the reservoir at the beginning of the next event, *ds* the outflow discharge coefficient used in the production function.

The choice of a **production model** must be made for each class of production : first, click in any class in the production class frame leads to its selection in the upper header. Then, the arrow on the right of Function makes it possible to choose between the programmed functions. Finally, the choice of the value of the model parameters must also be made in this header, and validated with the Apply button, in the right part of the header.

Each production model has a maximum number of 8 parameters, but only 4 parameters are displayed on the same screen. The other 4 parameters are accessed in a second screen, by clicking left on the arrow , at the right of the production class frame.

The model parameters can vary from one event to another (see section 3.4).

The model and/or the parameters can vary over the catchment (see section 4.2 and section 6).

Transfer function

The choice of a transfer model must be made for each class of transfer : first, click left in a class leads to its selection in the upper header. Then, the arrow on the right of Function makes it possible to choose between the programmed functions. Finally, the choice of the value of the model parameters must also be made in this header, and validated with the Apply button, in the right part of the header.

Each transfer model has a maximum number of 8 parameters, but only 4 parameters are displayed on the same screen. The other 4 parameters are accessed in a second screen, by clicking left on the arrow , at the right of the transfer class frame.

As for the production parameters, the transfer parameters can vary from one event to another (see section 3.4). The transfer model and/or the parameters can vary over the catchment (see section 4.2 and section 6).

Base flow

The **Base flow** mode (Yes/No) makes it possible to take into account and to model the base discharge in the simulation of the flood events. The Base discharge mode — Yes makes it possible to rebuild a base discharge in the form:

$$Q(t)=Q_0.esp(-\alpha.(t-t_0))$$

where

- Q_0 and α are set as constant for all the events (FIX)
- Q_0 and α are estimated from observations at a reference station (OBS)
- Q_0 and α are estimated from the preceding event (AJUST)

These options have to be defined in the window that opens when the Base flow mode is activated.

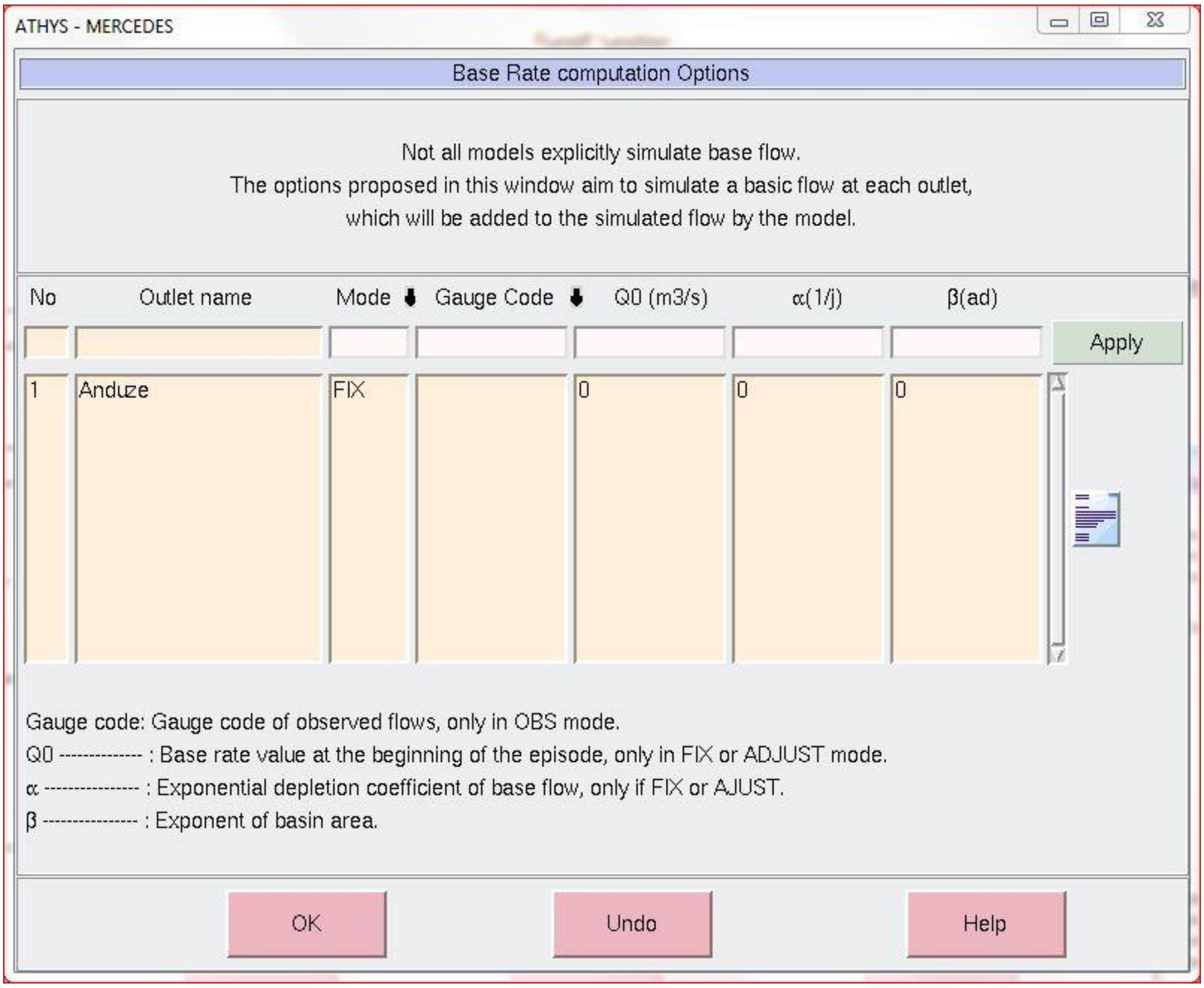
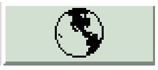


Figure 2-6

Icons

 makes it possible to spatially modify the parameters in the corresponding column, depending on a geographical map (see section 6)

 makes it possible to use parameters that vary from one event to another, depending on the values defined in a table (see section 3.4)

 makes it possible to fill the parameter table from a file formatted as follows, in the case of several production or transfer classes. . The format of such file must be made of sequential lines of 10 values separated by space, each line denoting a production or transfer class:

Class_Id function par1 par2 par3 par4 par5 par6 par7 par8

2.5.4 Menu 4 : Optimization

This menu makes it possible to automatically calculate the "most appropriate" parameters of a model by minimizing a deviation between the observed values and the values simulated by the model.

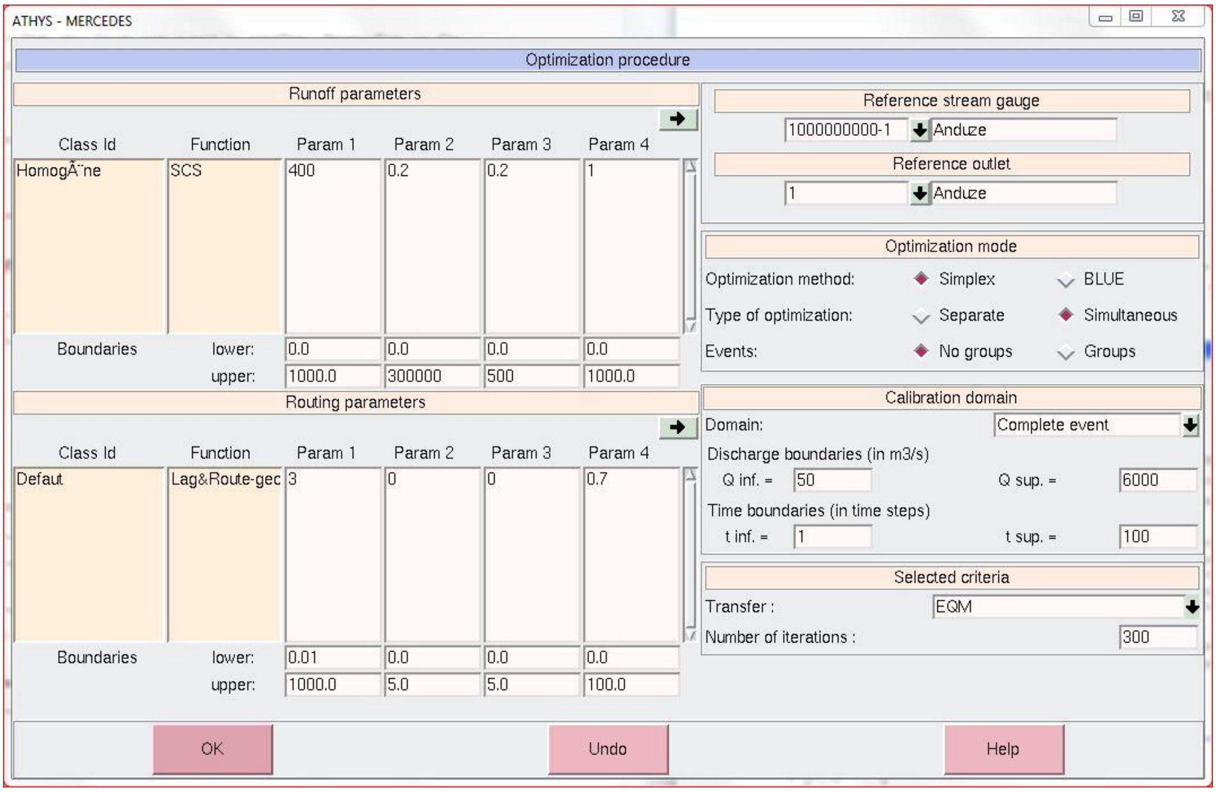


Figure 2-25

<u>Selection of parameters to optimize</u>

The parameters to be optimized must be selected by double clicking on the value of the parameter. The parameter value then appears between the > and < symbols.

Remark: when this menu is opened, the name of the parameters is not displayed. Just click on the name of the functions and the names will be displayed.

<u>Variation boundaries</u>

The variation boundaries that will be applied for every parameter can be chosen for calibration.

Remark: pay attention to the ***variation boundaries*** *of the parameter to be calibrated: the initial value of the parameter — the one given in menu 3 and displayed in this menu — must be included within the defined boundaries.*

Selection of the observation gauge and the catchment outlet

The observed values must be referenced to a gauge where data are available, whereas the simulated values refer to a catchment outlet, which has been declared in menu 1. Observed and simulated data, i.e. gauge and outlet, must refer to the same coordinates. If not, a warning is sent, in order to change the observation gauge or the catchment outlet, or to modify their coordinates in Menu 1 (catchment outlet) or in Menu 2 (Observation gauge).
Optimization method

Optimization method

Two optimization methods are available. Both search for the best parameters for the model, i.e. the parameters that minimize the error between the observed and simulated values of the discharges.

The Simplex method converges by means of geometrical transformation of the initial set of parameters, whereas the BLUE method converges according on the gradient of each parameter (slope — or derivative — of the model compared to the parameter considered). Convergence is more rapid with BLUE, but convergence with Simplex is more robust, and can force the values of the parameter to be optimized in a limited range (this is not always possible with BLUE).

Type of optimization

The "**separated**" type of optimization corresponds to a two-step calibration: first the parameters of the production model are calibrated by minimizing the errors in total runoff volumes at the outlet; then, once these parameters are fixed, the parameters of the transfer function are calibrated by minimizing the errors in the discharges at the outlet according to the chosen criterion.

The "**simultaneous**" type of optimization corresponds to the simultaneous calibration of all the requested parameters, by minimizing the errors in the discharges at the outlet.

The option "**Individual events**" or "**Grouped events**" means that each event will have its own optimized parameter set in the Individual events mode (there will be as many sets as events), whereas in the Grouped events mode, only one common parameter set is determined for all the events. In the latter case, the error is calculated from the discharges of all the events.

Calibration domain

The calculation can be based on :

The whole event: the criterion is calculated for the entire duration of the event

The flood peak: calibration aims to reproduce at the best only the peak values of the floods, independently of the timing of the peak discharges.

Fixed discharges: the criterion is calculated only for discharges measured between Q_{inf} and Q_{sup} defined in the corresponding fields.

Fixed times: the calculation is computed only for the discharges measured between the times t_{inf} and t_{sup} defined in the corresponding files. T_{inf} and T_{sup} must be expressed as a number of time steps.

Fixed discharges and time: this is the association of the two preceding constraints.

Choice of the error function

According to the choice of the previous optimization mode, a calibration criterion is chosen for the production and transfer functions.
If we have chosen a type of simultaneous optimization, we only choose one criterion for the transfer function, because the calibration will be done only on the comparison measured flows / calculated flows.

Four error functions are currently available for the calibration of both the production function and transfer function:

- Mean arithmetical deviation **EAM** = $\frac{\sum |X_i - Y_i|}{\sum Y_i}$
- Mean quadratic deviation **EQM** = $\frac{\sqrt{\sum (X_i - Y_i)^2}}{\sum Y_i}$
- Nash criterion **Nash** = $1 - \frac{\sum (X_i - Y_i)^2}{\sum \left(Y_i - \bar{Y}\right)^2}$
- CREC Criterion **CREC** = $\sum \left(1 - \frac{\bar{X}}{Y_i}\right) * \sum \left(1 - \frac{Y_i}{\bar{Y}}\right) * \frac{1}{N}$

where X_i stands for the N calculated values and Y_i for the N observed values and $\bar{Y}$ is the average value of the N observed values.

X and Y represent the total runoff volumes of the events in the case of the separate calibration of the production function, and the discharges in the case of the separate calibration of the transfer function, or in the case of a simultaneous calibration of the production and transfer functions.

If the simultaneous optimization type is chosen, only one criterion is required for the transfer function, because the calibration will be done only on the comparison between the measured/calculated discharges.

Remark: when the Nash criterion is chosen, only the couples of observed and calculated values corresponding to strictly positive observed values are considered for computing Nash criterion.

2.5.5 Menu 5 : Sensitivity analysis

This menu is complementary (or alternative) to the previous one, and provides additional information such as: the area of possible other sets of parameters (whose error is close to the minimum error value), the sensitivity of the model to the parameters, possible dependency between the parameters, etc.

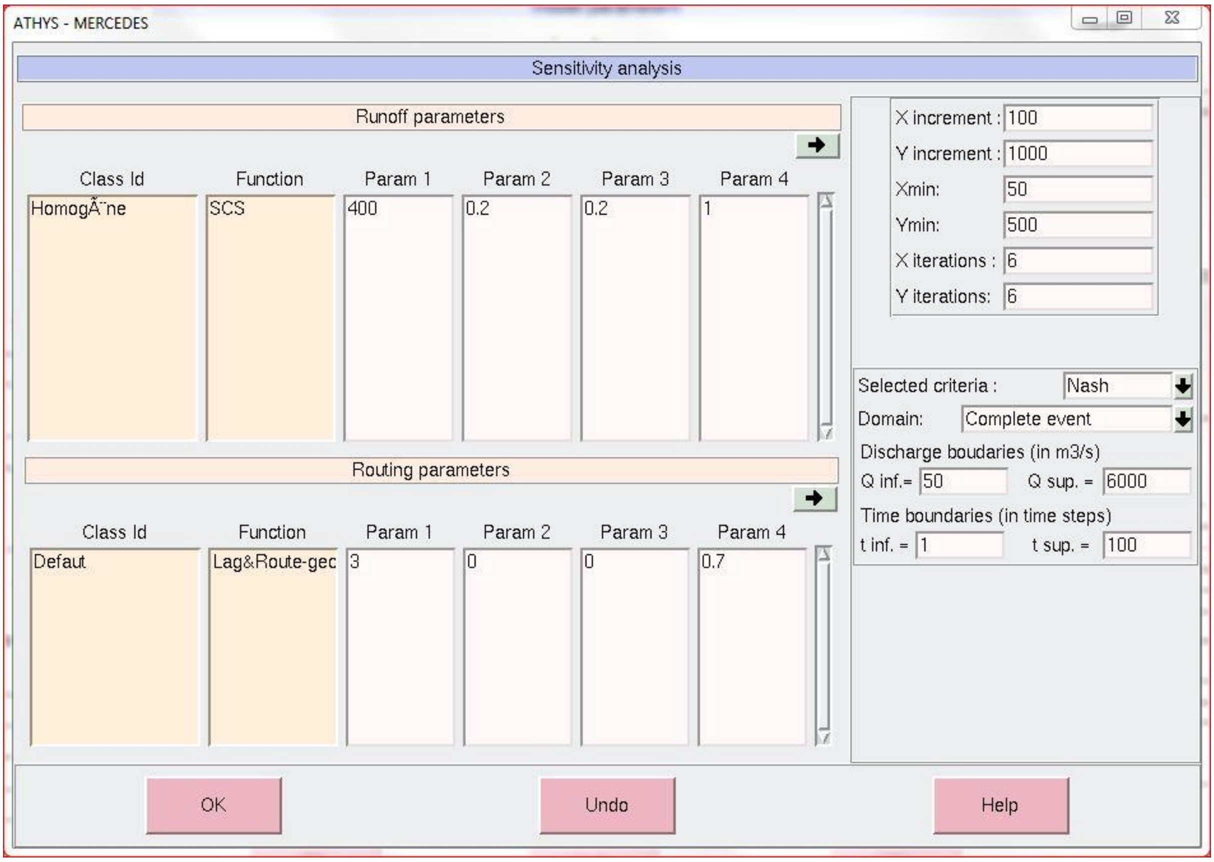


Figure 2-76

Selection of the parameters to be modified:

For reasons linked to the display of the results, the number of parameters to be modified is **limited to 2**. The selection (or deselection) of a parameter is done by double-clicking left on the field corresponding to the value of the parameter. In the window displayed above, 2 parameters were selected: *S* parameter of the SCS production function, V_0 parameter of the Lag and Route transfer function.

NB

- Variation of the parameters is only allowed in the range of the **inferior and superior boundaries** declared for every parameter in the menu 4 (optimization) .

- The error function criterion for the sensitivity analysis is systematically calculated for the discharges
- The analysis of sensitivity can be computed for each event considered as an individual event, or for a group of events. This choice is determined in Menu #4 (optimization) by choosing the Individual event or Grouped events option.
-

The variations of the selected parameters are fixed by:

- The investigation step, which defines the increment of the variation of the selected parameter;
- The initial value of the selected parameter;
- The number of iterations to be performed from the initial value of the selected parameter.

N.B.

- The X parameter is always the first parameter selected, in the order of the lines, then the rows; the Y parameter is the second parameter selected

Choice of the error function: several error criteria are available: EQM, EAM, Nash, and CREC, the same as in section 2.5.4.

Calibration domain : The calculation of the criterion function can be run on different parts of the flood hydrographs, complete hydrograph, maximum flood discharge, discharges included between two values Q_1 and Q_2, and/or between two moments, t_1 and t_2, the same as in 2.5.4.

When the sensitivity analysis procedure is activated, the results are displayed on the screen, and stored in the listing file, writing the parameter values and the corresponding error function value:

Calculation of the variations of the criterion pending....

Param1 Param2 Critere

50. 0. -0.230813111

50. 0.2 -3.18387821

50. 0.4 -3.39101582

Etc.

Variations in the criterion function can also be stored as a map of the error function variations, obtained as an output of MERCEDES in the menu #6 (output files). This file can also be displayed in VICAIR.

2.5.6 Menu 6 : Output files

This menu makes it possible to name and locate the files in which the simulation results will be stored.

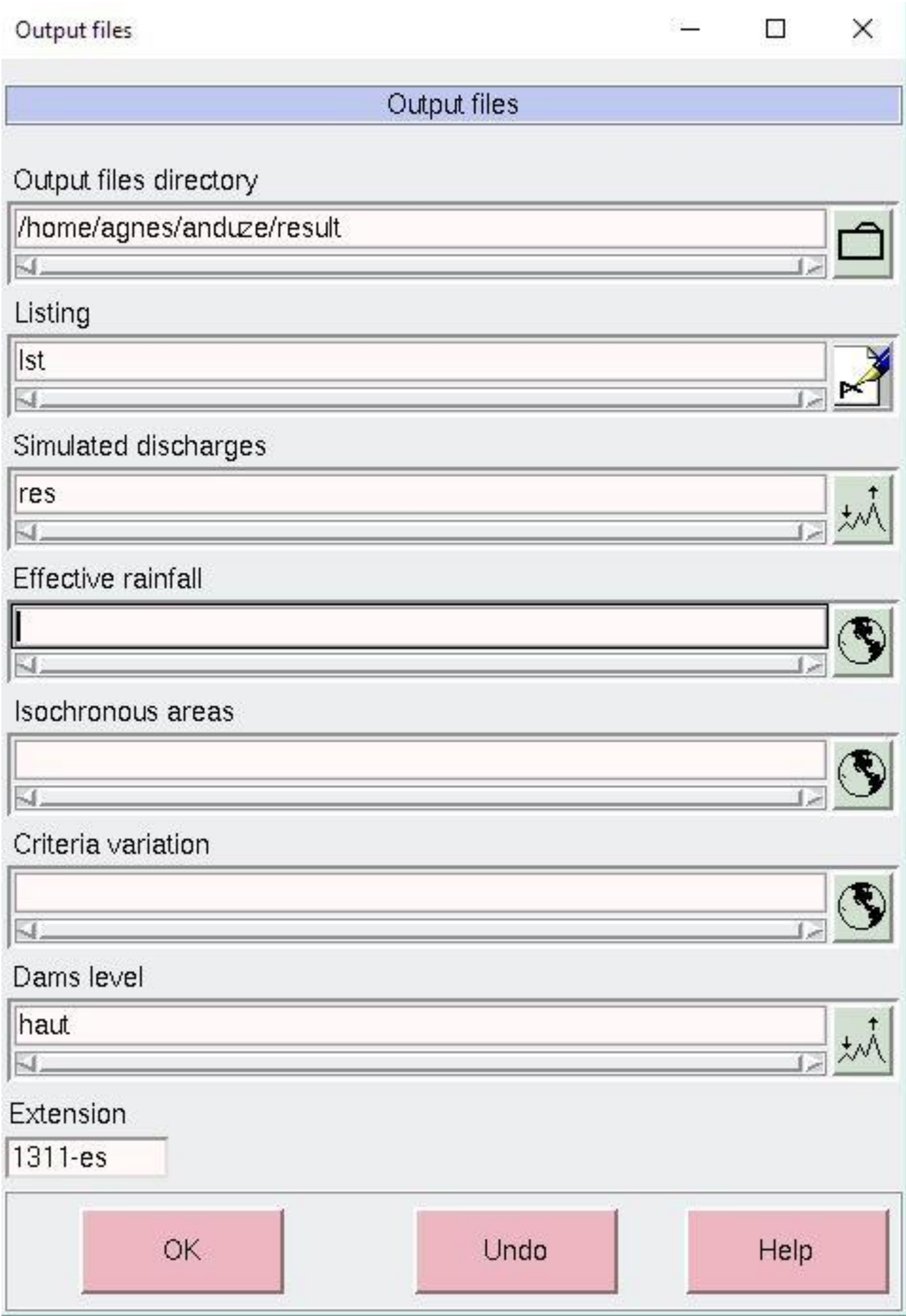


Figure 2-27

***Output file directory* field** : enter or select the directory in which the files will be stored;

Listing file **field** : enter the filename in which the results of the simulation will be stored. This file can be opened by clicking on

Simulated discharges **field** : enter the file name in which the simulated hydrographs will be stored. This is a TXT file, where columns emulate observed rainfall data and simulated discharges at the catchment outlets which have been declared in Menu 1.This file can be displayed by clicking on

Effective rainfall **field** : enter the file name in which the sum of the simulated runoffs generated at the event scale by each cell will be stored. . The format of the file is the same than the one of the DME used in Menu1.This file can be displayed by clicking on . One file will be generated for each event.

Isochrone areas **field** : enter the file name in which the travel times of each cell to the outlet are stored. The format of the file is the same than the one of the DME used in Menu1.This file can be displayed by clicking on . One file will be generated for each event. . This file is only provided with Lag and Route transfer function, where travel time does not vary in time.

Criterion variation **field** : generates a matrix containing the values of the criterion function associated with a sensitivity analysis, as a function of the variations of 2 parameters. The format of the file is Surfer ascii format.This matrix can be displayed by clicking on . One file will be generated for each event.

