PRESAGES: a tool for low flow forecasting

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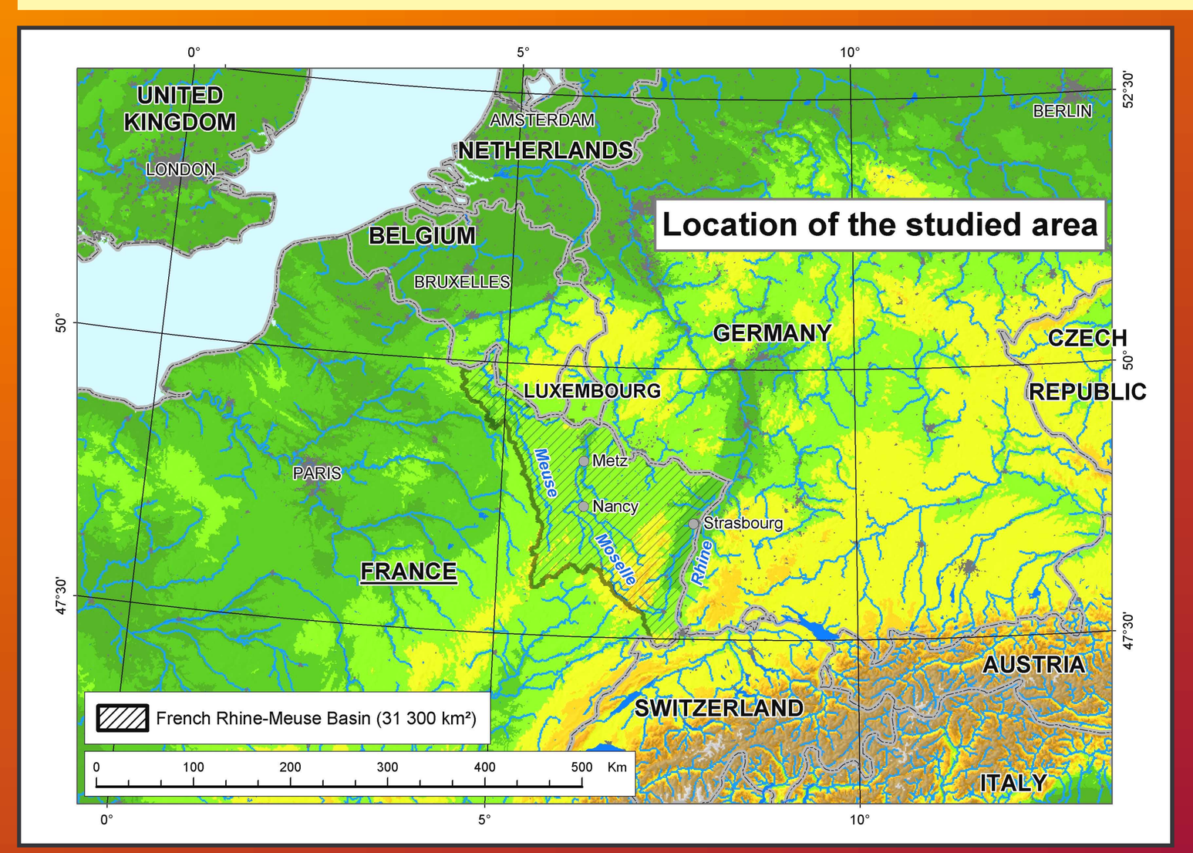
The summer 2003 hydrological drought has clearly shown the vulnerability of human activities exposed to water scarcity. Public authorities who have to monitor hydrological extremes should provide water resources assessment and forecasting tools. The objective of this research is to combine these two concerns through the development of a decision support system: PRESAGES. Low water levels generation being a long-time process, monitoring the monthly runoff production has been made with simple indicators. The long-term assessment of the worst case scenario can therefore be considered through modelling. If severe low flows may occur, short-range forecasts of daily mean discharges are proposed for the summer period.