Dams level **field** : enter the file name in which the simulated dams levels will be stored. This is a TXT file, where columns emulate the water levels in the dams which have been declared in Menu 1. This file can be displayed by clicking on

Extension **field** : the extension entered here will be automatically added to the declared file names. For instance, if the name `res` is given to simulated discharges field and if extension 1 is given, the final name of the file will be res.1.This option makes it possible to modify only the extension to save the output files, when several simulations are run.

2.6 Hands-on exercises

Note: The episode numbers on the graphical output examples are old numbers, but represent the requested episodes.

Simulation of an event (exercise 1)

The aim of this exercise is to familiarize the user with the use of MERCEDES. The events stored in the base28.txt file will be simulated. The exercise will be performed using the first event in the file.

In addition to the information already provided, the coordinates of the outlet of the basin at Anduze must be defined as:

X = 732087; Y = 1896930

This first exercise will be done using:

Menu 1:

MNT file is anduze.mnt and drainage file is anduze.dr1. Both files are available in ~user/anduze/geo. The sampling will be 50 X 50

Menu 2:

Hydro-meteorological data are in ~user/anduze/pluvio/base28.txt. Only the average rainfall will be selected here X=700000 and Y=1900000. To be recognized, a rain gauge must stand in the DEM area.

N.B. if only one rain gauge is selected, the interpolation mode can be either Thiessen or IDW.

Menu 3:

Mode not continuous;

Production function : SCS with S = 300 mm Ia/S = 0.2; ω=0.2; ds=1;

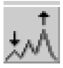
Transfer function : Lag and Route with V_0=1m/s, □=0, □=0, K_0=0.7, K_1=0.

Menu 6:

Listing file: lst;

Result file: res;

Extension: 1.

To browse the results, activate the  and  icons in menu 6.

Comparison with an observed hydrograph (exercise 2)

In menu #2, move the stream gauge at Anduze station as a selected gauge, which will make these discharges appear in the file res.1, in addition to the simulated discharges.

Run the simulation and compare the observed and the simulated hydrographs.

See also the error function values at the end of the listing file, which gives an idea of the accuracy of the model simulations.

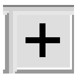
Modification of the parameters (or of the model) (Exercise 3)

Simulate different values of S (100,200, 300 mm) and of V_0 (1, 2, 3 m/s). Note how the hydrographs change in each case.

Comparison between 2 simulations — (Exercise 4)

The preceding simulations using different parameter sets, will now be compared. If res1 and res2 are 2 simulations, the following steps make it possible to include simulated discharge n°2 in the file of simulation n°1:

Open res1 file with VISHYR;

Add station –> 

Choose the res2 file;

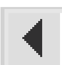
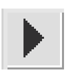
Select the station to be added:

Activate the process –> *OK:*

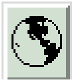
If you wish, save the modified original file.

N.B. extensions 1, 2, 3, etc. will be given to the different simulations.

Simulation of a series of events — (Exercise #5)

Now select events n°1, 2 and 3 in menu #2, and activate a new run Mercedes. The simulations can be displayed by using the icons  of the graphical framework. If the main framework of VISHYR is already open, the previous icons will be disabled and the icons  and  of the main framework will need to be activated.

Simulation with spatialized rainfall — (Exercise 6)

In menu #2, the average rainfall will be replaced by the rainfall locally observed at the different rain gauge stations. The location of the rain gauge stations in the watershed can be controlled with the  icon.

Try interpolation with Thiessen.

3. CALIBRATION OF THE SCS-LR MODEL

In some cases, the parameters of a model can be fixed as a first approximation, taking into account abacuses or formulas in the literature, for instance, the S parameter of the SCS model or the V_0 parameter of the lag and route. If regional syntheses exist, they can also be used to determine the parameters.

Nevertheless, when possible it is preferable to calibrate the model with observed rainfall-runoff values. At the present time, the relationships linking the parameters of a model to the watershed characteristics are still poorly known, and the aim of the calibration is to define the vademecum of the model, how to fix the parameters and, for each event, how to guarantee the best extrapolations beyond the observed conditions. We provide some examples in the following section.

3.1. Flood sensitivity to parameter uncertainty

For the SCS-LR model, it will be assumed that the parameters to be calibrated are S and V_0 (the other parameters are fixed, $Ia/S = 0.2$, , $ds = 1\ d^{-1}$, w = 0.2, $K_0=0.7$, it will be assumed that these are regional characteristics for the South of France). These 2 parameters have relatively well distinguished effects: S affects the volume and does not modify the position in time, V_0 affects the rising time and the moment of the maximum, but does not modify the volumes.

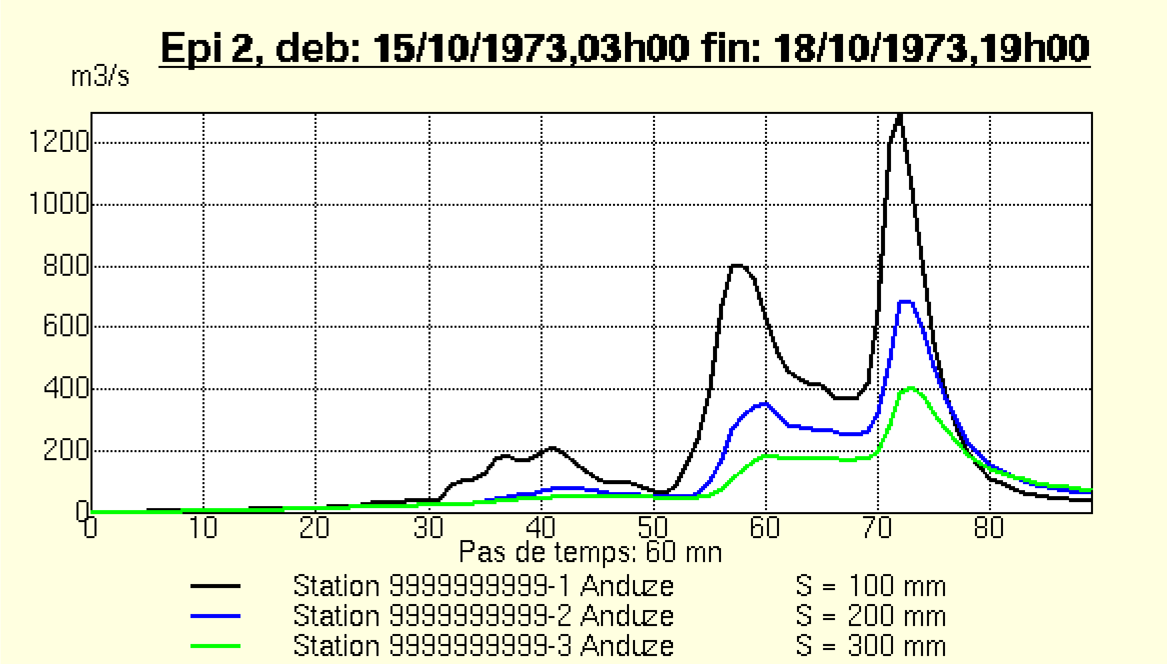


Figure 3-1

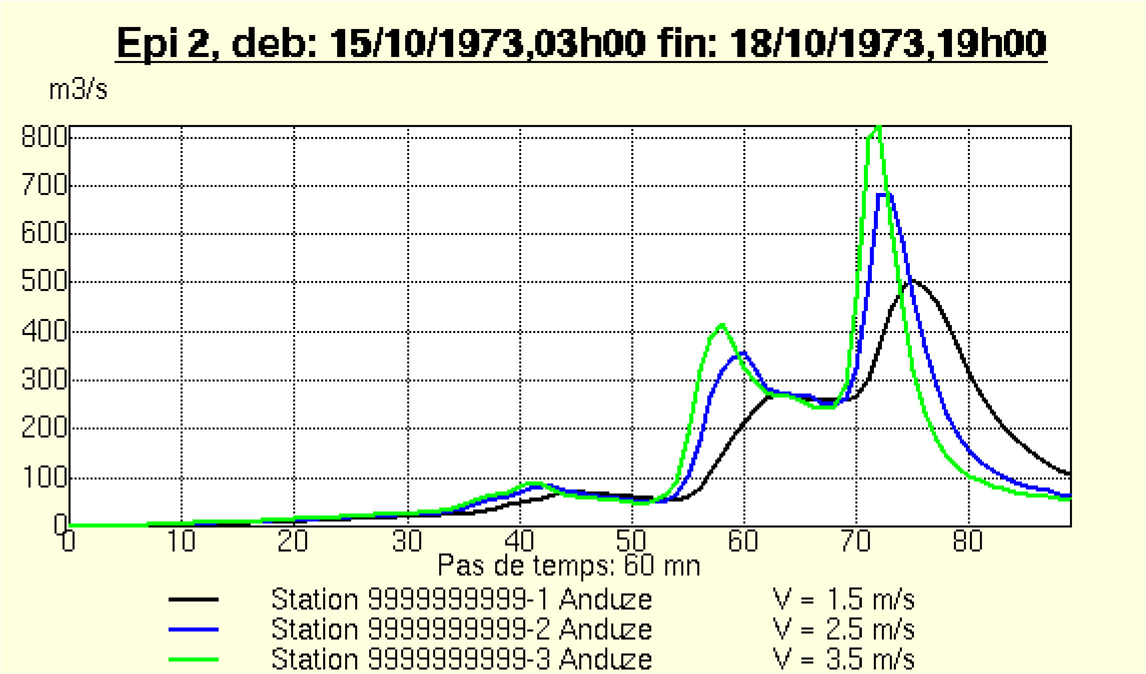


Figure 3-1

3.2. Calibration of the model with observed values

<u>Exercise</u>: In this exercise, we will use again, in the file base28.txt, the event from 15/10/1973 to 18/10/1973. The *S* and V_0 parameters will be calibrated manually. For instance, what will the final values be with event #2 using initial values S=300mm, V_0 = 1 m/s? Try to optimize an error function, for instance the Nash criterion, and to

graphically control the fitting of the calculated discharges with the observed discharges. Three or four attempts could be sufficient to find satisfactory parameter values.

To complete this exercise, the use of automatic model calibration procedures can be added. Optimization consists in determining the parameters associated with the optimal value of the criterion (the closest to 1 for the Nash criterion, the closest to 0 for the other criteria), in this case using the Simplex iterative method (RAO, 1978).

Exercise: an automatic calibration of the model should be computed for this event. Among the different calibration options, use the Nash criterion, simultaneous production and transfer calibration for the whole hydrograph. Use different calibration options and evaluate the results. What are the final values of the parameters? Are they close to those you obtained in the previous step, i.e. at the end of the manual calibration? Do these values fit all the events? How should parameter variability be interpreted?

Exercise : an automatic calibration of the model should be computed for this event. Among the different calibration options, use the Nash criterion, simultaneous production and transfer calibration for the whole hydrograph. Use different calibration options and evaluate the results. What are the final values of the parameters? Are they close to those you obtained in the previous step, i.e. at the end of the manual calibration? Do these values fit all the events? How should parameter variability be interpreted?

N.B. Choose high sampling (10x10 or more) for this exercise to reduce the time needed for the calculation.

Solution to the exercise (with 10 X 10 sampling and spatialized rainfall)

Analysis and interpretation of the variability of the parameters per event

N°	date	S (mm)	Vo (m/s)	Qp m3/s	Qb m3/s	Nash
2	15/10/1973	168.7	2.6	477.1	1.8	0.95
6	11/09/1976	244.2	3.1	1009.1	15.6	0.92
7	08/11/1976	161.7	2.5	914.3	18.6	0.93
9	19/10/1977	258.2	2.6	1058.2	0.4	0.9
12	07/12/1977	145.0	3.1	418.5	27.0	0.88
21	22/09/1994	349.9	2.8	665.7	9.7	0.92
22	19/10/1994	336.5	2.5	814.0	16.3	0.91
23	02/11/1994	207.0	2.5	791.7	34.0	0.85
27	18/09/1995	215.2	3.6	672.9	41.0	0.84
28	03/10/1995	197.3	2.5	1096.2	38.0	0.7
29	13/10/1995	232.8	2.1	1247.9	27.0	0.92
34	11/01/1996	60.2	1.1	526.7	155.0	0.7
37	20/01/1996	123.7	1.2	689.3	91.0	0.1

54	03/11/1997	200.2	2.0	762.2	4.5	0.92
56	16/12/1997	183.4	5.6	1504.2	10.6	0.85
58	15/04/1998	163.4	2.0	368.5	3.9	0.86
59	29/04/1998	105.7	1.6	377.2	19.2	0.85
60	27/05/1998	98.2	2.2	472.9	13.0	0.85
65	17/05/1999	133.3	2.0	603.4	13.5	0.78
66	19/10/1999	233.5	2.8	685.8	37.0	0.98
70	28/09/2000	323.2	3.6	1224.6	3.4	0.99
79	09/10/2002	183.5	1.4	339.9	35.0	0.85
80	23/11/2002	67.4	2.0	567.8	103.0	0.94
81	09/12/2002	79.5	1.2	604.9	45.0	0.81
86	30/09/2003	300.2	2.4	452.3	9.3	0.94
87	15/11/2003	132.7	1.8	626.2	21.2	0.91
88	21/11/2003	84.7	1.9	940.1	40.0	0.89
89	29/11/2003	71.3	1.8	1071.7	46.0	0.85
Mean.		180.7	2.4	749.4	31.4	0.8
Std var.		83.2	0.9	301.9	34.3	0.2

Table 3-1

First, note that S and V_0 have a wide range of variation, meaning an average value may be not satisfactory for all the events.

S stands for the amount of water that can be stored during the event and the variability of S can be explained by the initial degree of soil saturation. Seasonal variations in S can be analyzed from the average value (in blue) and the standard variation (in red) of events occurring in the same month. A typical variation appears with a maximum at the end of summer in the following graph, then decreases rapidly during fall due to intense precipitation. But this pattern may not be valid in some years with different conditions, e.g. when drought continues until October or November, (as may be the case).

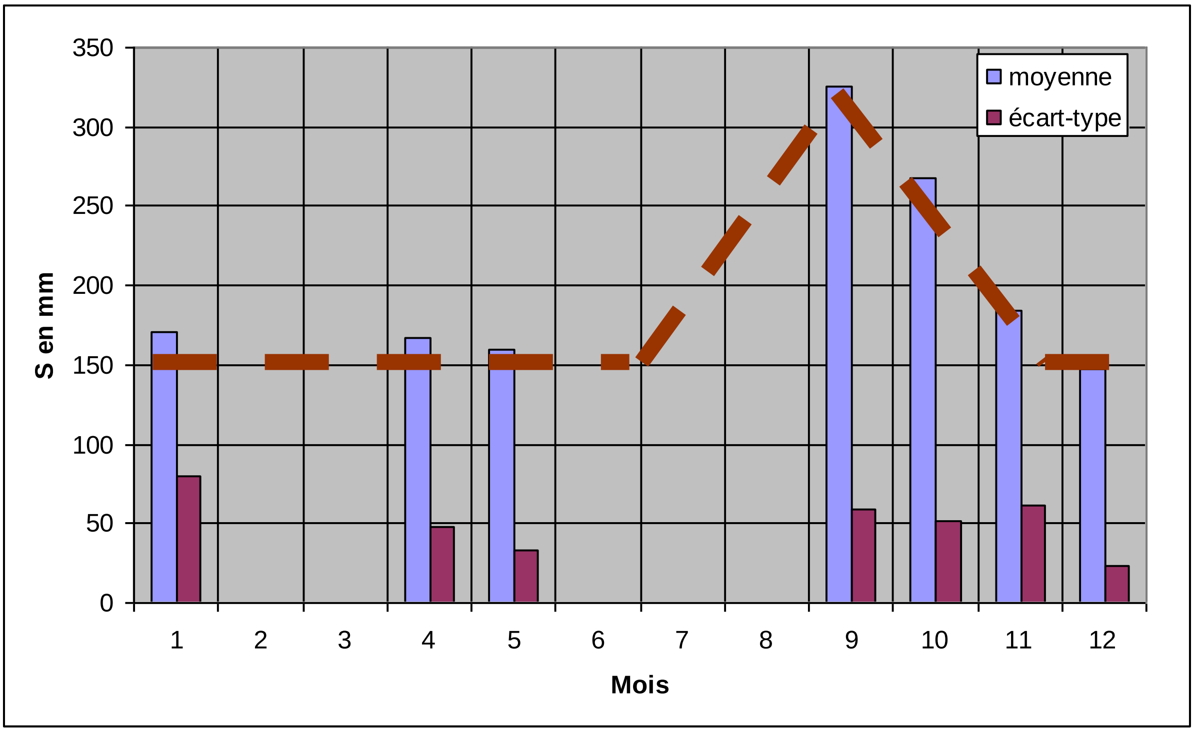


Figure 3-3

To better account for seasonal anomalies, the S variation can be linked to event-based indicators of the degree of saturation of the watershed.

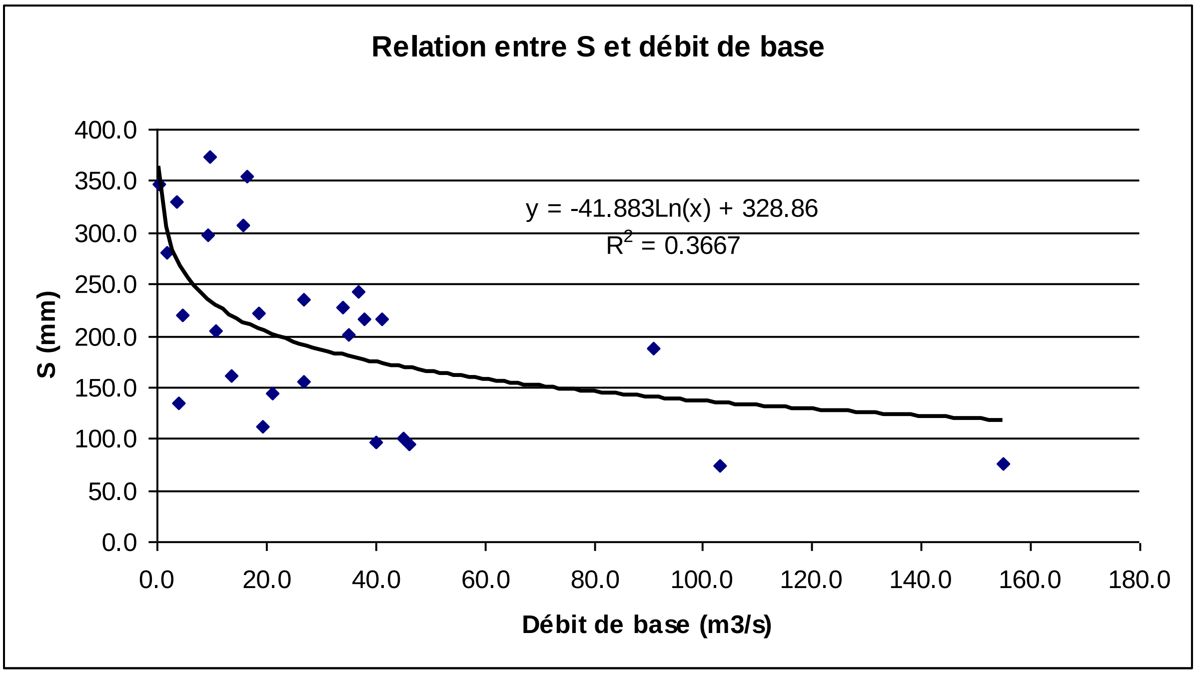


Figure 3-4

The *S* parameter of the SCS production function can thus be linked to base discharge according to the relation:

S_{mm} = -41.8.Ln($Sb_{m3/s}$)+328.8

S can also be linked to the Hu2 index produced by the SIM (Météo-France) model.

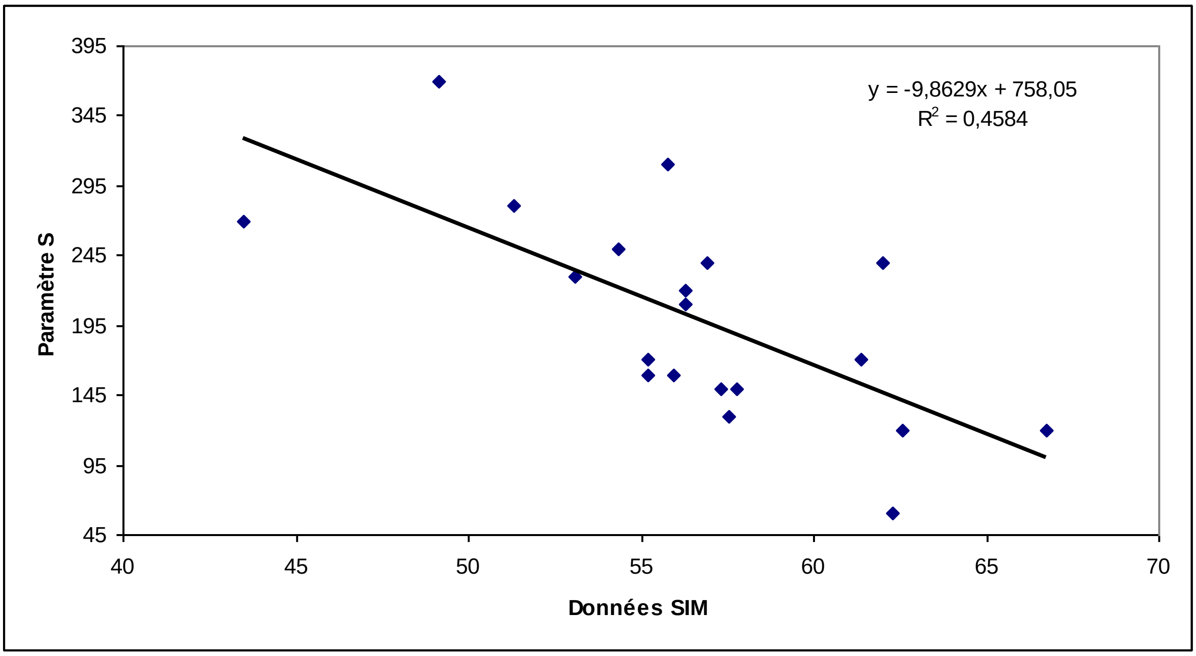


Figure 3-5

$$S_{mm} = -9.9.Hu2+758.1$$

Concerning parameter V_0, there is no clear correlation with any characteristic of the event (rainfall amount or intensity, peak flow, initial saturation). On the other hand, the simulation results show that V_0 is less discriminating than S, at least for peak flow values. Thus an average value for V_0 could be accepted.

3.3. Final evaluation of the model

The performance of the model can be assessed by the error functions or deviations between observed and calculated values:

The Nash criterion $= 1 - \frac{\sum(X_i - Y_i)^2}{\sum(Y_i - \overline{Y})^2}$

denotes the mean quadratic error between observed and simulated values, compared to the mean quadratic error between observed data and the averaged observed values. The Nash value is the complementary to 1 of this ratio.

$$\text{mean quadratic deviation} = \frac{\sqrt{\sum (X_i - Y_i)^2}}{\sum Y_i}$$

for the mean percentage of the deviation between the observed and calculated values compared to the average of the observations.

Beyond the nature of the error function, the performance of the model can also be estimated in different ways:

- By its optimal efficiency: i.e. its best adjustment to observations after the model is calibrated. Here, the average Nash criterion, calculated for the 28 events, is of the order of 0.8, ranging from 0.7 to 0.99. . In optimal calibration, i.e. the maximal potential efficiency of the model, the mean quadratic error on the simulated discharges is thus 20% of the mean quadratic error between observed data and the averaged observed values.
- By its efficiency when used in design mode: i.e. its ability to forecast events other than those already observed. This efficiency is usually the one to consider as proof of the performance of the model when it is used for future applications.

In our case, the performance of the model in design mode can be assessed by simulating floods with the S parameter estimated by the S–Hu2 (R^2=0.48) regression. Hereafter, we provide an example of a comparison between the criteria calculated during calibration, and the criteria calculated in the design project.

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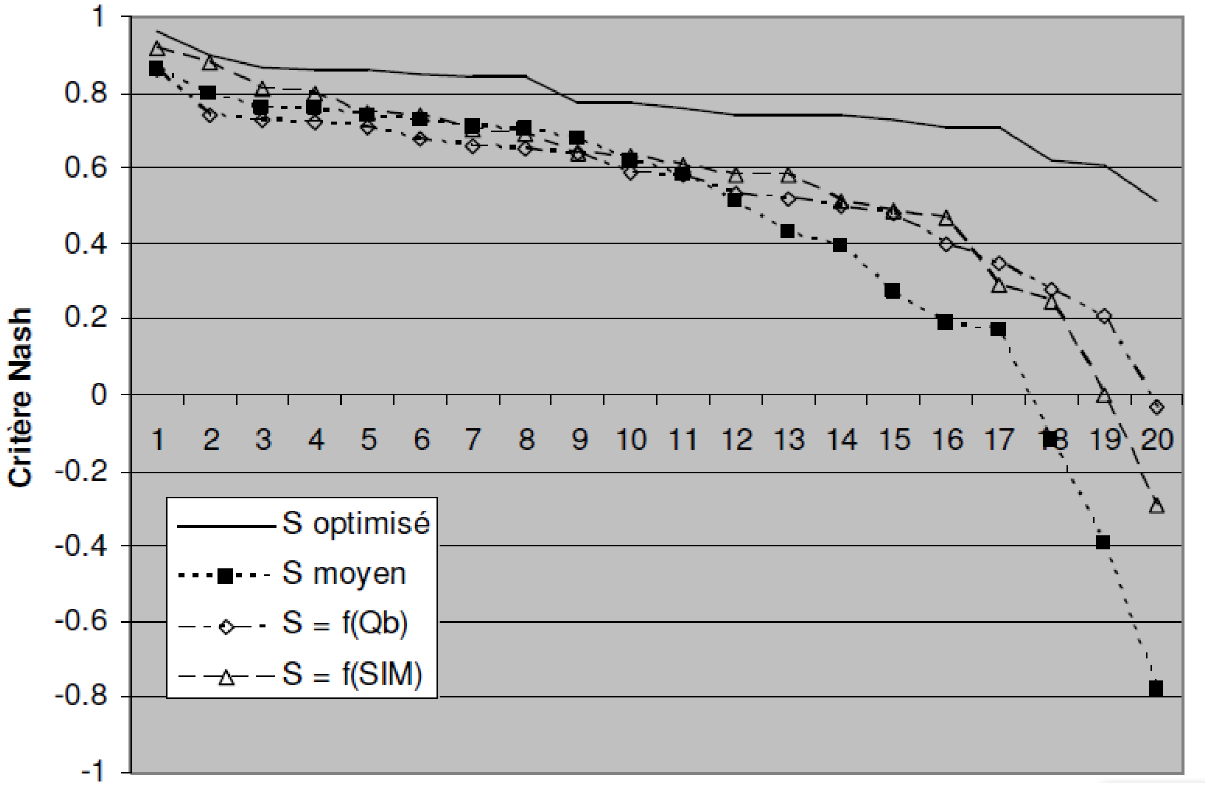
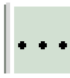


Figure 3-6

3.4. Management of the event variability of a parameter with MERCEDES

It is possible to assign a different value to a given parameter for each event. In this case the parameter must be declared as var1 (or var2, var3, …, var6; please follow exactly this syntax), the values of var1 being read in a window activated by the  icon in menu 3.

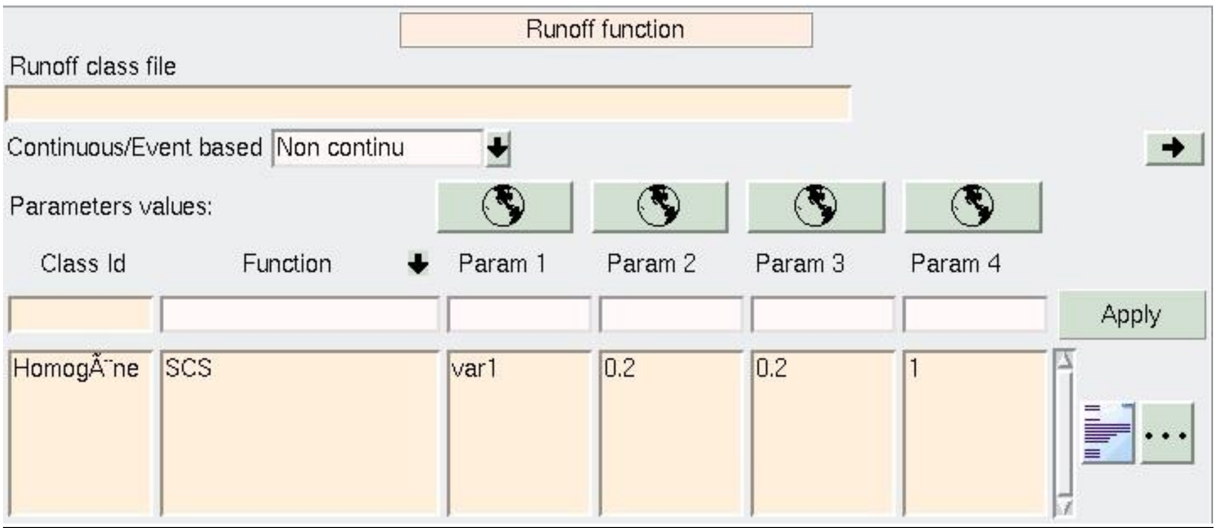


Figure 3-7

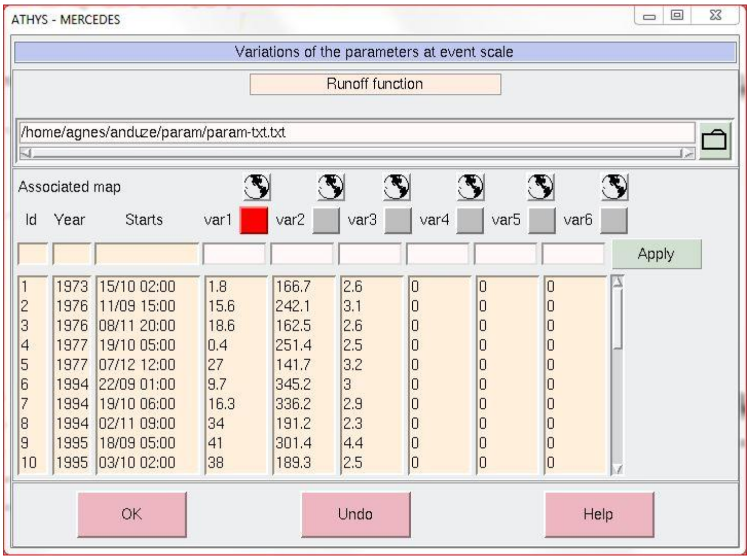


Figure 3-8

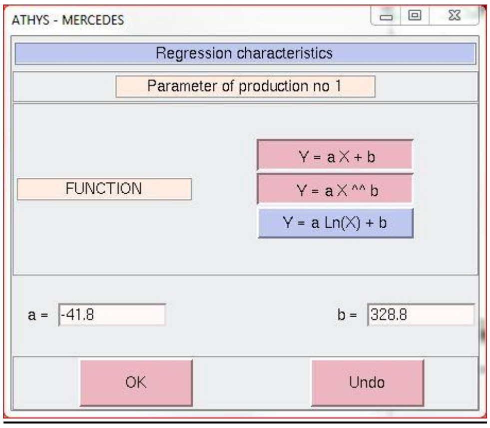


Figure 3-9

Here, var1 stands for the base discharge, var2 for the optimum values of S, and var3 for the optimum values of V_0. In figure 3-8, if the choice is to associate S with var2, the values for S will be 281.3, 307.3, etc. for the different events to be simulated.

If the choice is to associate S with var1, the red square shows that the var1 values will be used in a regression of type Y=f(X), where Y is the parameter and X the var1 value.

It is possible to access the regressions by clicking directly on the red/grey button.

The values in figure 4-9 can be entered manually. They also can be read out of a file that has to be formatted as follows:

2	1973	10150200	1.8	166.7	2.6	0	0	0
6	1976	9111500	15.6	242.1	3.1	0	0	0
7	1976	11082000	18.6	162.5	2.6	0	0	0
9	1977	10190500	0.4	251.4	2.5	0	0	0
12	1977	12071200	27	141.7	3.2	0	0	0
21	1994	9220100	9.7	345.2	3.0	0	0	0
22	1994	10190600	16.3	336.2	2.9	0	0	0
23	1994	11020900	34	191.2	2.3	0	0	0
27	1995	9180500	41	301.4	4.4	0	0	0
28	1995	10030200	38	189.3	2.5	0	0	0
29	1995	10130200	27	229.9	2.2	0	0	0
34	1996	1112100	155	67.5	1.3	0	0	0
37	1996	1200800	91	116.3	1.1	0	0	0
54	1997	11030400	4.5	190.4	1.9	0	0	0
56	1997	12161100	10.6	170.8	4.6	0	0	0
58	1998	4142300	3.9	149.9	1.8	0	0	0
59	1998	4291300	19.2	106.4	1.7	0	0	0
60	1998	5271200	13	100.2	2.3	0	0	0
65	1999	5170500	13.5	300.9	3.4	0	0	0
66	1999	10192100	37	235.5	2.8	0	0	0
70	2000	9281000	3.4	301.2	3.5	0	0	0
79	2002	10090200	35	177.4	1.3	0	0	0
80	2002	11231300	103	66.9	2.0	0	0	0
81	2002	12090700	45	78.1	1.2	0	0	0
86	2003	9301200	9.3	293.5	2.5	0	0	0
87	2003	11151100	21.2	129.6	1.9	0	0	0
88	2003	11210800	40	72.8	1.8	0	0	0
89	2003	11291800	46	65.5	1.7	0	0	0

Table 3-2

The first three columns contain the characteristics of the event: number, year, start date. The remaining six columns contain the values that can be associated with a parameter: var1 to var6.
When the file is read, a test run on the first three columns is the condition for updating the var1 to var6 values.

N.B. this file was generated after the first modification of the var1 to var6 values was saved.

Exercise: use the param.txt file to simulate floods with variable values for the S parameter: optimum values (var2) or a regression between the logarithm of the base discharge (var1) and the S value.

4. IMPACT OF THE SPATIAL COMPONENT

In this part, we do not deal anymore with the model calibration, but we use the model with given values of the parameters for sensitivity analysis.

4.1. Impact of the spatial organization of the rain

Exercise

The aim is to analyze the effect of the spatial variability of the rainfall on the floods. The hydrographs will be simulated while using (a) average rainfall, b) spatialized rainfall, as model inputs. We will use the base28.txt file, selecting average rainfall as uniform rainfall input for a, and the local Thiessen interpolated rain for b. The hydrographs of the events 10 and 28 will be compared. We will use constant parameters S = 300 mm, Vo = 2.5 m/s.

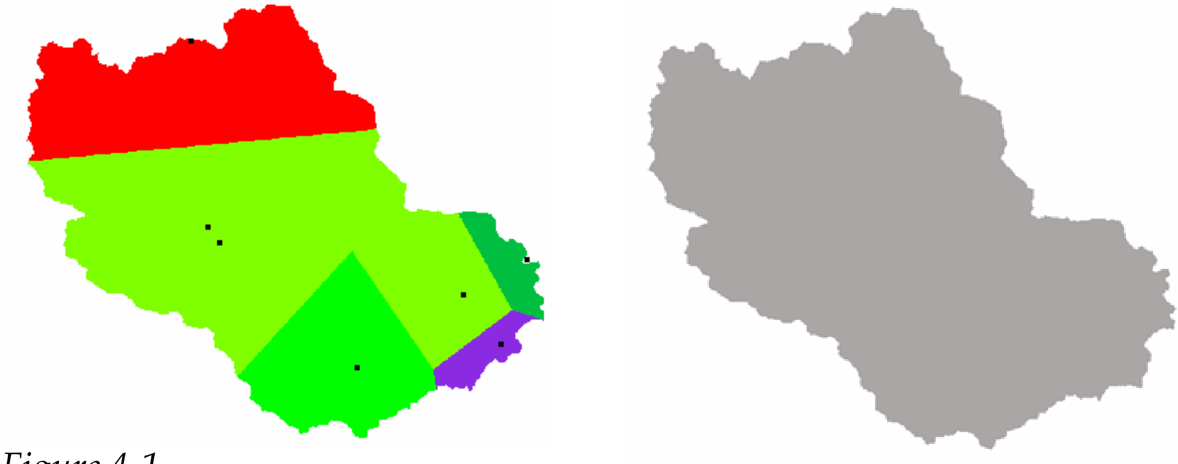


Figure 4-1

Answers to the exercise

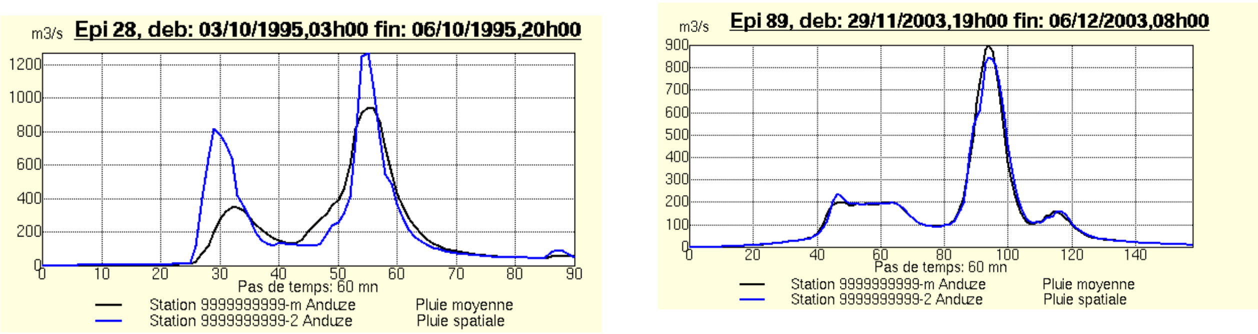


Figure 4-2

For event 28 (10 in fact), for which the spatial variation coefficient (CV= σ/m) of the rain field is of the order of 0.4 (CV=0.1 for event 89, 28 in fact), the hydrographs are different. Using the average rainfall tends to underestimate the volumes and the peak discharges of the floods. These differences are mainly due to the localization of the rainfall and to the spatial non-linearity of the production function (the runoff volume obtained is not the same with average rainfall or a rainfall variable in the area). Fig.4-3 compares the simulated floods by using mean rainfall and distributed rainfall, for the 12 first events.

With equal parameters, the volumes and flood peak discharges are underestimated when average rainfall is selected as input in the model. The distributed model ensures greater accuracy of the calculation of the flood, <u>without complicating the model</u> (no new parameter was added)

More generally, the differences can be linked to the variation coefficient of the rainfall field (Arnaud et al., 2002). For a variation coefficient equal to 1 (roughly that of the rain that fell on the Gardon watershed at Anduze in September 2002), the volumes and peak discharges are reduced by about 30-40% by the lumped model.

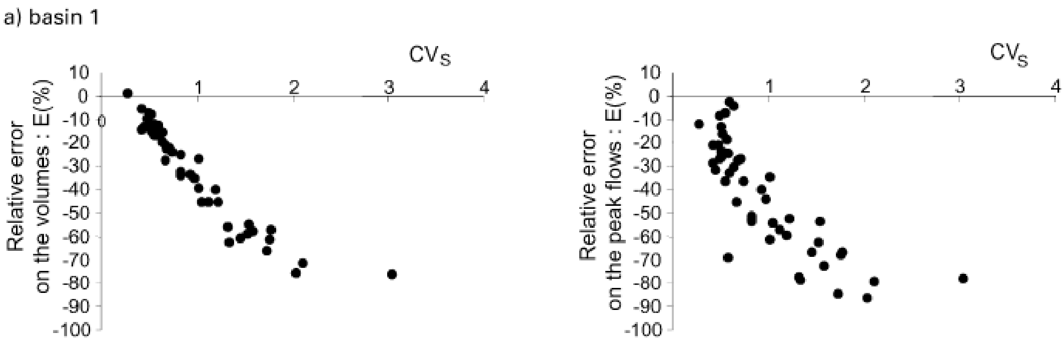


Figure 4-3 (From Arnaud et al., 2002)

4.2. Impact of the spatial variability of the soils

The distributed model makes it possible to distinguish the conditions of production (and of transfer). Is this the same as considering an average permeability value (or an initial condition) on the whole watershed, or taking the spatial variability of these values into account?

<u>Exercise</u>:

The aim is to analyze the effect of the spatial variability of the soils (and of the underlying permeabilities) on the calculation of the floods. The hydrographs will be simulated using: (a) the watershed divided into three soil units whose S parameter values are respectively S=100 mm, S=200 mm, S=300mm (the average value of S is 200 mm over the watershed), (b) only one unit, S=200 mm for the whole watershed. The anduze.alt file will be used to distinguish between the production functions:

Elevation<400m →S=100mm
400<elevation<600m→S=200mm
600<elevation→S=300mm
The hydrographs of events 28 (10) and 89 (28) will be compared (see exercise 4).

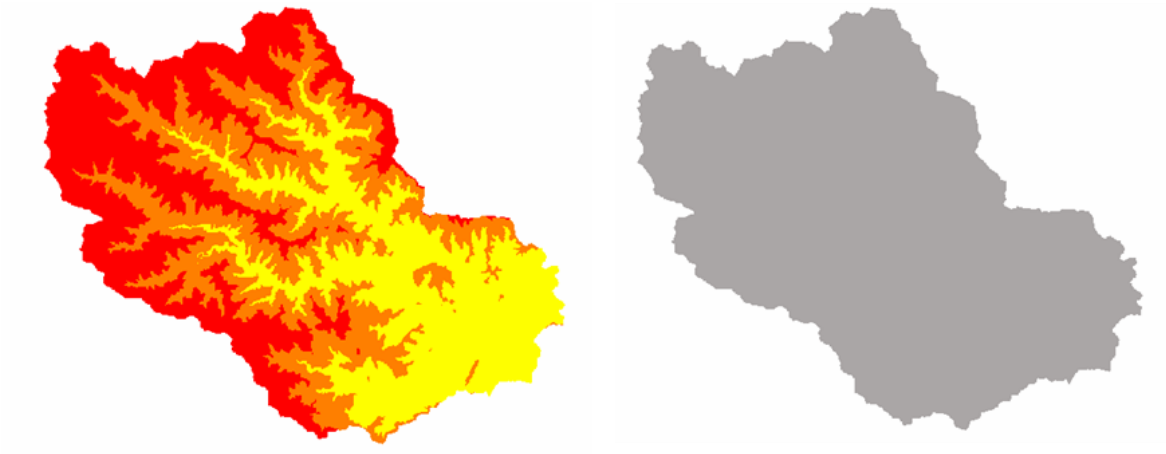
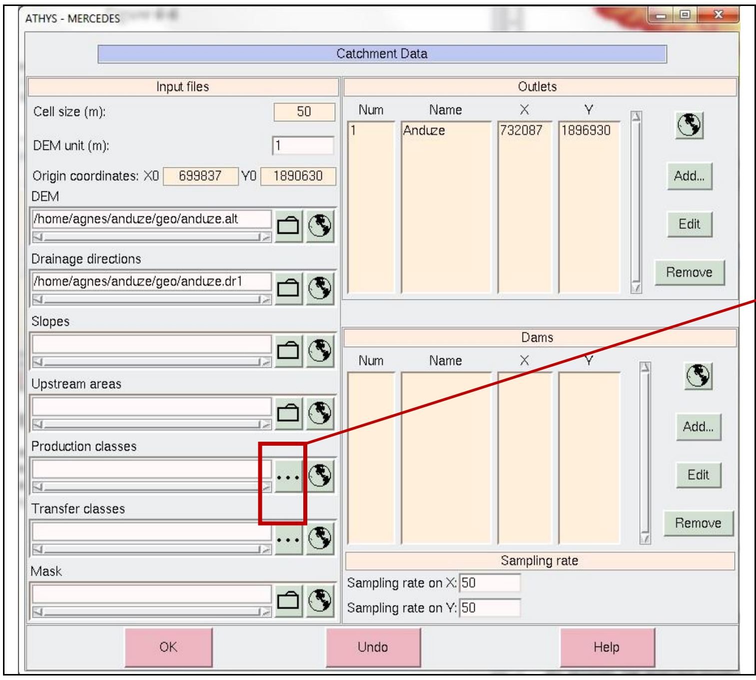


Figure 4-4

<u>Answers to the exercise</u>

It is necessary to differentiate the classes of production using the map of elevations. To do so, the file anduze.alt will be used, and three classes of production are defined: <400 m, from 400 to 600 m, >600 m in menu 1



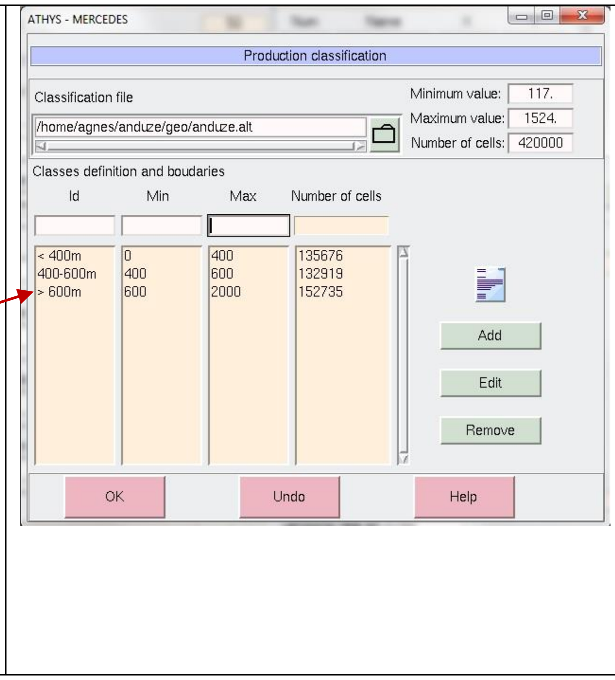


Figure 4-5 *Figure 4-6*

Once they are validated, these classes appear in menu 3, after which the production functions must be defined in this menu.

By default, the selected model is Reservoir-1, of which the parameters are set to 0. It is thus necessary to substitute the SCS model to Reservoir-1, and to set the S values to 100, 200, 300 mm for the corresponding class.

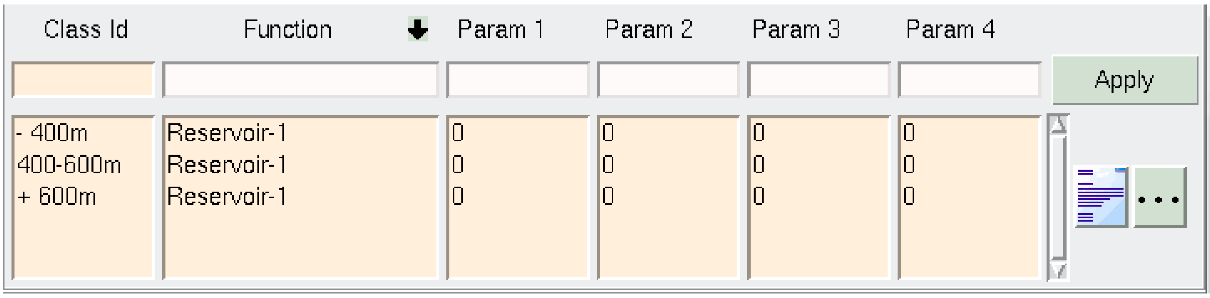


Figure 4-7

The figure below shows the comparison of the simulations carried out with S average (200 mm) or S spatialized (100, 20, 300 mm) for the first 12 episodes.