1. CONTEXT AND OBJECTIVES



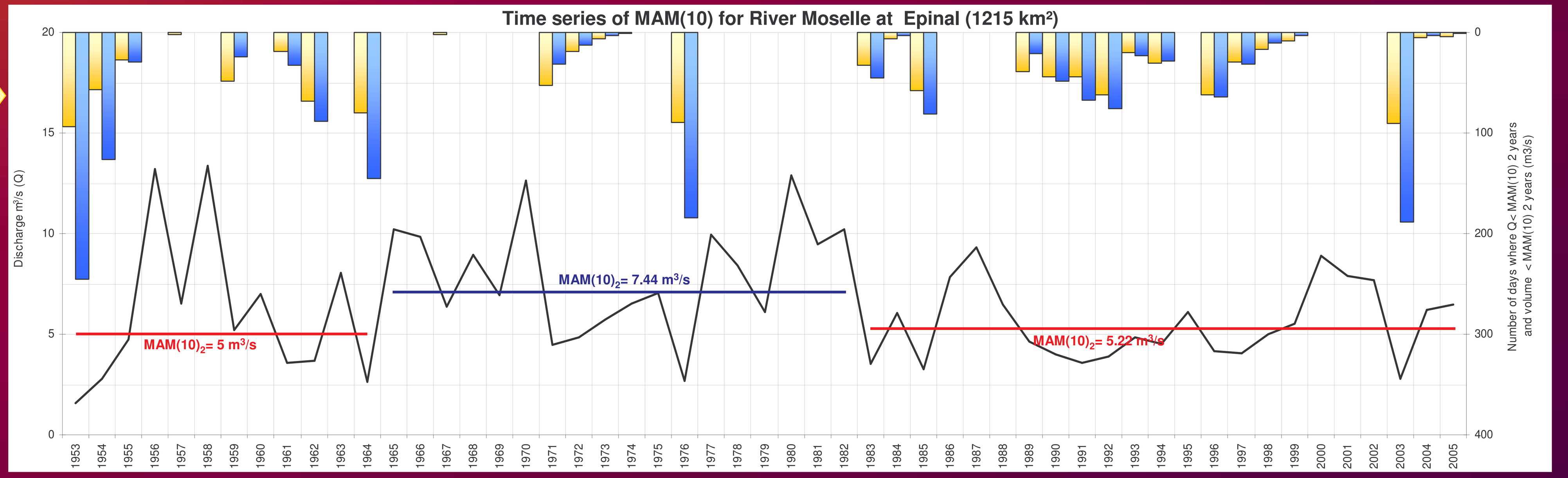
The domain of application of this study is the Rhine-Meuse basin in its French part (see the location map). The motivations of this research are to develop both tools to forecast and to evaluate low flows. Forecasting and prediction tools are developed for about 60 stations even though assessment tools are applied at 108 gauging site.

The particularly long genesis of low water allows long-term prediction. Low flows prediction is so realized by simple indicators before low water period in order to anticipate the risk in hydrological drought. Long and short-term forecasts are then proposed by using monthly and daily conceptual models. The main objective is to base all the methods on previous hydrological analyses.

Many methods have been developed to characterize streamflow drought. We prefer to favour FdF method as classical frequency analysis because this one consider the low water duration.

Stationarity and trends in hydrological data:

The Epinal long-term station presents the longest time series of discharges in the River Moselle catchment. The statistical treatment of the MAM(10), Mean Annual Minimum during 10 consecutive days, shows 3 periods : 1953-1964, 1965-1982, 1983-2005, determined by "jumps" of median (method of CUSUM). The most recent period is not exceptional compared to 1953-1964, but it appears that low flows are weaker then during the 70's.



2. CHARACTERIZATION AND EVALUATION OF LOW FLOWS

2.1. CHARACTERIZATION OF LOW FLOWS

The Flow-Duration-Frequency model (FdF) is used to characterize the severity of a low water. This model allows to consider the duration of low flows, from a statistical method (Galea & al.[1] 1998; 2000). Hydrological variables concerned are the MAM for various durations « d » (1 day ≤ d ≤ 30 days). MAM used were extracted from 1971-2000 (the longest period which is common to all gauging stations). FdF is a three parameters model :