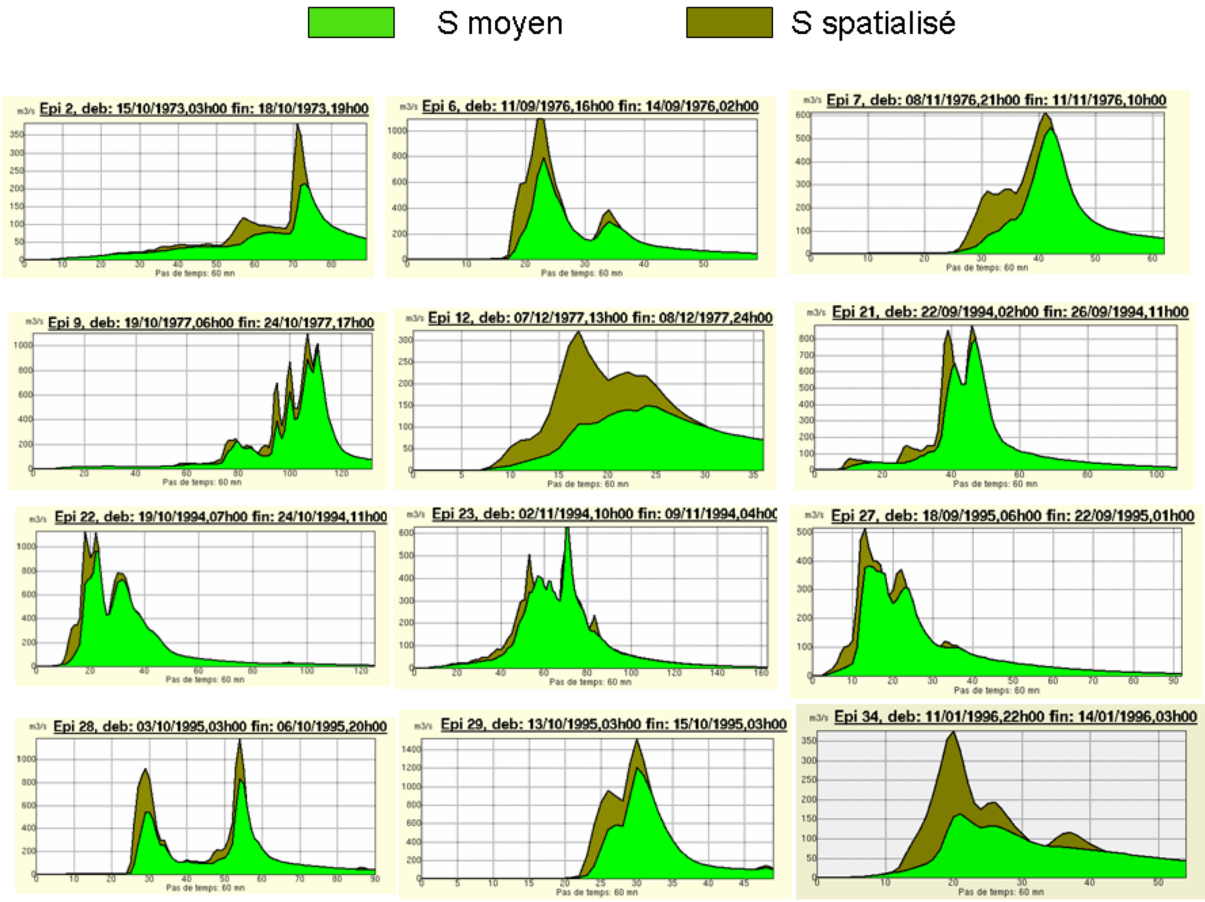


Figure 4-8

For equal rainfall, an average permeability has a tendency to underestimate the volumes and the peak flood discharges. In this case, the distributed model ensures greater accuracy of the flood calculation, but the cost is a more complicated model (new parameters are added).

4.3. Impact of the climatic or geographical modifications

The distributed model makes it possible to consider different conditions of production (and of transfer). For instance the effects of urbanization or the extension of farming over one part of the watershed can be simulated.

<u>Exercise</u>: the aim is to characterize the impact of urbanization on the watershed (in grey in figure 4-10). S=20 mm is assumed for the urban area. The simulations will be compared with S=300 mm over the whole watershed, and in one part of the watershed, with S=20 mm for the urban areas and S=300 mm for the rest of the watershed. The file anduze.sol, containing 9 classes of permeability of soils, coded from 1 to 9, will be used.

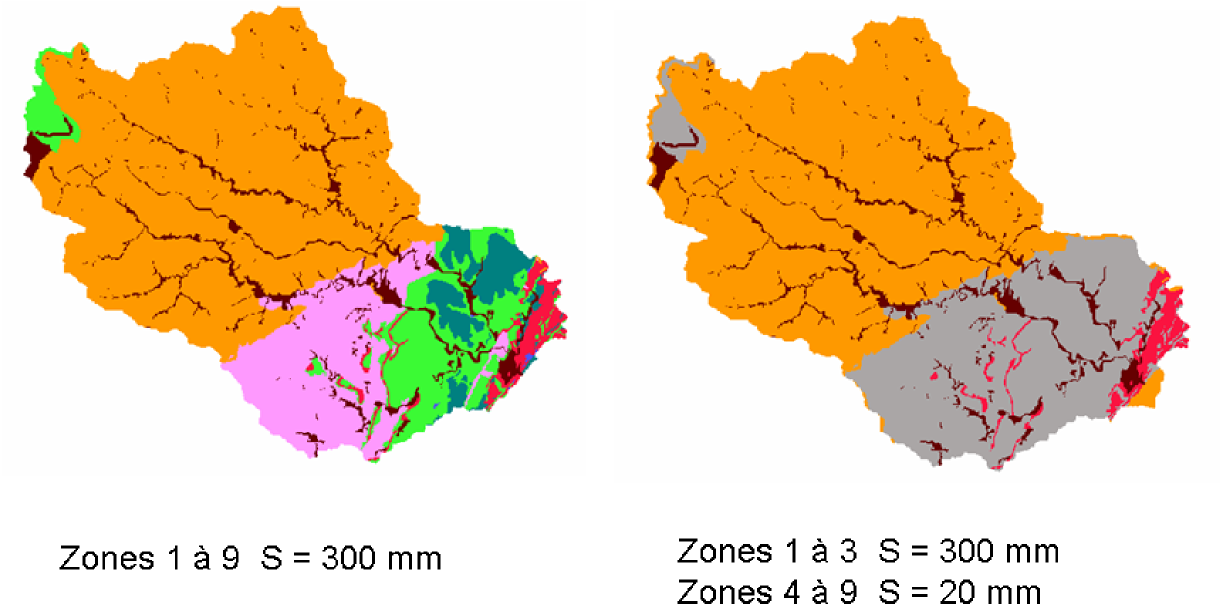


Figure 4-9

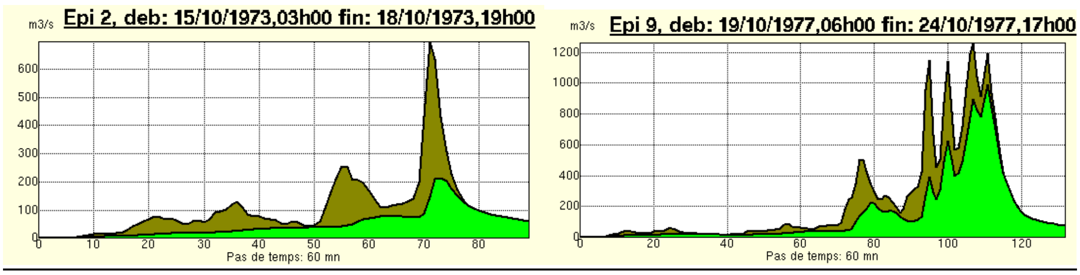


Figure 4-10

<u>Exercise</u>: the influence of snow on a flood event will be processed. We assume that several cases can be observed, involving an elevation threshold. Compare the following situations:

a) Normal conditions on the watershed;
b) Snow falls above 600 m (by coding S=100000 m and ds=0, the total precipitation is stored);

c) Liquid rain falls on a snow cover or frozen soil above 600 m (by coding S=0, the entire volume of precipitation runs off).

The anduze.alt elevation file will be used to define the different classes of production.

.

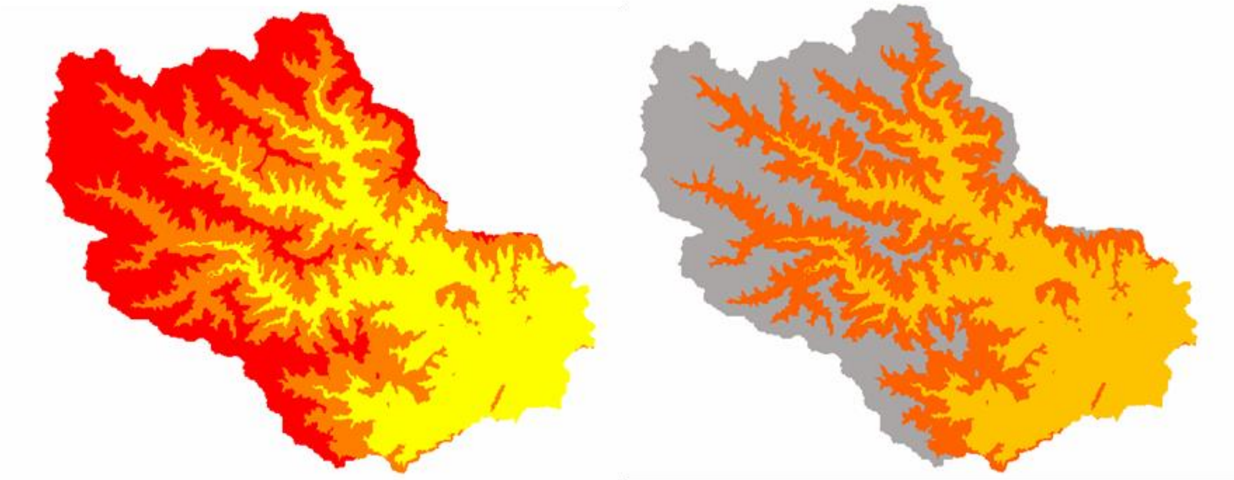
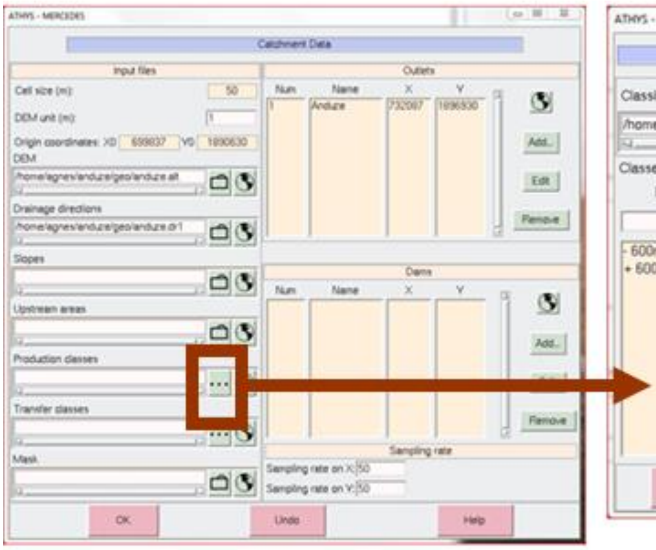


Figure 4-11

<u>Answers to the exercise</u>

The classes of production must be identified by the elevations, the anduze.alt file will be used, and 2 classes of production must be defined: <600 m and >600 m in menu 1.



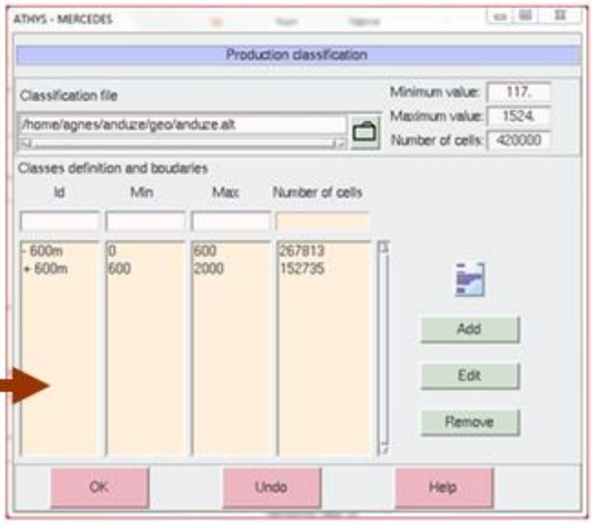


Figure 4-32

Figure 4-43

The SCS function will be applied with a very high value for S, meaning that almost the entire snow fall is stored, in case b, and with S=0, meaning that on snow cover or frozen soil runoff is almost 100% in case c.

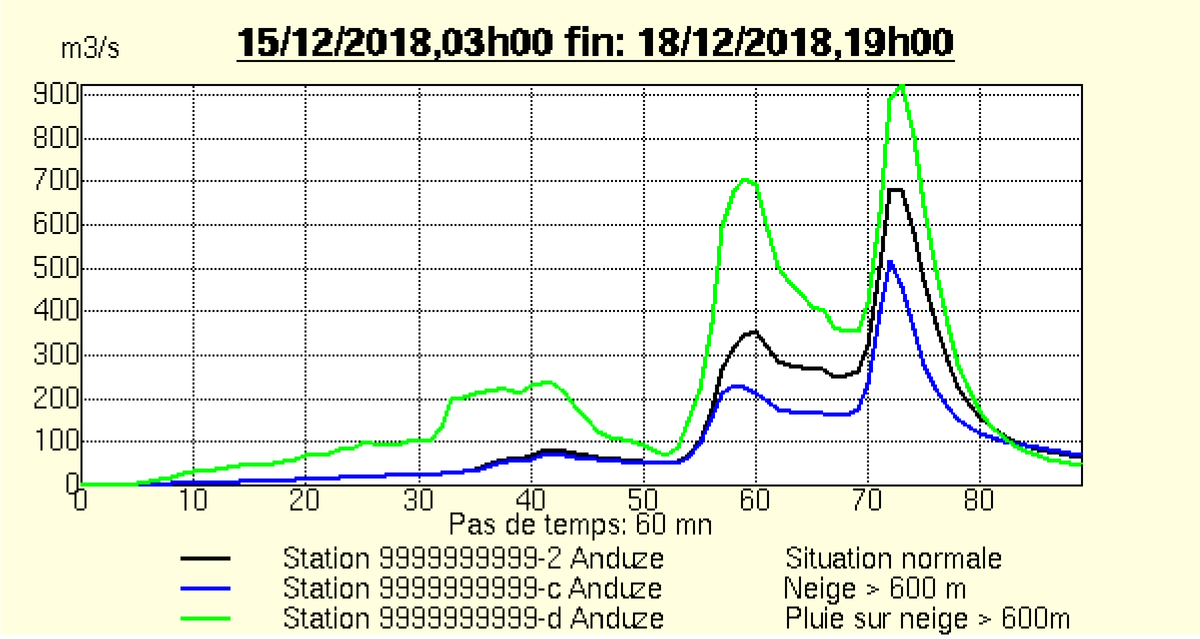


Figure 4-14

4.4. **About data sampling**

Questions :

- What is the optimal size of the cell in watershed discretization?
- What is the optimal spatial resolution of the radar rainfall cell?

4.4.1. Sensitivity to watershed spatial discretization

The spatial discretization of the watershed is based on the use of a Digital Elevation Model. The size of the cell can vary depending on the available product, and be modified through operations available in VICAIR or MERCEDES. Here we will study the sensitivity of the flood simulations to the cell size, using the sampling function available in MERCEDES, from a DEM with a 50 m cell:

Sampling 1: all the cells, i.e. 50 m resolution;
Sampling 2: 1 cell out of 10, i.e. 500 m resolution;
Sampling 3: 1 cell out of 100, i.e. 5000 m resolution;
Sampling 4: 1 cell out of 200, i.e. 10000 m resolution.

The sampling computed in MERCEDES consists in selecting one cell out of N on the X axis and one cell out of N on the Y axis, then, the surface area of this cell is "expanded" by a factor of N x N. The model operates on a reduced number of cells, the factor of reduction is N x N on the watershed.

<u>Operating mode</u>

The input data used will be:

Anduze.alt *digital elevation model*;
Anduze.drl *drainage model*;
Base28.txt *file containing the hydro-meteorological events*;

***SCS** (S=400, w = 0.2, ds = 1), **Lag-route** (V_o = 3, Ko = 0.7).*

The sampling factors must be defined in menu 1: catchment data. The simulations will be carried out for several events.

Simulations will be superimposed using the Vishyr Add Station feature.

<u>Example of a result</u>

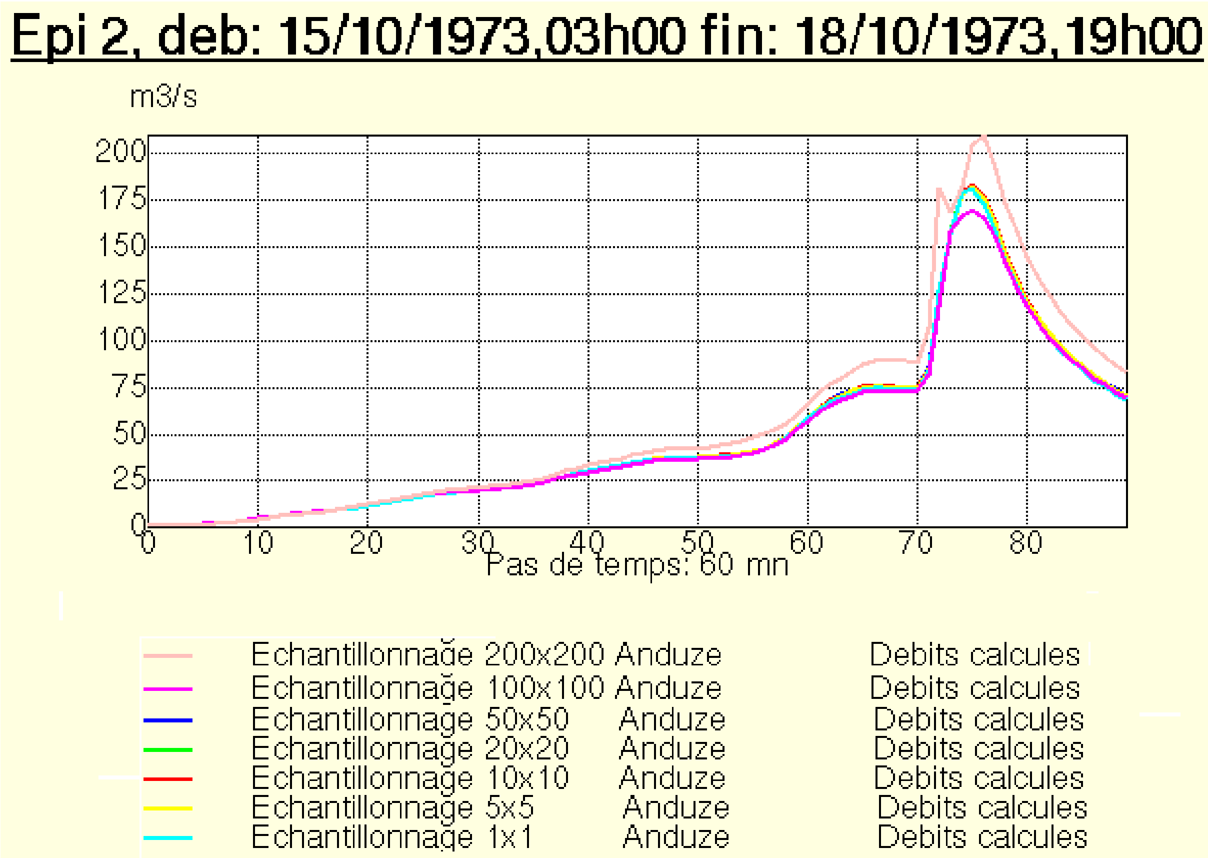


Figure 4-55

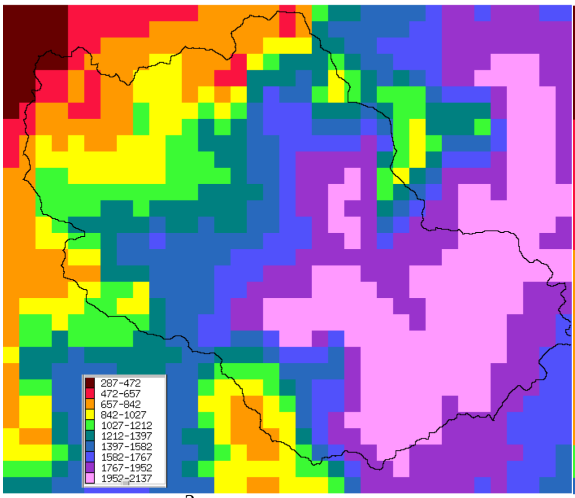
The simulations are almost equivalent up to a resolution of 50 X 50, beyond this, they are different. There are about 87 cells in a 50 X 50 sample.

Are the results the same for the other events? For other models?

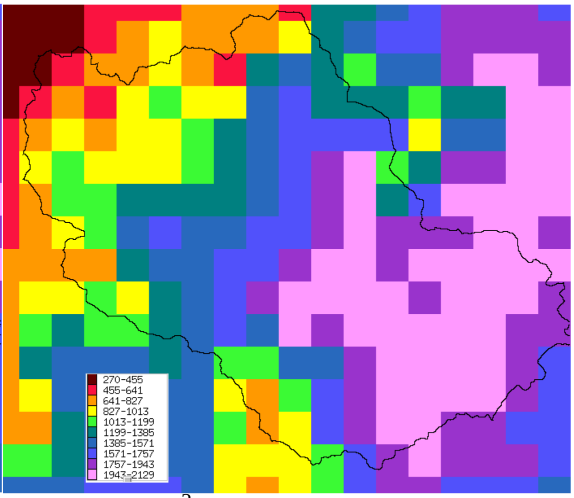
4.4.2. Sensitivity of radar rainfall to spatial resolution

The French metropolitan radar network (*ARAMIS*) makes it possible to measure the rainfall at a 5 minute time step for 1 km² pixels. The measurements are based on the reflectivity of an electromagnetic wave on the water drops, which is a function of the diameter of the drops. Reflectivity R is then linked to the intensity of the Z rainfall by a Marshall-Palmer type relationship $Z=aR^b$.

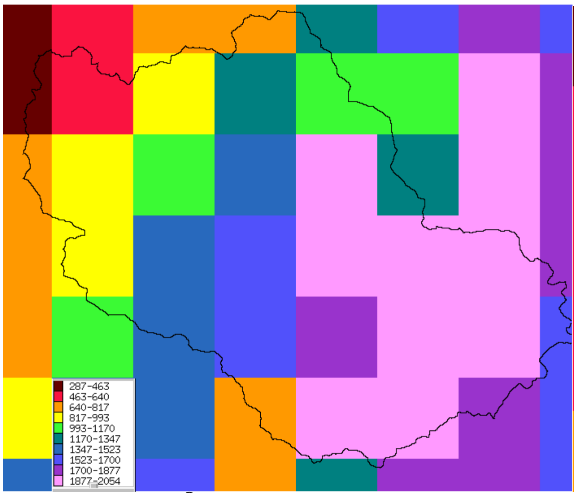
The rainfall measurement is thus not direct, but is subject to various uncertainties linked to the measurement device as well as to the rainfall characteristics. Without going into too much detail about the process, this means that radar data usually have to be corrected using the rainfall observed on the ground. Different products are available including Meteo-France products Antilope and Panthere, Calamar products from Rhea.



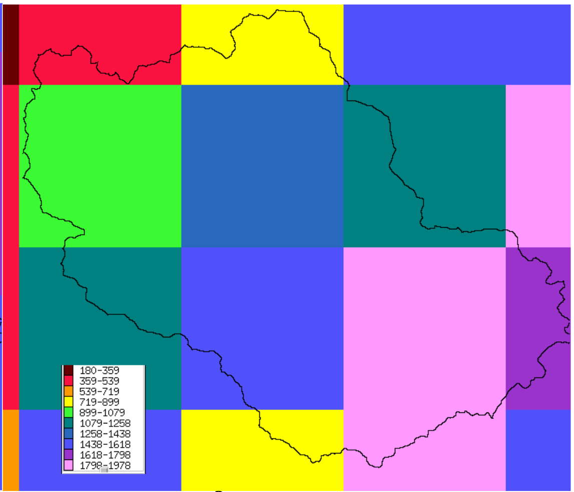
Radar 1x1 km^2 Pmoy = 150.5 mm



Radar 2x2 km^2 Pmoy = 151.0 mm



Radar 5x5 km^2 Pmoy = 146.9 mm



Radar 10x10 km^2 Pmoy = 140.8 mm

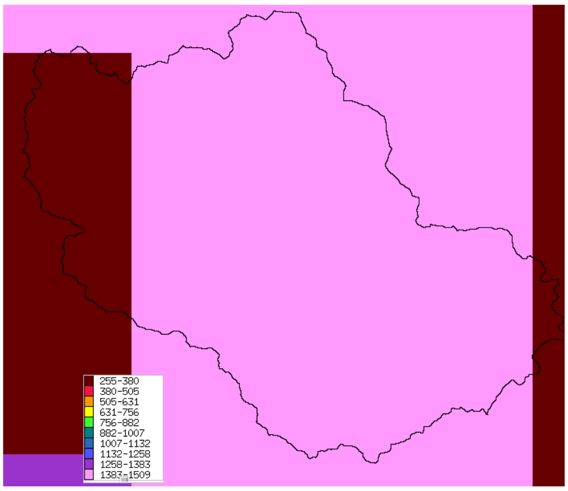


Figure 4-66

Radar 25x25 km^2 Pmoy = 150.9 mm

The question is, how sensitive are the simulations of the models to the resolution of the radar rainfall? Is it necessary to keep a 1 km² resolution? How much precision is lost if only one radar pixel is kept out of 2, out of 3 etc.?

Here we will study the sensitivity of the flood simulations as a function of the radar images, whose resolution is 1 km²:

Sampling 1: 1 pixel out of 2, i.e. 4 km² resolution;
Sampling 2: 1 pixel out of 3, i.e. 9 km² resolution;
Sampling 3: 1 pixel out of 5, i.e. 25 km² resolution;
Sampling 4: 1 pixel out of 10, i.e. 100 km² resolution;
Sampling 5: 1 pixel out of 25, i.e. 625 km² resolution.

N.B. the sampling computed on the radar image consists in calculating the average value on every sampled block, i.e. 4 km² for the sampling of 1 pixel out of 2.

Operating mode

The data base used:

> Anduze.alt *digital elevation model*;
> Anduze.drl *drainage model*;
> 200901021200.grd, 200901021205.grd…. *Panthere radar files*;
>
> ***SCS*** *(S=200, w = 0.2, ds = 1),* ***Lag-route*** *(Vo = 3, Ko = 0.7).*

The files containing the hydro-meteorological events will be built from the radar data, using different samplings: 1, 2, 3, 5, 10, 25. These files are located in the *radar_panthere* directory.

We will use the VISHYR function: File/Import-Export/Calamar-Panthere → txt to build the input files for MERCEDES (cf. paragraph 8.4.2). The dates of the event to build are fixed between 02/01/2009 at 12h00 and 02/03/2010 at 14h00.

Simulations will be superimposed using the Vishyr Add Station feature.

Result

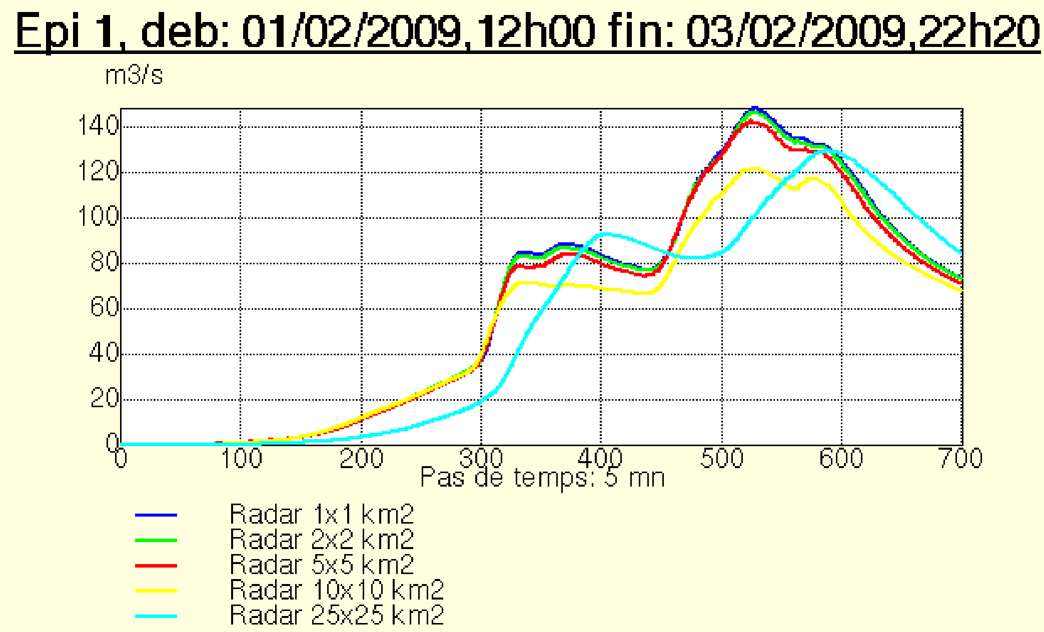


Figure 4-77

The simulations produce almost equivalent results for resolutions up to 5 km, this corresponds to 22 radar pixels on the watershed. Beyond, a marked degradation is observed. For this event, the conclusion is that 22 measurement points are sufficient for the spatial organization of the rainfall events to be taken into account.

Can these conclusions be extrapolated to any radar event?

5. APPLICATION OF THE KINEMATIC WAVE MODEL (TRANSFER)

5.1. Introduction of the model

The kinematic wave transfer function computes a runoff transfer from upstream to downstream on every cell of the watershed. At each time step of the calculation, the budget of the available runoff volume is computed for every cell, taking the upstream inflows, the initial available runoff at the beginning of the time step, and the downstream outflows into account. **Compared to a transfer function of lag and route type, this function has several advantages:**

i) A more physical interpretation of the runoff velocities; these can vary as a function of the hydraulic water level, which can be estimated from the cross section profiles, etc.

ii) **The ability to deal with more complex cases, which require knowledge of the actual volumes flowing through every cell at every time step. Examples of these cases are: storage in reservoirs or overflow areas, infiltration in the river bed during the transfer.**

On the other hand, the calculation times are longer, and the results can be influenced by the spatial resolution of the square cells chosen.

The model equations are:

The continuity equation

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0$$

The dynamic equation, in which the loss of energy through friction is disregarded:

$S_0 = S_f$

where Q is the discharge (in m^3/s), A is the surface area of the wet section (en m^2), S_0 and S_f are respectively the bottom slope of the watercourse and the friction slope (in m/m), x the abscissa (in m) and t the time (in s).

The discharge is given by the Manning-Strickler formula, integrating the slope of the watercourse in the friction slope of:

$$Q = K\sqrt{S_0}R_h^{0.66}.A$$

where K is the Manning-Strickler coefficient, in $m^{1/3}.s^{-1}$ and R_h is the hydraulic radius (ratio of the wet section by the wet perimeter) in m.

In MERCEDES, this model is applied according to the following principles:

- We consider that a rectangular channel of λ width and *Pc* depth crosses every cell along its complete length. The direction of the channel is determined by the flow direction derived from the DEM (i.e. 8 possible directions, one for each 45° angle)

NB : since version 5.0, it is possible to deal with trapezoidal or triangular cross-sections

- The time needed for the transfer of the water on the cell to the canal is disregarded. The transfer time on the cell is thus the transfer time in the channel
- When the depth of water in the channel exceeds the depth of the channel, the flow occurs in a minor/major bed made of 2 superimposed rectangles.

The numeric stability of the model is ensured by the Courant's condition.

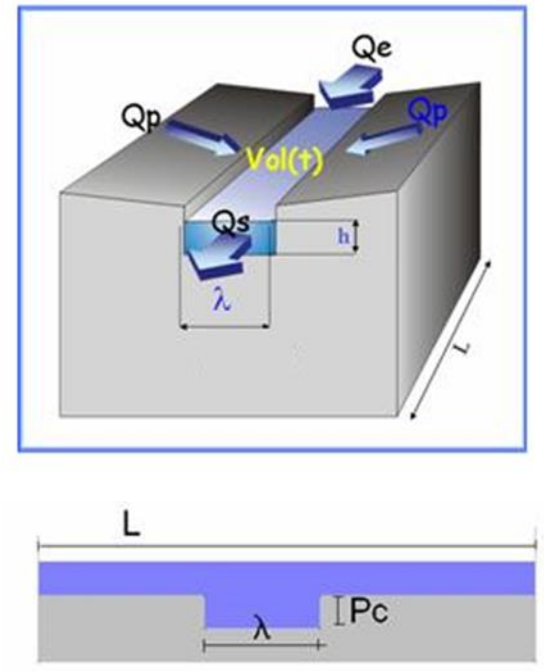


Figure 5-1

Model parameters

The schema involves 4 parameters:

K_1: Strickler coefficient, in $m^{1/3}.s^{-1}$
λ : width of the canal in m;
Pc: depth of the canal, in m;
***γ*.** : coefficient that defines the proportion of the upstream inflows to be taken into account for the calculation of the losses due to runoff, dimensionless.

The model uses the DEM to calculate the slopes; for each cell, these correspond to the difference in elevation from upstream to downstream in the flow direction, divided by the length of the cell.
To calibrate the model, the cross-section width will be 50 m over the whole watershed, and the depth will be infinite, meaning that there is no overflow in the flood plain. To gain time in the process of the calibration, the sample rates will be 50x50 in X and Y.

Results

The 28 events of the sample will be recomputed. The production function is the SCS function.

Comments

The results are good with K_1= 5 to 10 $m^{1/3}.s^{-1}$. However, this value is far from the values usually used to describe the roughness of the natural beds (~20 $m^{1/3}.s^{-1}$). How can this be explained?

i) Note that this value partially depends on the values chosen for the width or the shape of the runoff sections. The impact of the section width on the hydrographs can be estimated by choosing channel widths of 10 or 100 m.
ii) The slopes derived from the DEM can be affected by errors, which can be limited by using the Smoothing function available within Vicair. Test the effect of 1 or more smooths of the slopes on the calibration of K_1.
iii) The sampling factors which were used, 50x50, might be too coarse. Test other sampling factors like 5x5, 10x10 for 1 or 2 events.
iv) The conditions governing transfer in channels and hillslopes are assumed to be different. On the hillslopes, the runoff has a low hydraulic head. The corresponding roughness coefficients are probably around of 1, or even less. You can check this by partitioning the transfer classes:

channels (S>25 ha) $\rightarrow K_1=20\ m^{1/3}.s^{-1}$

hillslope (S>25 ha) $\rightarrow K_1=1\ m^{1/3}.s^{-1}$

(use the file of the upstream areas, see function Process of DEM – Files derived from the drainage model – File of the upstream areas in VICAIR)

5.2. Application to the simulation of dam impacts

Figure 5-2

The distributed structure enables any reservoirs/dams on the catchment to be taken into account.

<u>N.B.</u> To account for reservoirs, it is indispensable to use the transfer function in interactive cell mode, like for instance the Kinematic Wave model. These functions are indeed the only ones that can manage the volumes stored in every cell at every time step.

Adding a reservoir requires two steps:

1) the reservoir must be declared with its coordinates in menu 1 "Catchment data"
2) the functional characteristics of the reservoir must be declared

The first step consists in entering the coordinates of the reservoirs, using the option *Add* on the panel *Dams* in the C*atchment* data menu.

The following coordinates are entered:

```
Reservoir R X= 726212 Y=1901101
Reservoir J X= 712037 Y=1910680
Reservoir O X= 723287 Y=1905730
Reservoir V X = 708737 Y=1906330
```

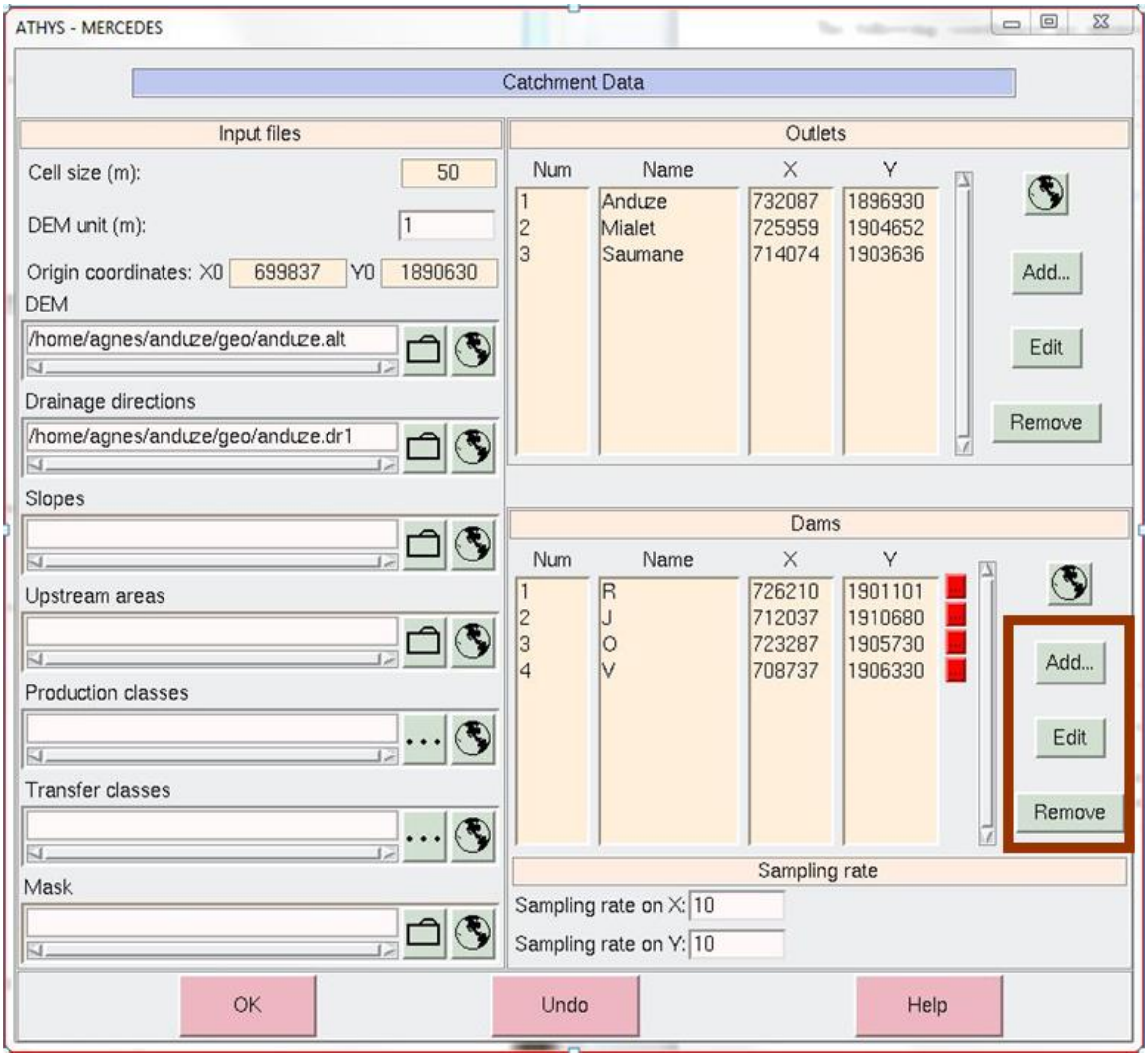


Figure 5-3

The coordinates of the reservoir have to be checked by viewing the watersheds controlled by the reservoirs; this can be done using the control function  in the *Dams* panel.

After the reservoirs are declared, the functional characteristics of each reservoir must be declared, by clicking on the button at the right side of the line corresponding to the reservoir

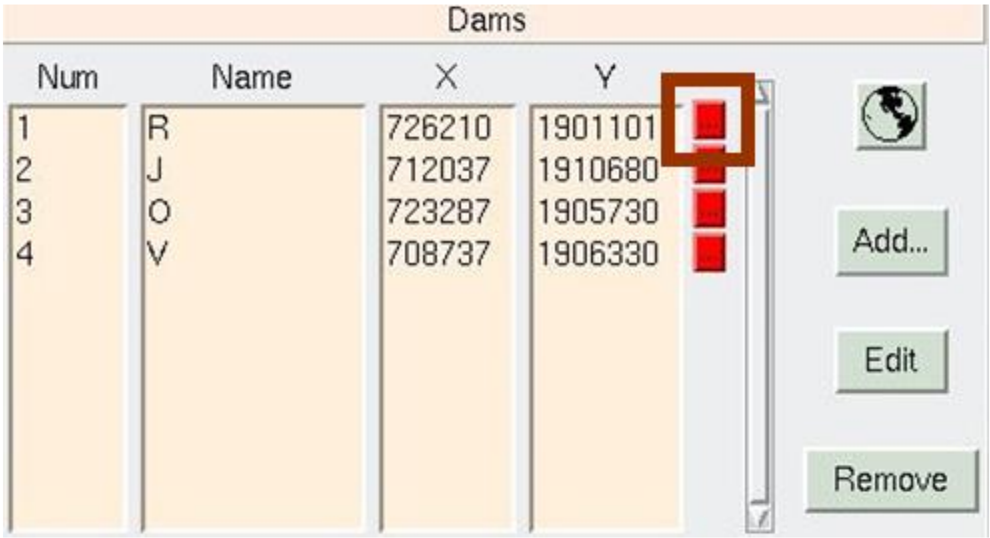


Figure 5-4

Then, appears the table of the correspondence between water level, volume and output discharge, to be filled

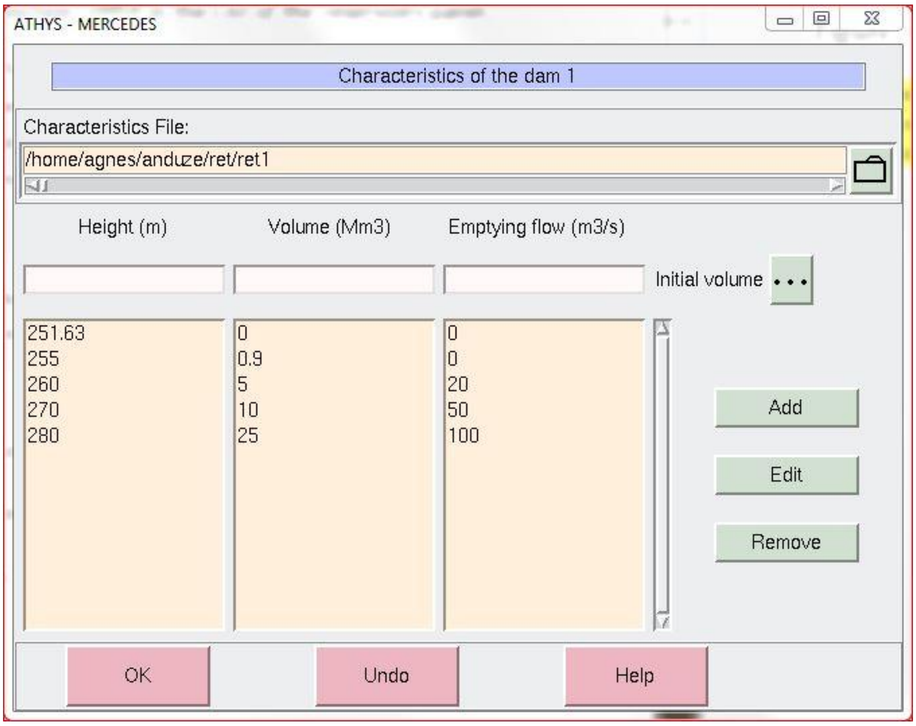


Figure 5-5

The output discharge can be due to a bottom gate or infiltration/evaporation losses, etc… The water levels are not directly used in the computation, but are displayed as a graphical output in the menu 6 in Mercedes (the units are meters), Fig.5-6. The last line of the table must denote the maximal capacity of the reservoir ; beyond this capacity, the output flows are considered to be the same than the input flows.

The variations of the water levels in the reservoirs are stored in a file that must be declared in the menu 6 of MERCEDES, output files. The water depths are expressed in m

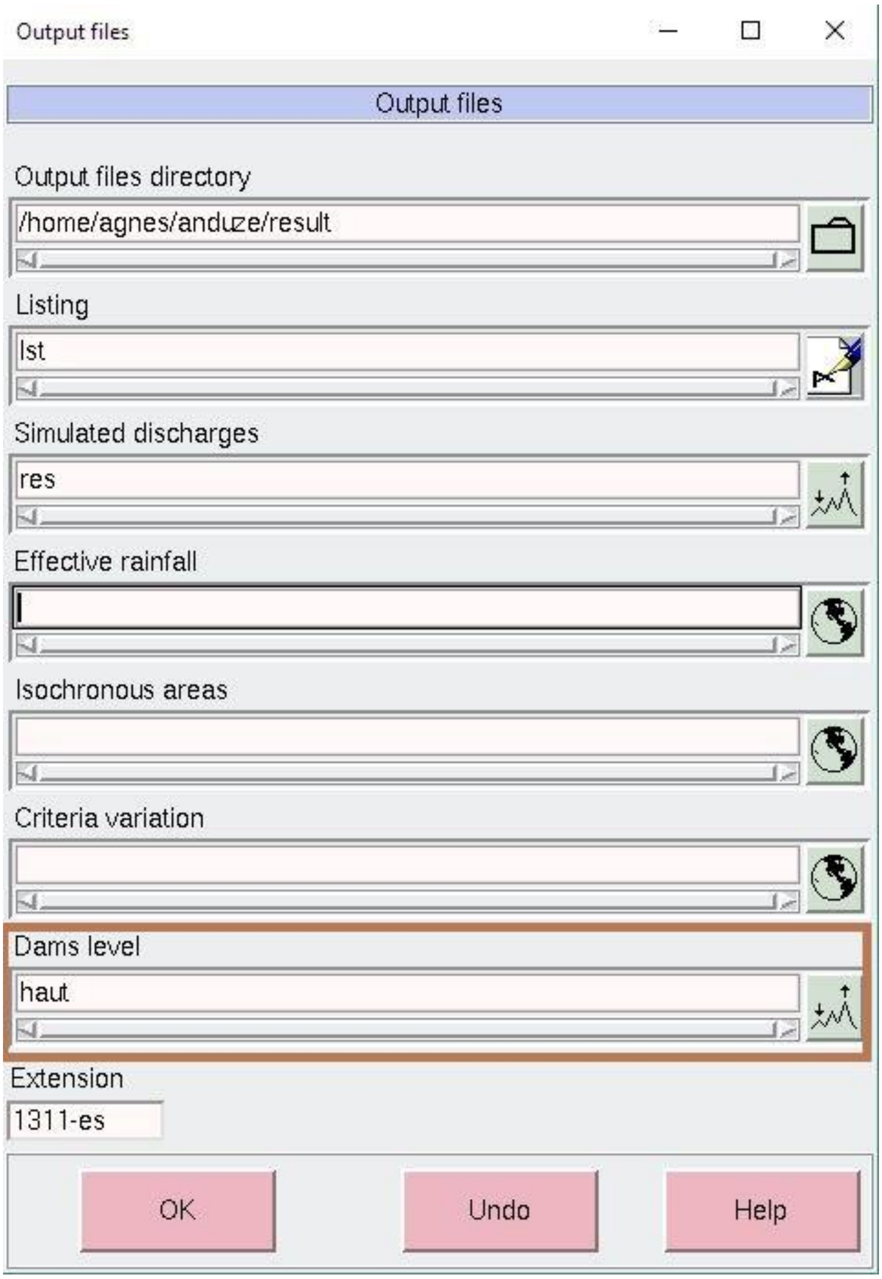


Figure 5-6

<u>Exercise</u>: simulate the impact of the reservoir during flood event n° 2 (11/09/1976), at the outlet of the catchment and at the output of every reservoir. The following parameters will be chosen:

Production SCS : S=230.7 mm, Ia/S = 0.2, w=0.2, ds=1 d^{-1} for the cells of the watershed;

Transfer KW rectangular : K_1 = 6.99 $m^{1/3}.s^{-1}$, λ = 50 m, Pc=10000 m for all the cells of the watershed.