SCALE PARAMETER

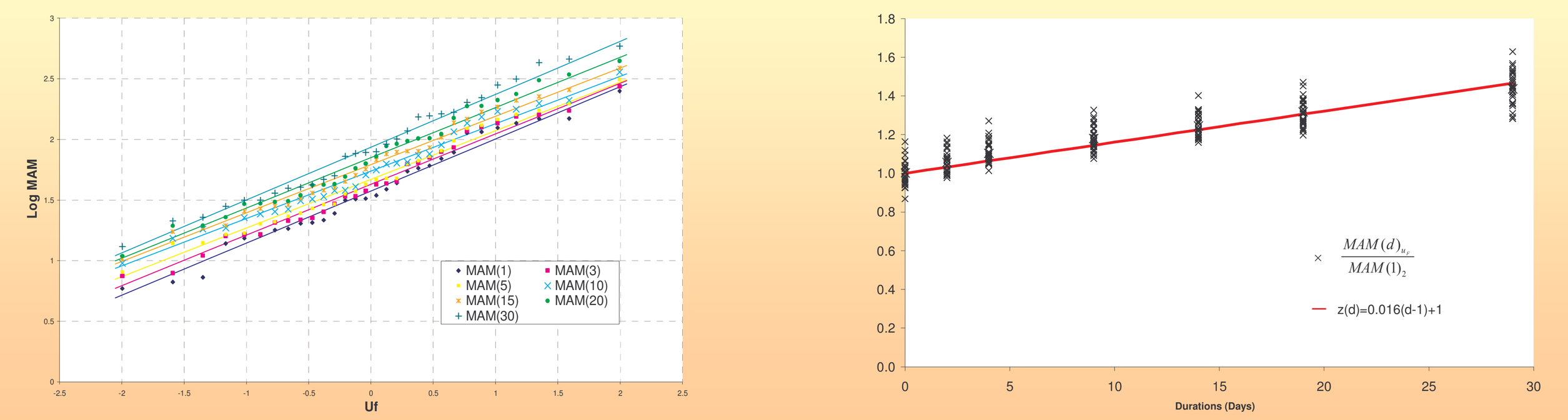
Distributions of MAM with various durations are adjusted to the two-parameters log-normal distribution. The parallelism observed between distributions of different durations means that a single slope can be calculated, independently from their durations. This single slope is determined by the "consolidated" standard deviation: S^C

NB: u_F are the reduced variates of Gauss corresponding to each non-exceedance probability.

DETERMINATION OF PARAMETERS OF FdF MODEL

$$MAM\ (d)_{u_F} = e^{S_C \times u_F} \times (a \times (d-1) \times MAM\ (1)_2$$

Example of the River MOSELLE at Epinal



The FdF model allows determination of the non-exceedance probability of any MAM values and any durations

LOCATION PARAMETER

MAM 1 day recurrence interval 2 years: $MAM(1)_2$

PARAMETER « a »

This parameter corresponds to the slope of the straight line (z(d)=a*(d-1)+1). It establishes the link between rapports of different durations of the MAM observed ($MAM(d)_{uf}$) and the MAM 1 day recurrence interval 2 years ($MAM(1)_2$).
The parameter « a » represents the theoretical decrease of discharges in periods of low flow.

FREQUENTIAL MAM(10) DATA BASE

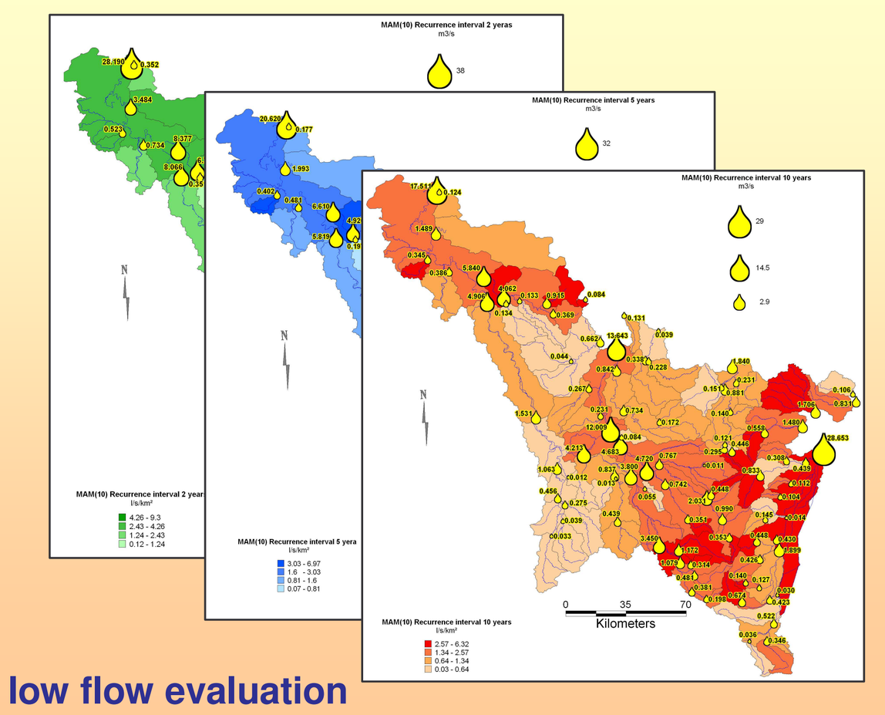
The MAM(10) is the most representative hydrological variable of low flow because lower durations may involve anthropic influences.
MAM(10)'s characteristic values of non-exceedance probabilities are calculated according to the formula of FdF model:

$$u_F = \frac{\ln(MAM(d)) - \ln[(a \times d - 1) + 1) \times MAM(1)_2]}{S^C}$$

Characteristic non-exceedance probabilities:
-F0.5 : recurrence interval 2 years
-F0.2: recurrence interval 5 years
-F0.1: recurrence interval 10 years

CARTOGRAPHIC DATA BASE

Rivers	Hydrometric stations	$MAM(10)_2$ (m³/s)	$MAM(10)_5$ (m³/s)	$MAM(10)_{10}$ (m³/s)
Albe	Sarralbe (Rech)	0.322	0.181	0.123
Alzette	Audun-le-Tiche	0.141	0.102	0.084
Amezule	Lay-Saint-Christophe	0.052	0.036	0.029
Andlau	Andlau	0.178	0.125	0.104
Aroffe	Vannes-le-Châtel	0.026	0.015	0.012
Bar	Cheveuges	0.726	0.472	0.377
Brenon	Autrey	0.032	0.017	0.012
Bruche	Russ ["Wisches"]	1.255	0.949	0.819
Bruche	Holtzheim [2] & Oberschaeffolsheim	0.890	0.546	0.399
Canner	Koenigsmacker	0.219	0.155	0.126
Chiers	Carignan	8.288	6.547	5.788
Chiers	Montigny	1.239	1.008	0.897
Chiers	Chauvency	6.801	4.858	3.973



This cartographic data base constitutes a reference for low flow evaluation

MAPS OF MAM(10)'S CHARACTERISTIC FREQUENCIES

A map of each MAM(10)'s characteristic frequency is made for the Rhine-Meuse basin. These maps represent specific discharges (l/s/km²) for all catchments (colored areas) and discharges (m³/s) at gauging stations (proportional symbols).