The dams characteristics are the same for R, J, O, V, as set in Figure 5-5.

Sampling 10x10

<u>Solution</u>

The results of the simulations are compared, with or without reservoirs, at the outlet of the watershed.

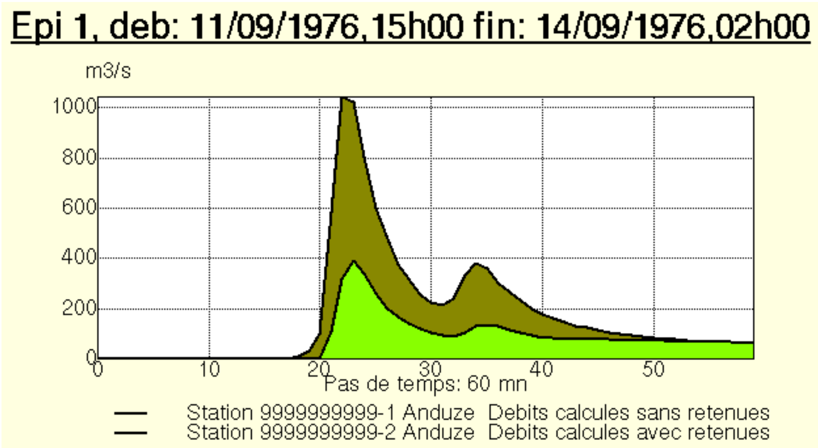


Figure 5-7 : Discharges at Anduze with or without reservoirs.

The levels in the dams can be seen by viewing the file defined in Fig.5-6. The dams did not overflow, since the maximum levels were less than 280 m during the event.

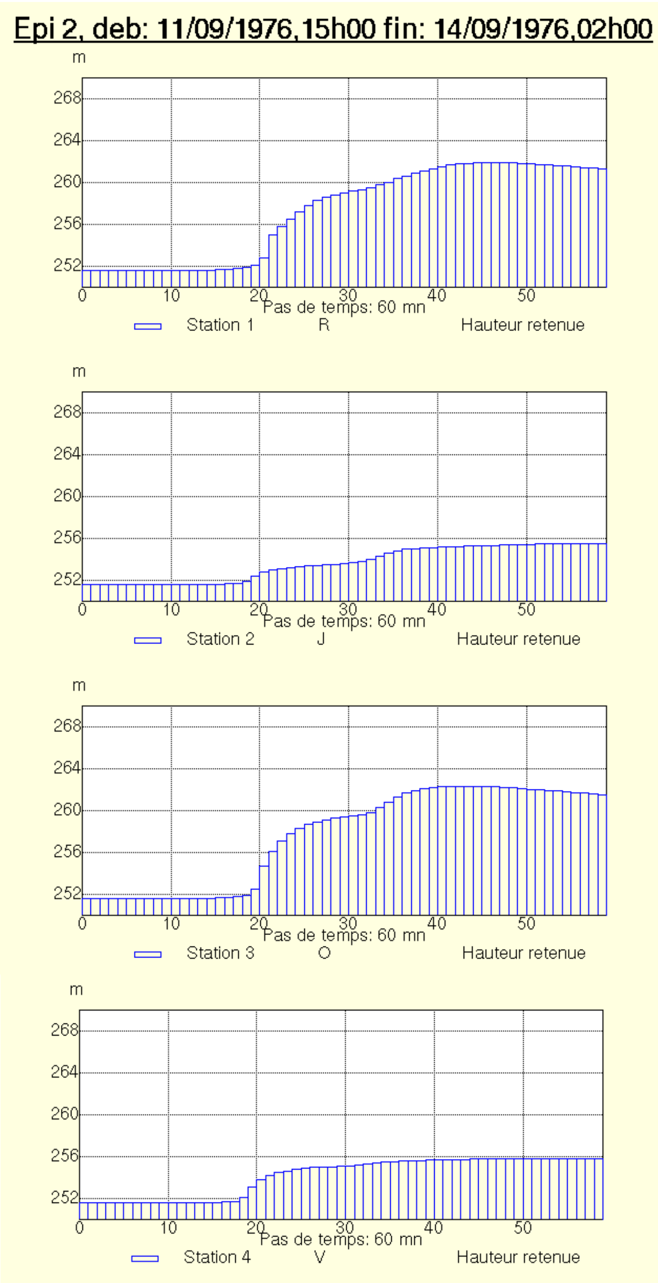

Epi 2, deb: 11/09/1976,15h00 fin: 14/09/1976,02h00
m
268
264
260
256
252
0
10
20
30
40
50
Pas de temps: 60 mn
Station 1
R
Hauteur retenue
Station 2
J
Hauteur retenue
Station 3
O
Hauteur retenue
Station 4
V
Hauteur retenue

Figure 5-8

6. APPLICATION OF THE GREEN & AMPT MODEL (PRODUCTION)

The Green & Ampt production function is a physically-based model, which describes the process of infiltration of water into the soil, assuming a rough distinction of the soil profile between a saturated area above a non-saturated area, whose the water content is constant in space and over time. These approximations can be accepted for infiltration in the soils with a coarse texture. The expression of the infiltration is:

$$f(t) = Ks\left(\frac{\Psi\Delta\theta}{F(t)} + 1\right)$$

$f(t) = \frac{dF(t)}{dt}$ = infiltration capacity [L/T]

$F(t)$ = cumulated infiltration [L]

$\Delta\theta = \theta_s - \theta_i$ = difference between moisture at saturation and initial moisture [ad.]

Ks = hydraulic conductivity at saturation ([L/T]

Ψ = matrix potential at the level of the wetness front [L]

The advantage of this function is linked to its physical basis, and its theoretical ability to estimate *a priori* parameters from the soil data or the "in situ" measurements.

This schema was included in MERCEDES. A soil reservoir was added, of which the level describes ongoing changes in water storage in the soil. The level depends on the infiltrated inflow from the surface, on the deep percolation outflow towards the water table, and the lateral subsurface flow along hillslope. The deep outflow discharge is calculated using a linear reservoir model. The lateral subsurface flow is considred as a fraction of the deep outflow. An additional parameter represents the soil depth, which enables a limitation of the soil reservoir capacity, and allows simulating surface runoff when soil saturation is in excess.

The model is made of 5 base parameters: θ_i, θ_s, K_s, Ψ, Ho and 2 parameters associated with the reservoir outflow discharge: $\boldsymbol{\omega}$ and ds.

$\boldsymbol{\theta_i}$ in cm^3/cm^3 = initial water content of the soil. The values theoretically range from 0 to θ_s

$\boldsymbol{\theta_s}$ in cm3/cm3 : water content in the soil at saturation. In theory, these values range from 0 to 1 (in practice from 0.3 to 0.7) depending on the soils. For instance, the volume of water at saturation is around 0.3-0.4 for sandy soils, 0.4-0.5 for medium texture soils, and 0.5-0.6 for clay soils.

$\mathbf{K_s}$ in mm/h= hydraulic conductivity at saturation. These conductivity values can vary considerably, from 10^5 to 10^{-6} mm/h. The values 10^3 to 10^2 mm/h are generally used for sandy soils, 10^2 to 10^{-1} mm/h for clay soils. Empirical formulas such as the Kozeny-Karman or Allen-Hazen equation can usually be used, even if their efficiency appears to be very limited (Musy and Soutter, 1991).

Ψ, in mm= matrix potential at the level of the wetness front. The values of this parameter range from 100 to 1500 mm, it is rather difficult to determine them precisely. In the "Handbook of Hydrology" (5-15, 5-37) a method for estimating this parameter is given based on the Brooks-Corey formula.

Ho in mm= maximum capacity of soil storage, in water equivalent. This quantity theoretically corresponds to the product of the soil depth with the difference of the average porosity and the initial water content.

ω ad. = part of the outflow discharge that contributes to runoff, in the form of lateral subsurface flow. This parameter quantifies the delayed flow that comes from the outflow discharge of the upstream soil profiles, and has to be calibrated with observed recessions of the floods.

ds in $days^{-1}$ = coefficient of the exponential discharge of the deep infiltrated outflow, simulating the outflow discharge of the soil reservoir (evaporation, percolation, hypodermic lateral runoff). A value equal to 1 leads to a daily outflow discharge rate of 63% (=1—exp(-1)), and to a hourly rate of outflow discharge of 4% (=1–exp—1/24)).)). The theoretical values of *ds* range between 0 (no outflow discharge) and ∞ (complete outflow discharge at every time step of the computation). In practice, ds can be related to the slope of the recession, in logarithmic coordinates.

The following example uses the option of spatial variability of the parameters cell by cell, based on maps that describe the spatial variability of the model parameters: **θs** porosity (anduze.qsat file), **Ks** hydraulic conductivity (anduze.Ksat file), **Ψ** matrix suction (anduze.pse file), established from pedotransfer formulas:

Substratum	θs cm^3/cm^3	Ks mm/h	Ψ mm	Ho mm
Granites	0.45	250	60	500
Shale	0.45	150	110	500
Limestones	0.45	50	210	500
Miscellaneous	0.45	100	150	500

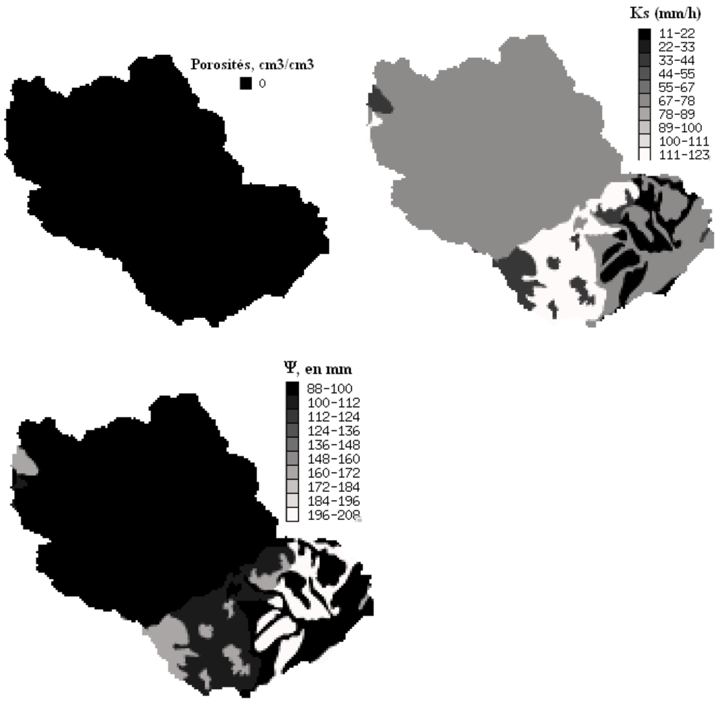


Figure 6-1

NB : the porosities equal 0.45, but up to now, the decimal values are not displayed in VICAIR, and the porosities are seen as 0 on Fig.6-1.

The file associated with each of the parameters must be activated with the  icon located just above this parameter. The icon opens a window that makes it possible to choose the reference matrix file.

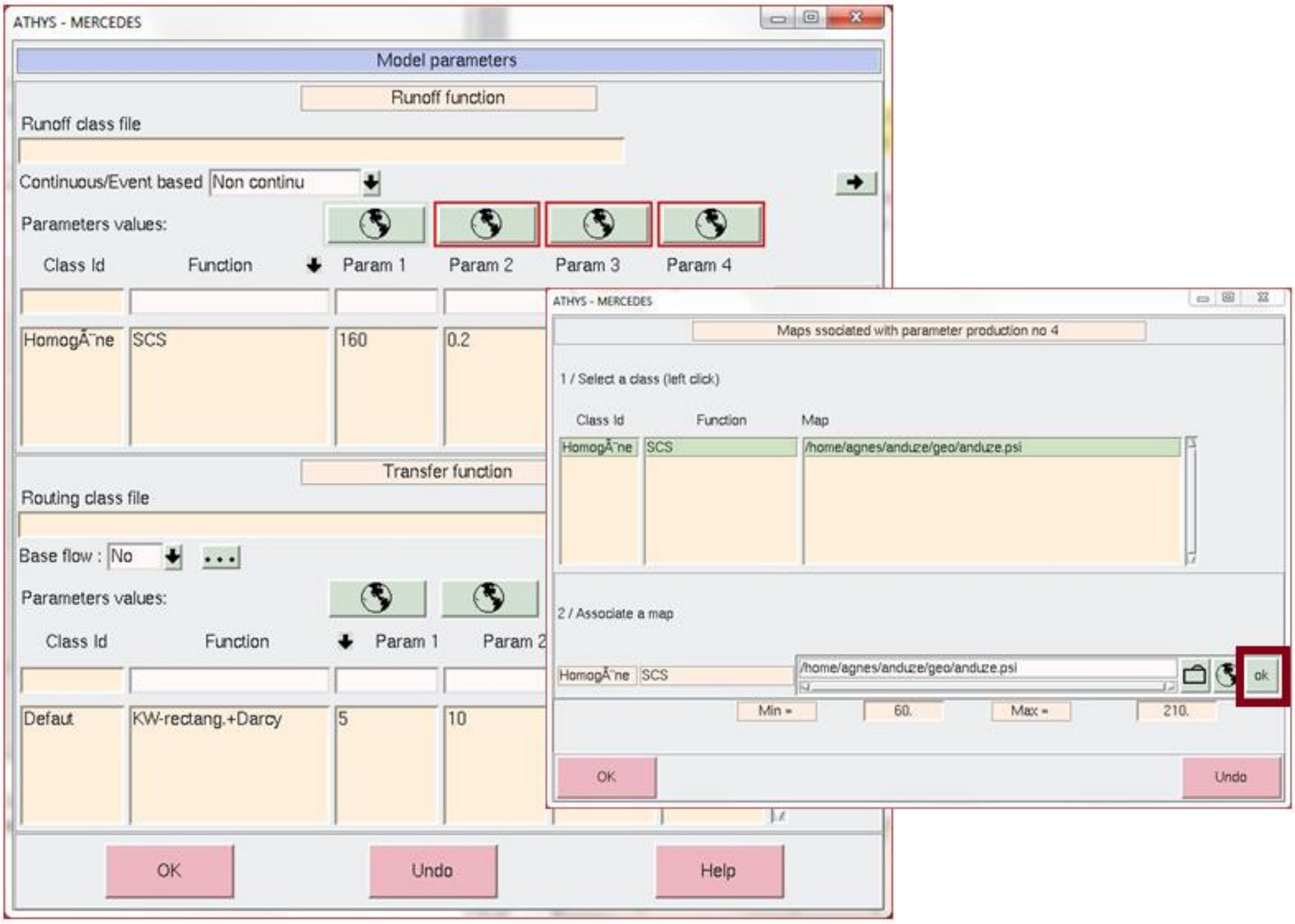


Figure 6-2

The  icon shows that a parameter is effectively associated with a file, and that the values of the parameter will be read in this file.

N.B. these values are automatically multiplied by the value of the column of the parameter (here 1), this value being used as a single coefficient. Take care to set this coefficient equal to 1 if you want the parameter to be identical to the value read in the matrix. Like any other parameter, this coefficient can be optimized, (simply double-click left on the corresponding box).

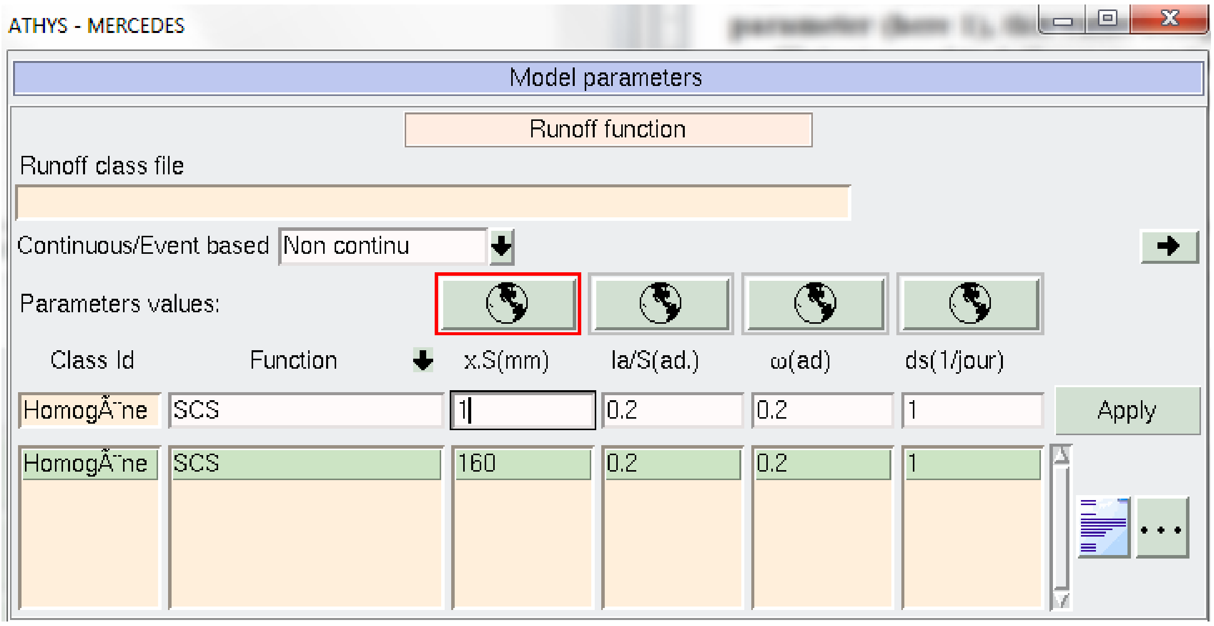


Figure 6-3 : before "Apply"

It is possible to combine a class-based spatialization of a parameter (production classes or transfer classes) and a matrix-based spatialization associated with a raster file. In this case, the parameters of each class (here, elevation) will be read directly in the file, and multiplied by the coefficients (possibly different) associated with each class.

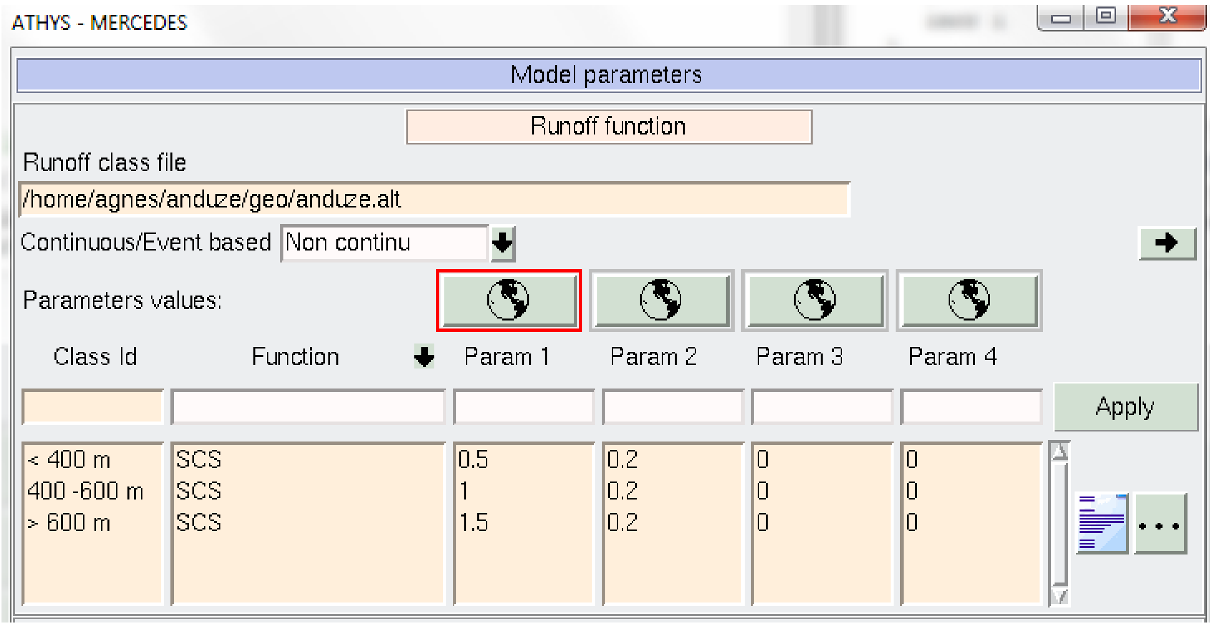


Figure 6-4

To deactivate, erase the name of the associated file in the window hereunder, and validate:

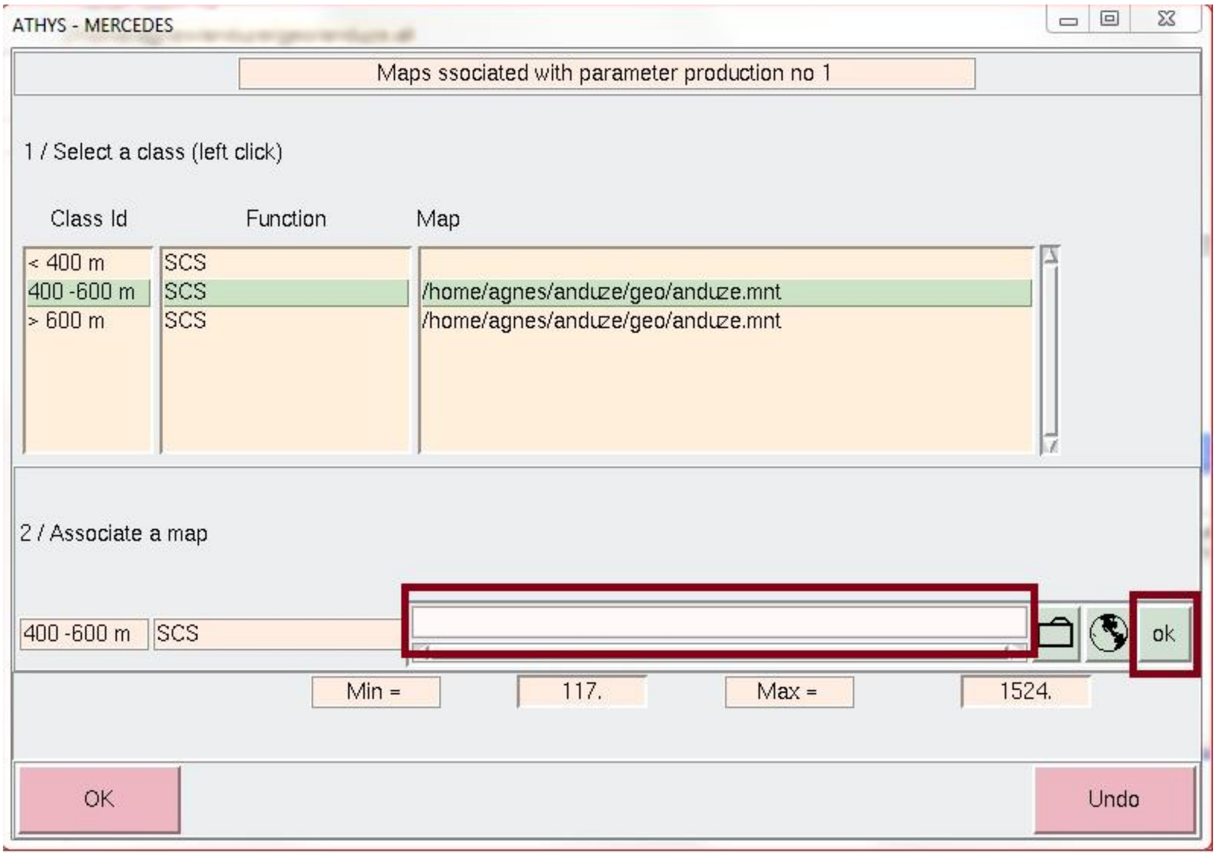


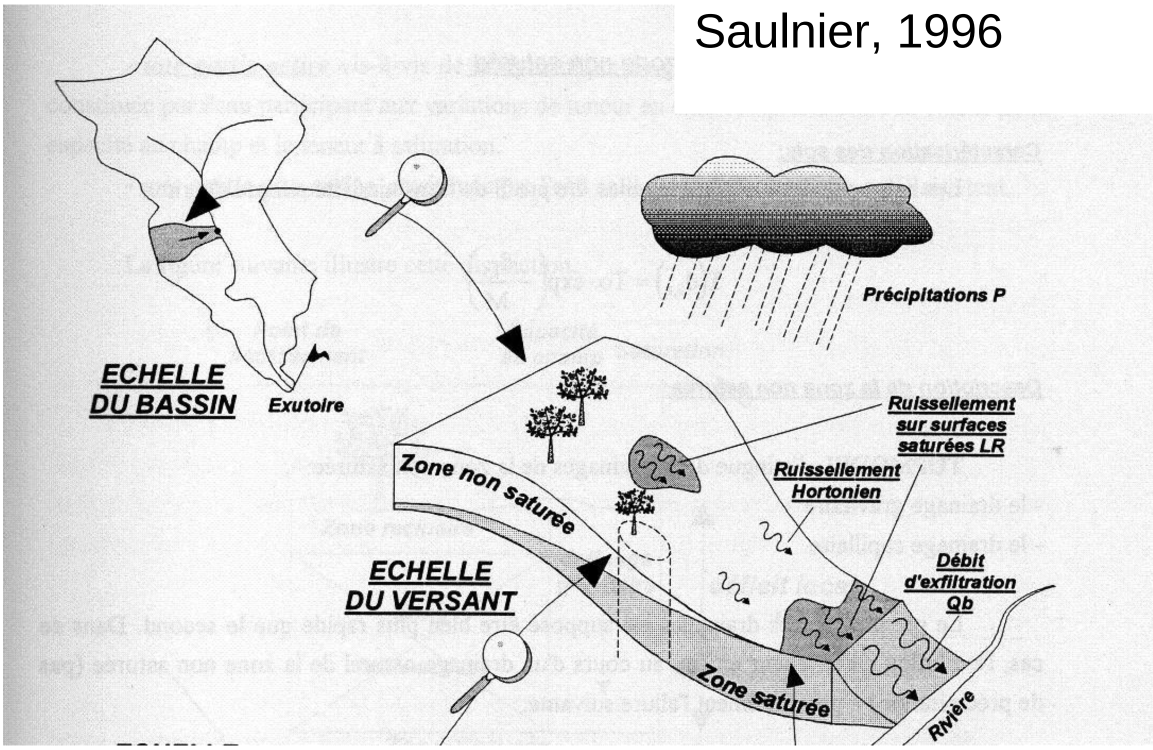
Figure 6-5

In the menu of the parameters, the corresponding icon is no longer in a red square. The parameter will then appear directly in the column (be careful to restore the correct value, which will probably differ from the previously used coefficient)

Exercise: calibrate the model on some floods in the base28.txt file. Good results are obtained when setting at 0.1 for the coefficient of the hydraulic conductivities. How can this result be interpreted? What is the sensitivity of the model to other parameters?