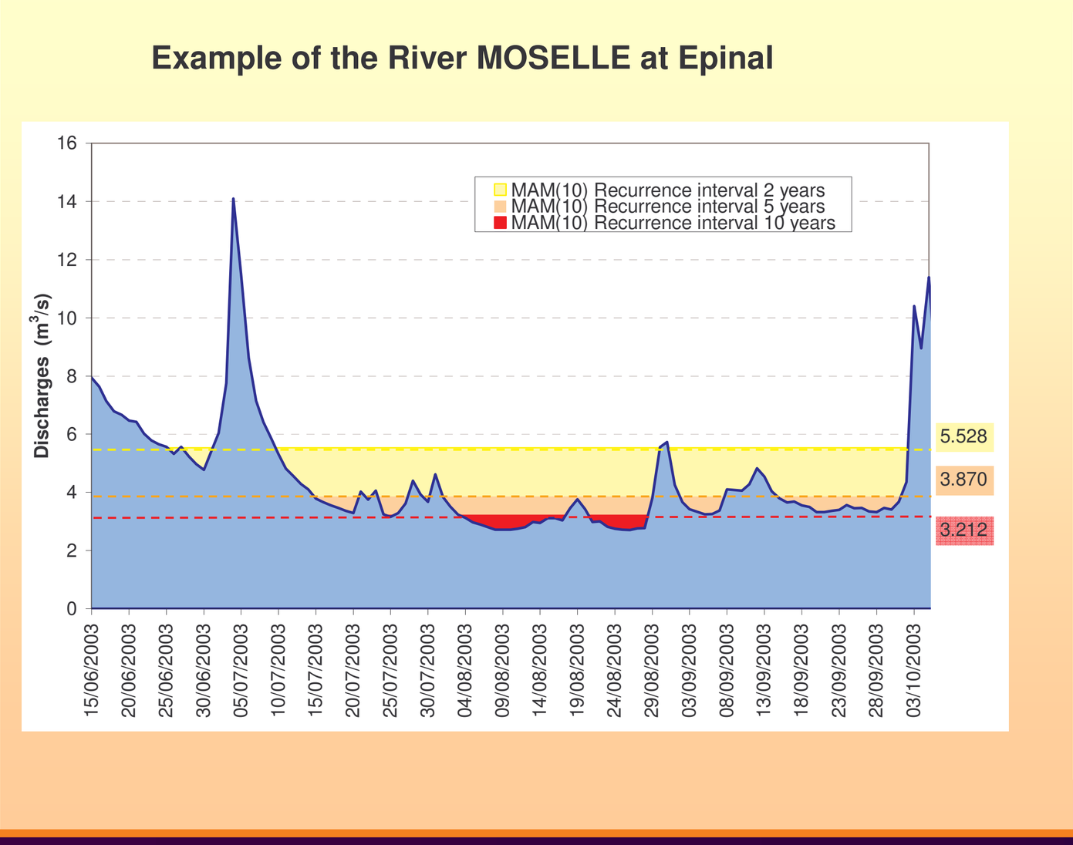
2.2. EVALUATION OF LOW FLOWS IN 2003

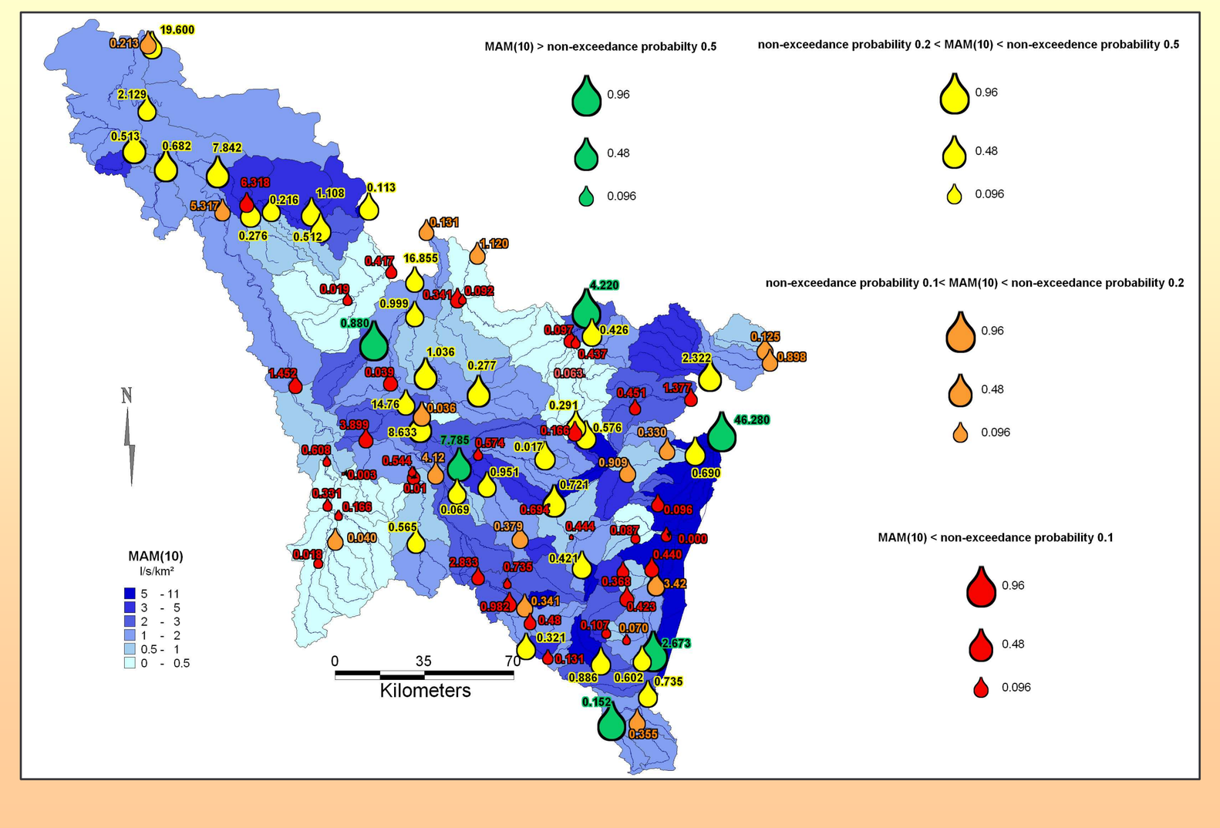
LOW FLOWS OF THE RIVER MOSELLE AT EPINAL IN 2003