7. TOPMODEL APPLICATION (PRODUCTION)

TOPMODEL (Beven & Kirkby, 1979, Franchini *et al*., 1996) is a set of concepts dealing with the production of runoff induced by the development of contributing variable area, due to the progressive saturation of the the bottom hillslopes (figure 7-1). Within TOPMODEL, the runoff induced by cell *i* at time *t* mainly depends on the saturation deficit $\delta_i(t)$, i.e.the equivalent of the water required for saturation of the vertical profile of the soil at time *t*. This type of functioning is relatively common in temperate zones, but can also be found in Mediterranean and tropical watersheds.



$$\delta_i(t)$$

Figure 7-1 : : Representation of the saturation deficit on a watershed (from Saulnier, 1996). The extension of the saturated zone is linked to local infiltration and to the existence of a sub-surface lateral flux.

Three main hypotheses underlie TOPMODEL:

- the hydraulic conductivity at saturation of the soil at depth z is given by: $K(z)=K_0.exp(-fz)$ where K_0 stands for the hydraulic conductivity at saturation at the surface;
- the top of the water table is parallel to the surface;
- the sub-surface water flows as steady flow;

under these assumptions, it can be shown that the deficit of saturation of every cell of the watershed is written:

$$\delta_i(t) = \bar{\delta}(t) - \frac{\tau_i - \bar{\tau}}{f}$$

where $\delta_i(t)$ stands for the water deficit on cell i, $\bar{\delta}(t)$ the mean deficit in water over the whole watershed, and f a parameter of the model. In the case of an exponential vertical profile of the hydraulic conductivities, the topographic index τ_i is defined as:

$$\tau_i = Ln(\frac{a_i}{tg\beta})$$

where a_i is the surface drained upstream from the cell, per unit of contour, and $tg\beta_i$ is the tangent of the cell slope.

The cell is saturated if $\delta_i(t)<0$, in this case, the runoff coefficient of the cell is equal to 1. Otherwise, $\delta_i(t)>0$, the runoff coefficient of the cell is equal to 0.

One advantage of TOPMODEL is that it can be "physically" initialized. The average deficit of the watershed is initialized as a function of the base flow observed at the beginning of the event $Q_b(t_0)$:

$$\bar{\delta}(to) = -\frac{1}{f} \times Ln\left(\frac{Q_b(to)}{A \times T_0 \times exp(-\bar{\tau})}\right)$$

A is the surface area of the watershed, $T_0=K_0/f$

Parameters of the model

In the current version, we will consider only 2 parameters:

K_0 *(mm.h^{-1}):* hydraulic conductivity at surface saturation. The values used in TOPMODEL are generally of the order of several (tenths of) m/h.

f(m^{-1}): coefficient of exponential decrease in hydraulic conductivities at saturation as a function of the depth.

These two parameters are generally strongly interdependent. For the Gardon at Anduze, K_O will be set at 3m.h^{-1} and the f parameter will be calibrated.

Results

The 28 events of the sample will be computed. The transfer function is the lag and route function, with K_0= *0.7*.

N°	Date	$f(m^{-1})$	Vo(m/s)	Qmax (m3/s)	Qb (m3/s)
2	15/10/1973	15.5	1.95	468.2	1.8
6	11/09/1976	9.2	2.06	1047.6	15.6
7	08/11/1976	10.2	2.18	986.7	18.6
9	19/10/1977	14.4	3.15	1159.6	0.4
12	07/12/1977	9.4	1.93	516.9	27
21	22/09/1994	7.8	2.1	663.5	9.7
22	19/10/1994	7.8	1.84	843.7	16.3
23	02/11/1994	6.6	2.06	666	34
27	18/09/1995	6.3	2.52	909	41
28	03/10/1995	7.7	1.62	1572	38
29	13/10/1995	9.6	1.76	1383	27
34	11/01/1996	3.3	1.27	553.5	155
37	20/01/1996	3.8	1.18	632	91
54	03/11/1997	12.1	1.97	805.5	4.5
56	16/12/1997	9.3	6.99	1139.4	10.6
58	15/04/1998	24	1.45	466.1	3.9
59	29/04/1998	14.9	1.17	480.8	19.2
65	17/05/1999	12.1	1.71	606.5	13.5
66	19/10/1999	5.5	2	622.6	37
70	28/09/2000	14.8	2.92	1186.6	3.4
79	09/10/2002	6.8	0.84	445	35
80	23/11/2002	6.9	1.67	605.4	103
81	09/12/2002	9.9	1.05	605	45
86	30/09/2003	9.1	1.43	510.7	9.3
87	15/11/2003	12.4	1.45	668.8	21.2
88	21/11/2003	10.3	1.75	1028.8	40
89	29/11/2003	8.2	1.82	1112.6	46
Moy		***9.92***	***1.99***		
σ		***4.28***	***1.13***		
CV		***0.43***	***0.56***		

Table 7-1

8. DATA SET UP

8.1. Setting up geographical data

This step sets up 2 indispensable files:

- The DEM (Digital Elevation Model);
- The flow direction file;

and of different optional files dedicated to the classification of the production and transfer units, or to mask one part of the study area:

- The production classes file;
- The transfer classes file;
- The mask file.

Different formats can be imported for the DEM file (like for all the geographical files used in ATHYS): GrassASCII or GrassBinary(export of Grass GIS), AsciiGrid (export of ArcInfo, ArcGis, or MapInfo), Surfer. VICAIR provides the facility required to shift from one raster format to another.

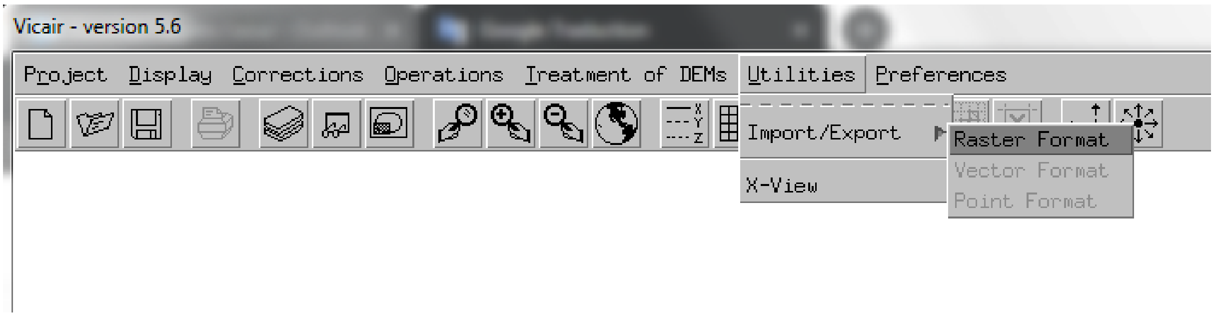


Figure 8-1

Satellite-derived DEMs can be found almost all over the world. The ASTER DEM (Advanced Spaceborne Thermal Emission and Reflection Radiometer, ~30 m), the STRM DEM (Shuttle Rdar Topography Mission, ~30 and 90 m), the ALOS DEM (Advanced Land Observing Satellite, ~30 m) are freely available and can be downloaded from Websites like :

https://asterweb.jpl.nasa.gov/gdem.asp
https://www2.jpl.nasa.gov/srtm/
https://www.eorc.jaxa.jp/ALOS/en/aw3d30/index.htm

The flow direction file is derived from a DEM raster, using the function *DEM process/DEM derived files*.

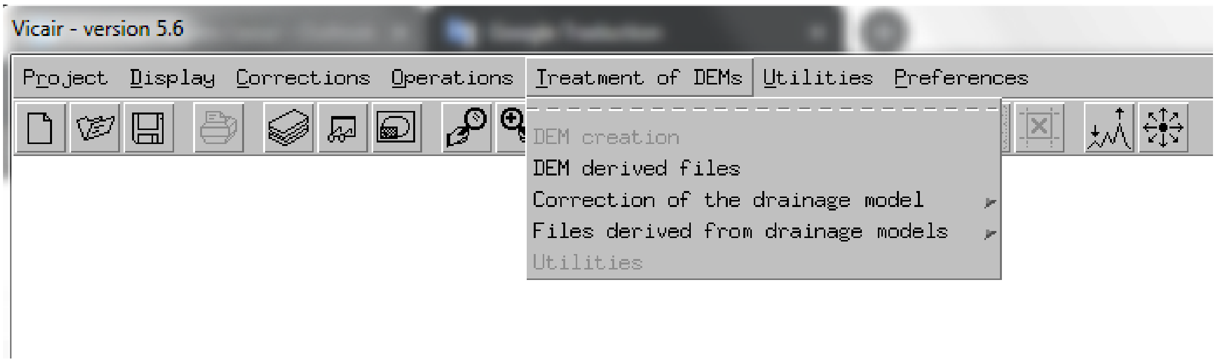


Figure 8-2

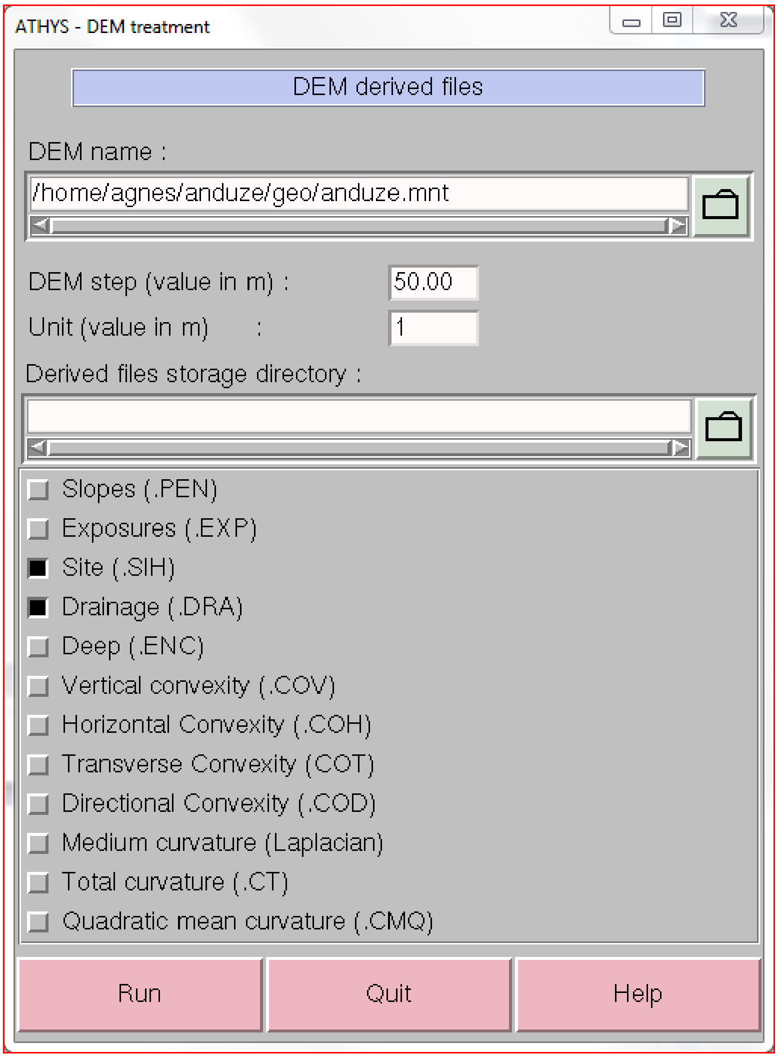


Figure 8-3

The drainage file must then be checked, especially to correct the sinks. This process is automatic and is carried out with the command DEM process/Correction of the drainage model/Detect Fill sinks.

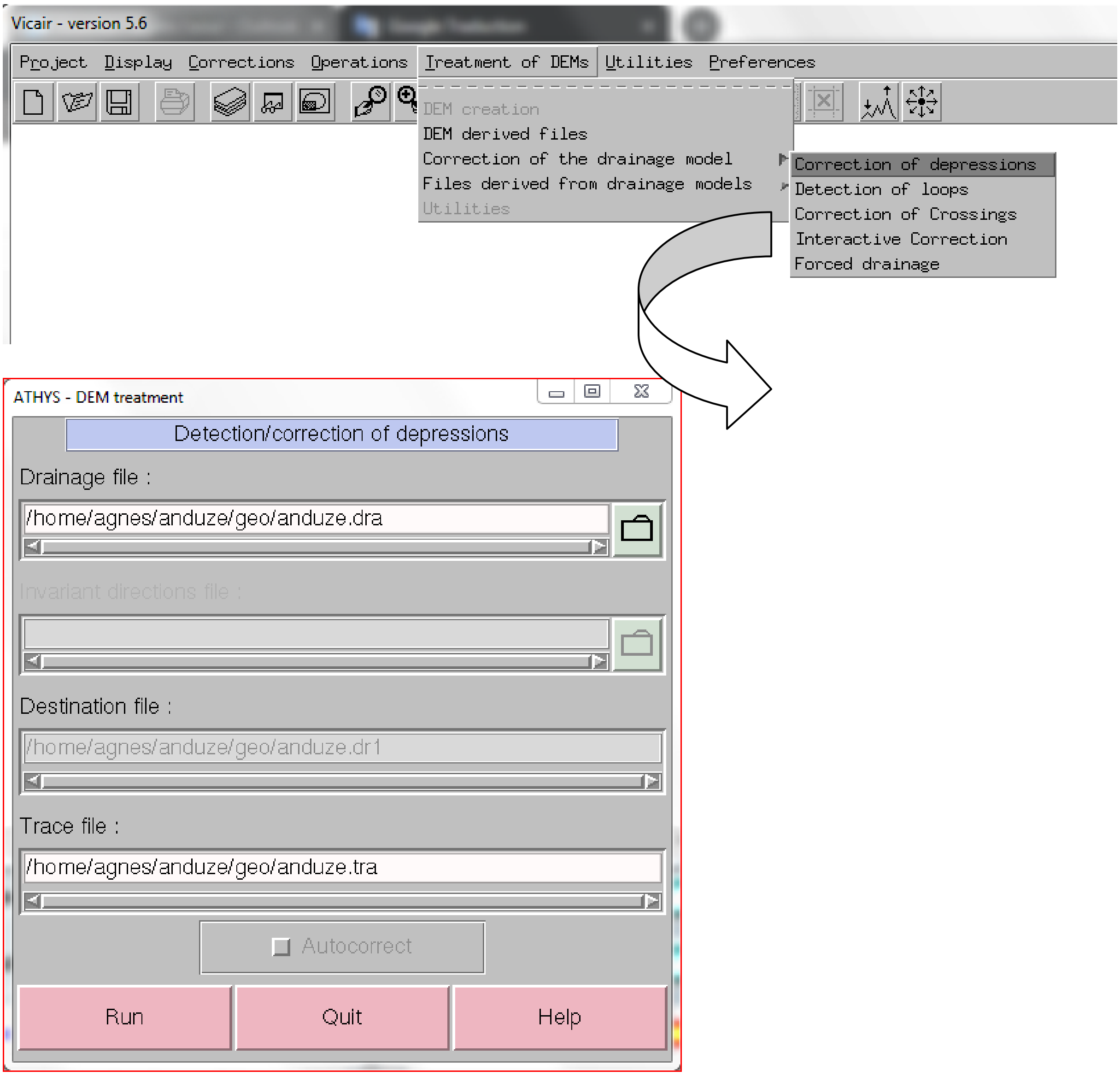


Figure 8-4

The first field corresponds to the drainage file to be corrected, here anduze.dra. The other fields are automatically filled:
The output file is a drainage file where the sinks are (partially or totally) corrected. This file systematically has the .dr1 extension.
The trace file is an image in which the locations of all the sinks of the drainage model to be processed are stored.

At the end of this process, the following is displayed:

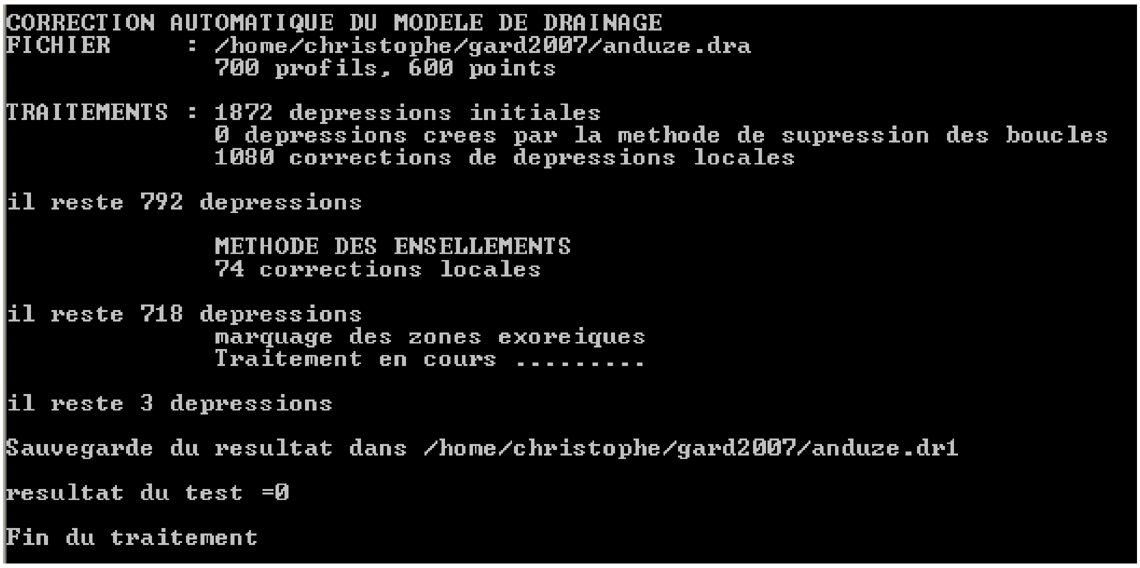


Figure 8-5

At the end of the process, 3 sinks remain. The process needs to be repeated, this time the input file will be the .dr1 file (this process should be run as many times as necessary to correct all the sinks).

Once the drainage file is corrected, two important files can be built to control the quality of the drainage mode:

- The file of the upstream areas, which can be used to represent the hydrographic network;
- The catchment file that draws the sub-watersheds for one or several cells.

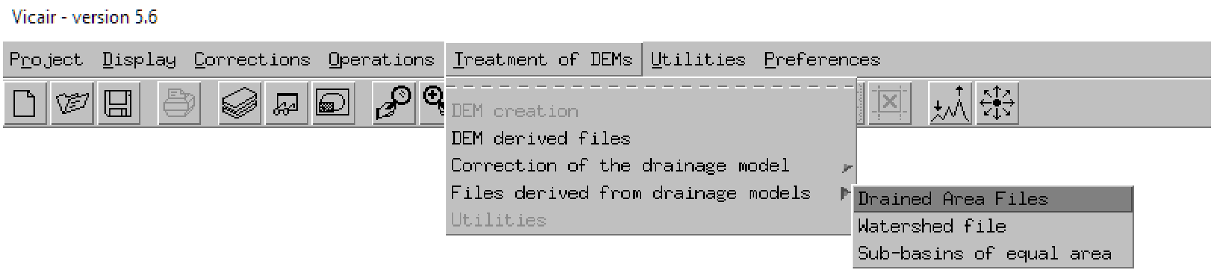


Figure 8-6

For every cell, the file of the upstream areas (flow accumulation) contains the area of the basin drained by this cell (expressed as the number of cells). This file makes it possible to represent the hydrographic network, for instance if only cells that drain more than 100 cells are displayed.

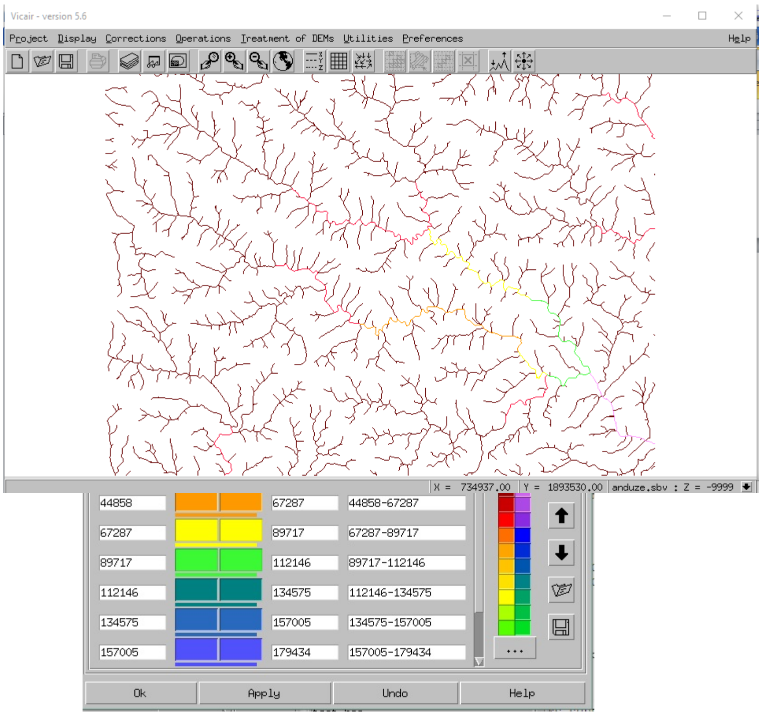


Figure 8-7

Displaying the flow accumulation file makes it possible to check that the river network is coherent with the one on the available topographic maps.

Displaying the watershed file makes it possible to compare the delineation of the watershed computed from the flow accumulation file. If they are different, the flow direction has to be modified using the function *Process of DEM/Correction of the flow direction/Interactive correction* (the file of the drained areas or of the delineated watersheds can be displayed as background).

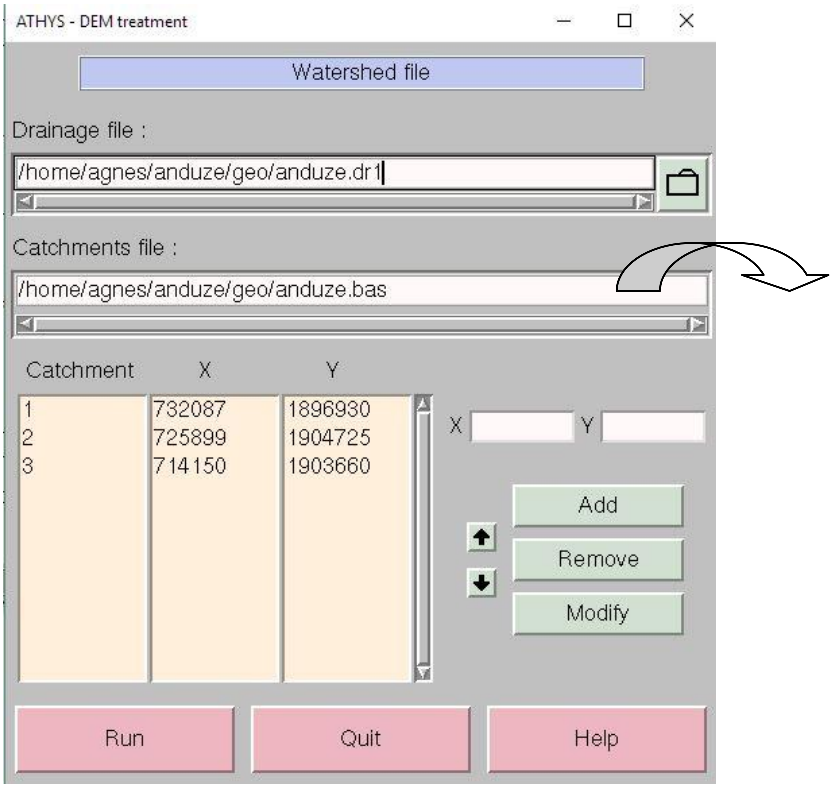


Figure 8-8

<u>Exercise</u>

The aim here is to simulate the discharges at the outlets of different watersheds. The available coordinates:

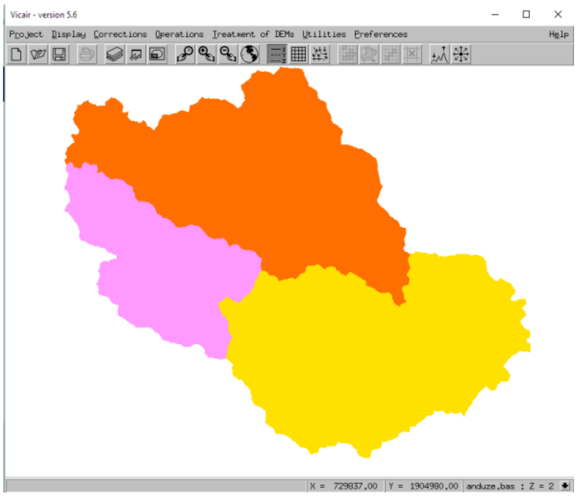
Mialet X = 725899 Y = 1904725 S ~ 230 km^2
Saumane X = 714150 Y = 1903660 S ~ 100 km^2

are not very accurate and do not allow one to determine the corresponding watersheds, because the cells defined by these coordinates are not located on the rivers drawn by the flow accumulation. So:

- enter the coordinates of the outlets of Mialet and Saumane in the list of the points to be calculated (menu 1 in MERCEDES) in order to check if the watersheds are correctly reconstituted;

- if not, build the file of the upstream areas that form the reconstituted network by flow accumulation, and use this file to define the appropriate coordinates of the outlets;

- run the simulations and compare the discharges



obtained in Anduze, Mialet and Saumane.

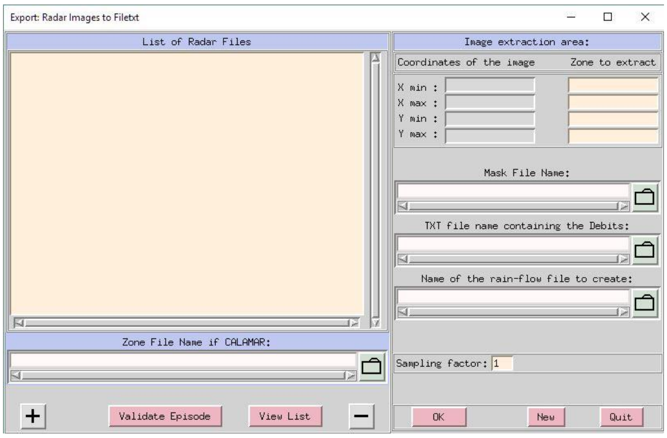
Clue:

The right coordinates of the stations are for instance:

Mialet X = 725959 Y = 1904652
Saumane X = 714074 Y = 1903636

The optional files can be built in different ways:

- Importation of formats Grass Ascii, Grass binary, AsciiGrid, Surfer Ascii
- DEM processing: the derived files from DEM (slopes, exposure, aspect, elevation, etc.) can be used to build production or transfer classes, or to mask one part of the study area;
- Numerical operations between files: two numerical attributes can be added, multiplied etc… to build a third; for instance, the product of soil thickness by porosity to determine the water storage capacity of the soils;
- Logical combination between files: two qualitative attributes can be crossed to form a third, for instance, a sub-classification obtained from a slope classification and a soil classification: thick soil steep slope, shallow soil steep slope, shallow soil gentle slope, etc.



8.2. Setting up the hydro-rainfall data

The files of the events can be set up within Excel , then have to exported in TXT format (space = tabulation). The TXT format is supported by Vishyr and by Mercedes.

Import CALAMAR®/PANTHERE/ANTILOPE files

The import procedure is available in VISHYR, the command is
File – Import/export – Calamar/Panther → txt

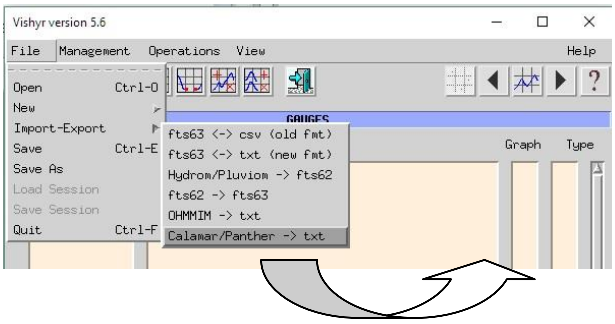


Figure 8-9

The radar measures the rainfall at a 5 minute time step, on a pixel of 1 km². Currently, the radar files are first converted into txt files (each pixel is turned into a pseudo rainfall gauge).

<u>Principles :</u>

- The radar file names must be of the type YYYYMMDDHHMN.grd for PANTHERE/ANTILOPE formats; xxZZ-yyyyMMjjhhmn.dat or other extension (where ZZ, for instance 05, stand for the CALAMAR zone number, and xx stand for any characters) for the CALAMAR® files.
- The radar files must be agregated per event: icon +. One event corresponds to a list of radar files, selected in the browser. The multiple selection keys are Shift and Crtl. The beginning of the event corresponds to the first date in the list of the files, the end of the event to the last date. All the files must cover the same zone. If files are missing on the list, rainfalls will have a no-data value for the corresponding time step.

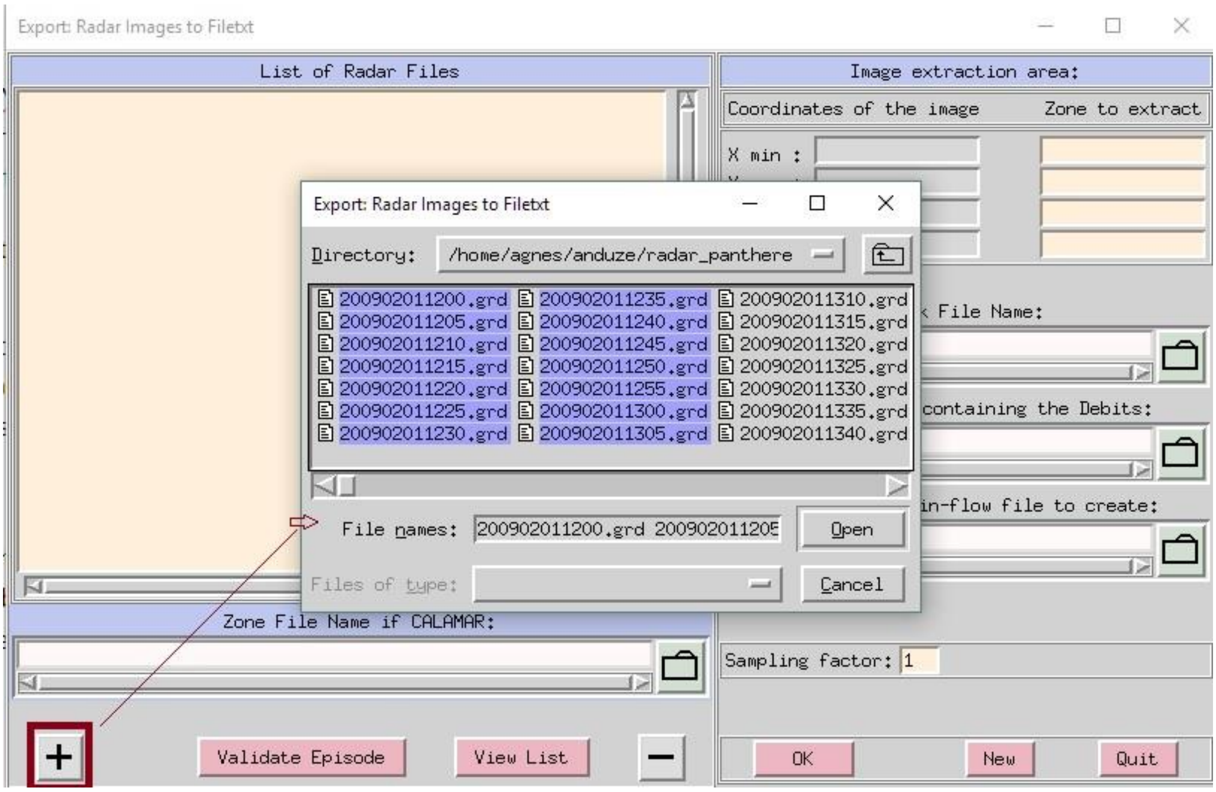
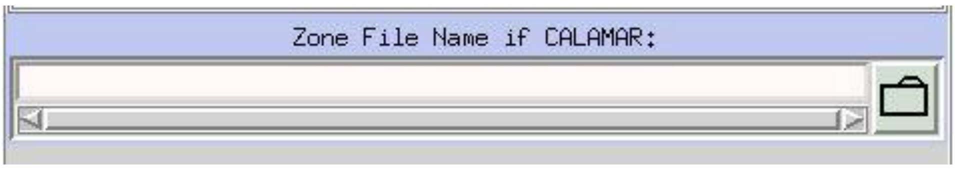


Figure 8-10

- For the CALAMAR® files, with no geographical references, the process is identical, but the file of the CALAMAR® zones has to be declared, as this defines the coordinates of each zone. These coordinates need to be entered in the geographical projection used (the coordinates may have to be converted).



Example of CALAMAR® zone file :

```
<?xml version="1.0" ?>
<defzones>
        <zone num="01" xlambert="738.7" ylambert="3185.1" nbcol="50" nblig="50" pas="1"/>
        <zone num="02" xlambert="705.7" ylambert="3195.1" nbcol="50" nblig="50" pas="1"/>
        <zone num="03" xlambert="697.7" ylambert="3241.1" nbcol="64" nblig="64" pas="1"/>
        <zone num="04" xlambert="742.7" ylambert="3232.1" nbcol="64" nblig="64" pas="1"/>
        <zone num="05" xlambert="768.7" ylambert="3268.1" nbcol="64" nblig="64" pas="1"/>
        <zone num="06" xlambert="797.7" ylambert="3257.1" nbcol="64" nblig="64" pas="1"/>
        <zone num="07" xlambert="806.7" ylambert="3214.1" nbcol="64" nblig="64" pas="1"/>
        <zone num="08" xlambert="713.7" ylambert="3283.1" nbcol="64" nblig="64" pas="1"/>
        <zone num="09" xlambert="744.9" ylambert="3326.1" nbcol="64" nblig="64" pas="1"/>
</defzones>
```

- Once this list is complete, the event has to be validated. The next process is the constitution of the next event. The coordinates of the zone covered by the radar are displayed once the first event has been is validated.

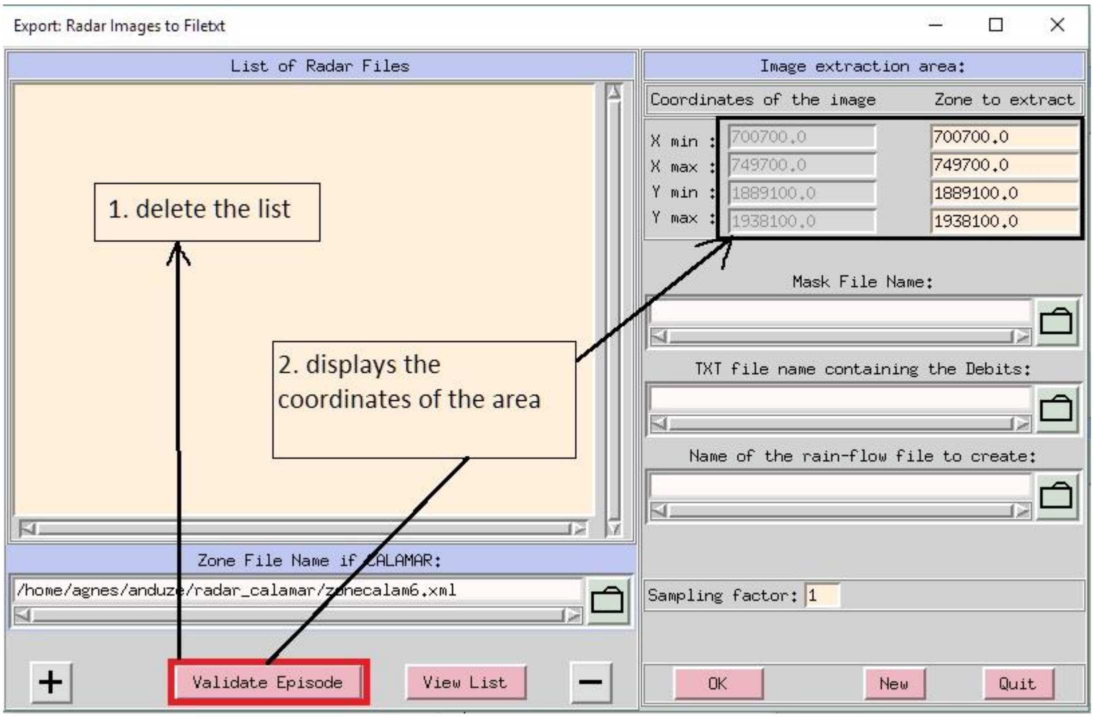


Figure 8-11

- You can then access the list of the events, control and possibly delete an event:

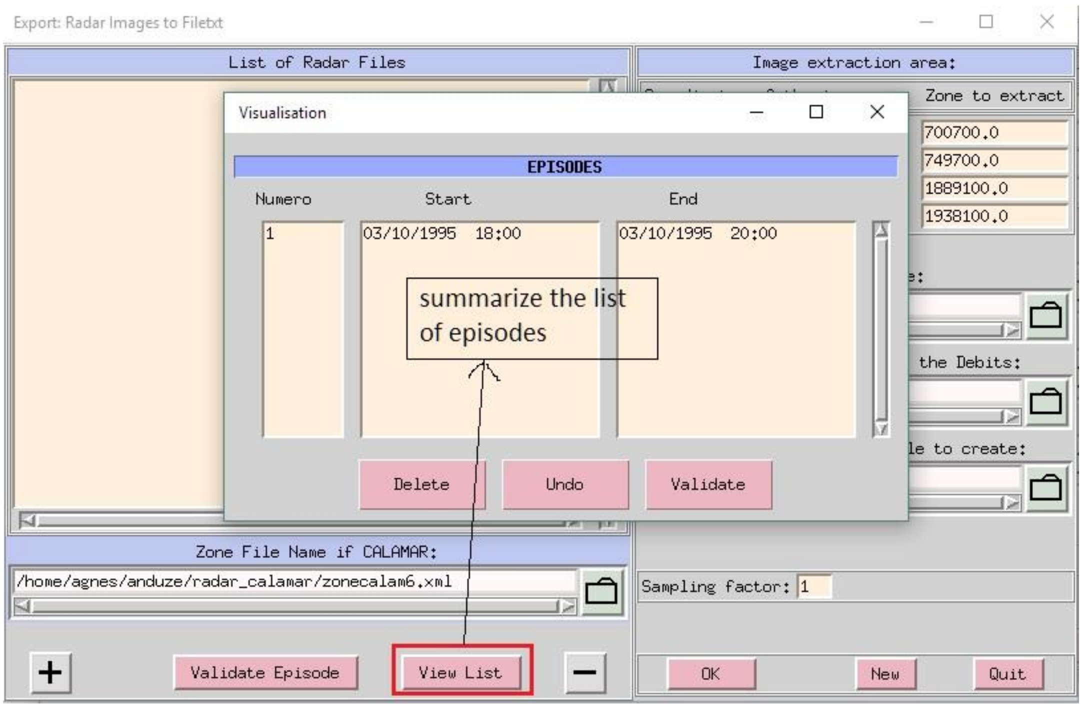


Figure 8-12

- The import options can be chosen as:

    - Selection of the radar pixels corresponding to a sub-region;
    - Use of a mask that makes it possible to select the radar pixels corresponding to a set of cells, example: watershed, altitude classes, etc., the mask file can be AAIGrid, Grass Ascii or Binary, Surfer Ascii, etc., formatted;
    - Output file name: txt files built from the radar rainfalls, to be used with MERCEDES;
    - File which contains discharge data. Discharge data will be merged into the output TXT file, for all the time steps which correspond to radar data.
    - Factor for sampling the radar pixels: select one pixel out of N in X and Y.

- The import process can then be launched by OK. The New key makes it possible to reinitialize the procedure, and to reset the lists and the fields.

N.B. the txt files built at the same time step is the one used by the radar files, and is usually 5 minutes. This time step can be modified with the function: *Vishyr/Management/Modify Time Step*

9. PROGRAM ORGANIZATION AND RECOMPILATION

If you modify the code (FORTRAN or C), you will have to recompile either ATHYS or one of its components. The compilation is done with the tool AcoTools, available in the Athys program bar:

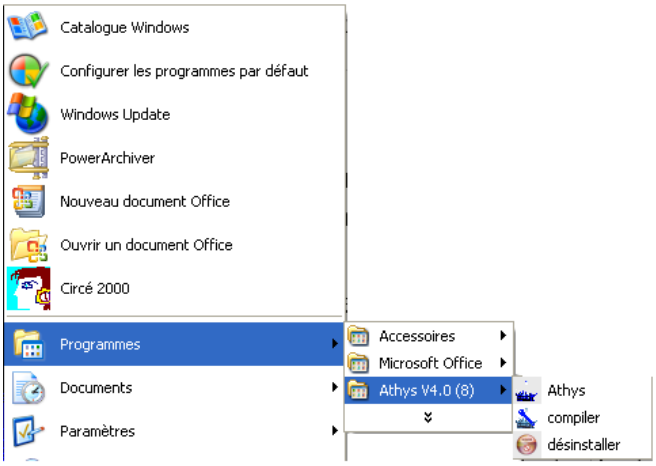


Figure 9-1

The item *Compiler* opens the compilation window.

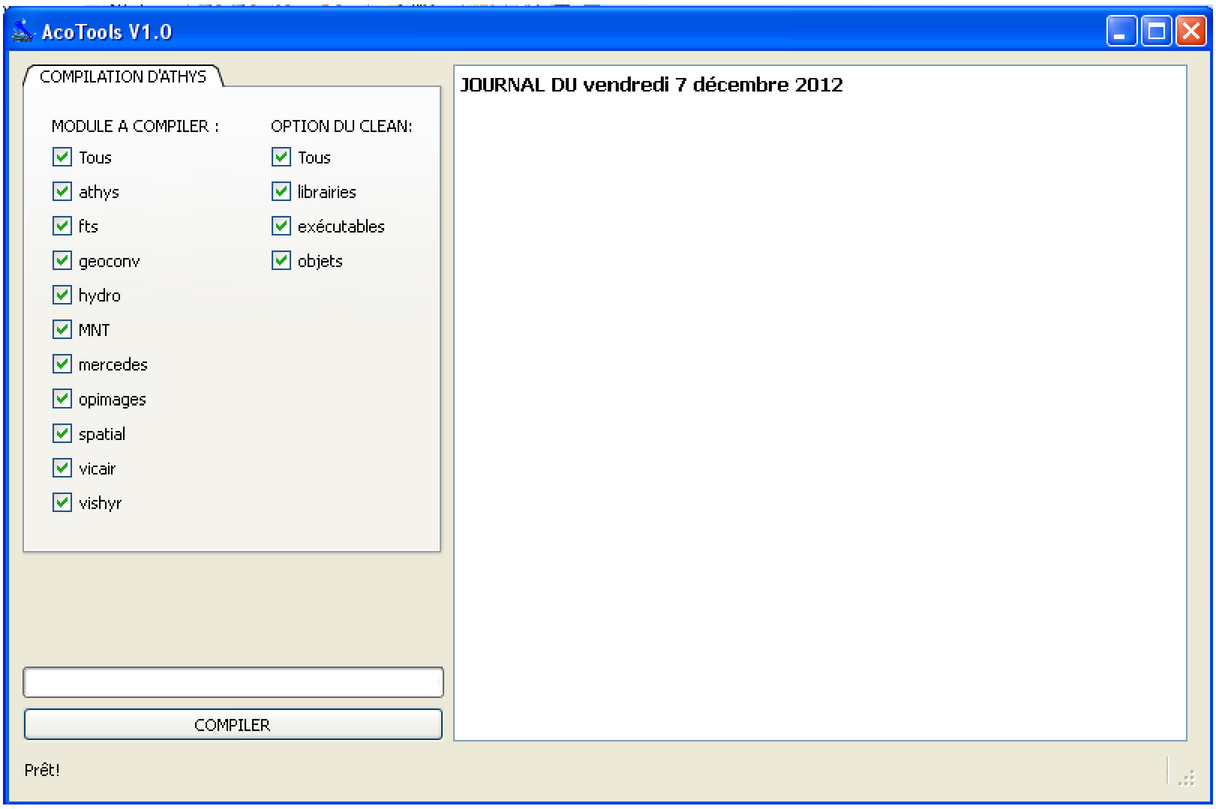


Figure 9-2

You just need to tick the modules that were modified and need to be recompiled. You also have to tick the *Clean* options to be executed, i.e. the types of modules that must previously be deleted to activate the compilation. In practice, this process is only required in the case of modifications concerning files involved in "include" processes.

10. REFERENCES CITED

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