The low flows of the River Moselle at Epinal in 2003 is particularly severe:

- 88 days have a value of discharge under the $MAM(10)_2$. The corresponding volume is 170 m³
- 64 days under $MAM(10)_5$ (38 m³)
- 23 days under $MAM(10)_{10}$ (7.5 m³)

Example of the River MOSELLE at Epinal





LOW FLOWS OF RHINE-MEUSE BASIN RIVERS IN 2003

This map represents specific discharges (colored areas) and discharges (proportional symbols) of the MAM(10) at gauging stations in 2003. Return periods of the MAM(10) are represented by the colors of the proportional symbols. They are calculated according to the FdF model equation.

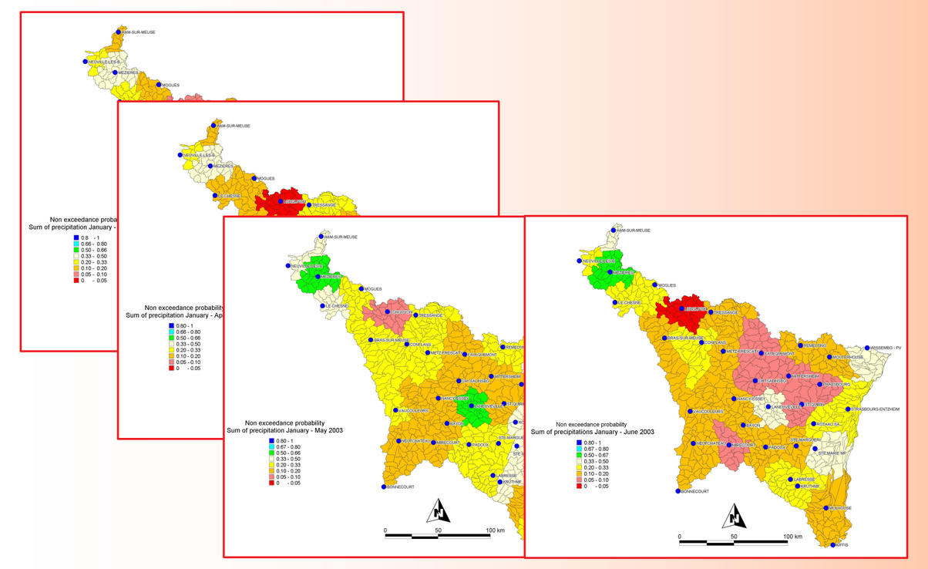
The low flow in 2003 is particularly critical for most of the Rhine-Meuse rivers. Return periods of the MAM(10) are higher than 5 years and they can even exceed 10 years for a lot of gauging stations. Only catchments with human influences present recurrence intervals equal or lower than 2 years.

3. LOW FLOW PREDICTION AND FORECASTING

3.1. SIMPLE INDICATORS FOR LOW FLOW ASSESSMENT AND TO ESTIMATE SEVERE LOW WATER RISK

I. 1. CURRENT FOLLOW-UP OF THE SITUATION BY SIMPLE INDICATORS

Maps about the frequency of monthly precipitations plurality: an information to monitor current situation



For low flow forecasting, cumulated precipitations recorded during the recharge period are an interesting indicator for basins having important aquifers.
We propose a tool which calculates the frequency of monthly sum precipitations in order to produce frequency maps months after months. The statistic of precipitations for one single month shows little interest. That is why we study the plurality of precipitations for several months, an evaluation of which can thus be realized starting from a method adapted from the QdF model (Galéa, 2000). A tool calculates the non-exceedance probability of a plurality rainfall (from January to March total precipitations to the ones from January to June) and draws the corresponding map. Public authorities are especially interested by this kind of maps.

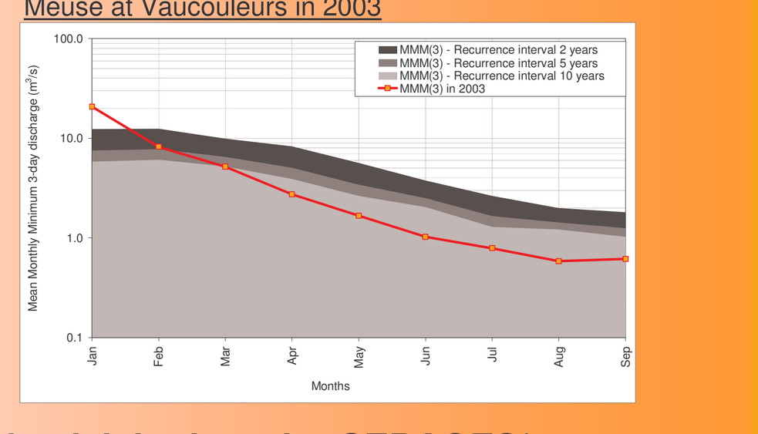
Follow-up of the Mean Monthly Minimum (3-day)

For each river the device proposes references values based on the Mean Monthly Minimum (3-day). So for each month a data base of following references is available:

- MMM (3-day) – Median
- MMM (3-day) – Non-exceedance probability 0.2
- MMM (3-day) – Non-exceedance probability 0.1

Current hydrological situation can be compared every month to these low frequencies.

Example of MMM (3-day) follow-up: The River Meuse at Vaucouleurs in 2003



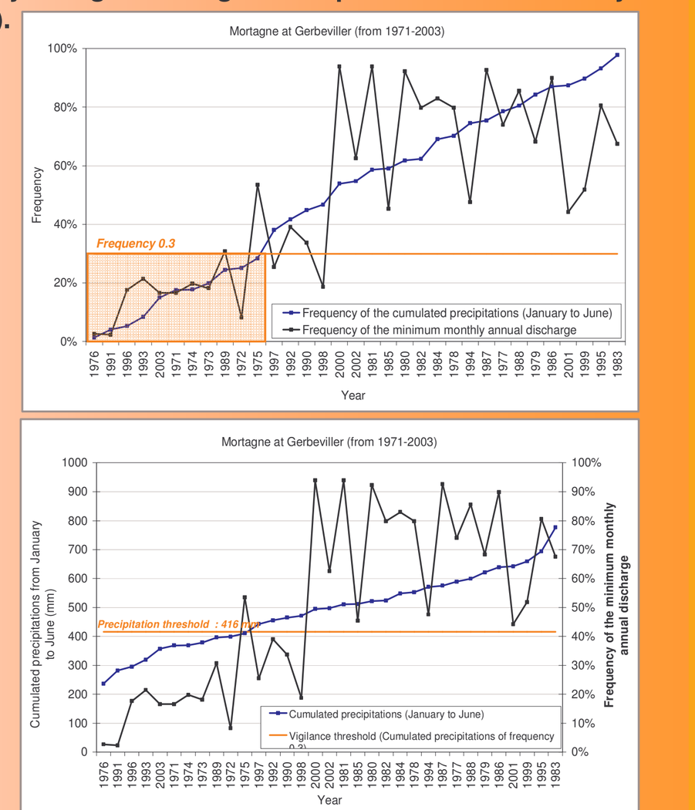
I. 2. A simple predictor to evaluate the possibility of a risk in drought: SEPAGES*

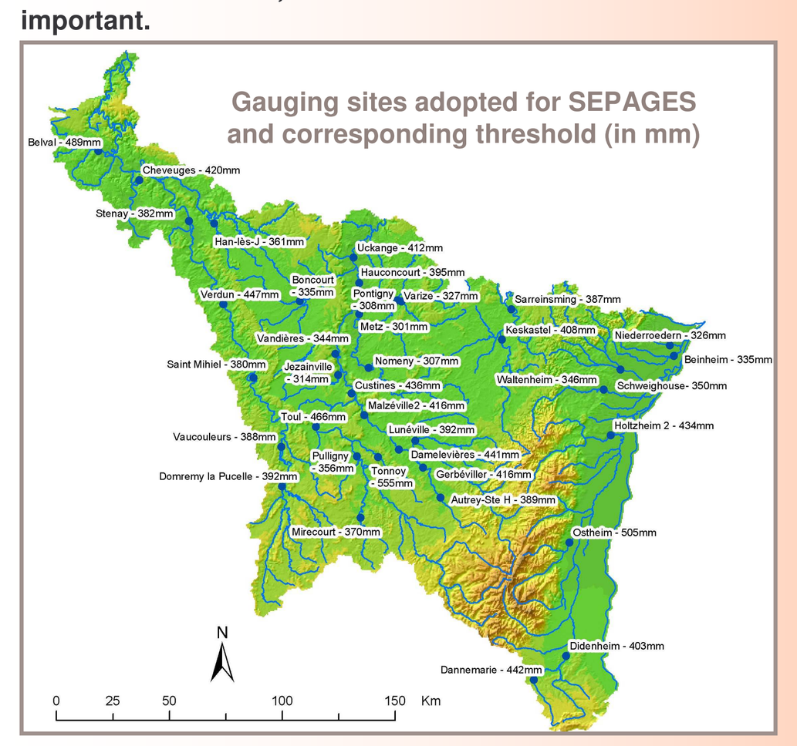
Our main motivation is to develop a simple indicator to evaluate the risk in hydrological drought. This predictor is exclusively founded on the total precipitations of winter and spring (period of recharge).

The frequencies of the total precipitations from January to June are compared with the frequencies of the minimum monthly annual discharge to determine if these two variables are related. The figures show a concomitant increase between them : The most severe low water levels, lower than a 5 years' recurrence, are often related to particularly weak winter and spring precipitations.

Many tries show that among all the frequencies of total precipitations from January to June, the frequency 0.3 (no-exceeding) best explains the severe low water levels. This threshold is thus adopted and its value is calculated for each gauging site (cf. map).

If the total precipitations observed between January and June are lower than this threshold, the risk that a severe low water level appears is important.



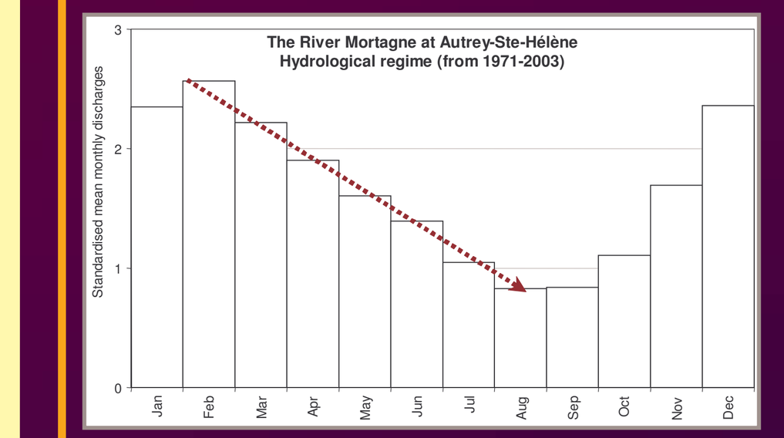


This observation testifies the inertia of the basins. Indeed they store rainfall during high flow period and restore it in low flow period. Thus this tool only applies to the basins which have big aquifers: for the impermeable basins for example in the crystalline Vosges, the rainfall deficit of the beginning of the year can largely be compensated by abundant estival precipitations.
The SEPAGES tool is tested for the year 2003 which has been particularly severe in France. For this year, this indicator has announced a severe low water level for all the stations. For only 16% of the cases, the low water level observed has not been particularly severe. Let's note that they are generally rivers which benefit from anthropic influences.

3.2. ANALYSIS OF RECESSION TO ESTIMATE MODEL BASEFLOW PARAMETERS

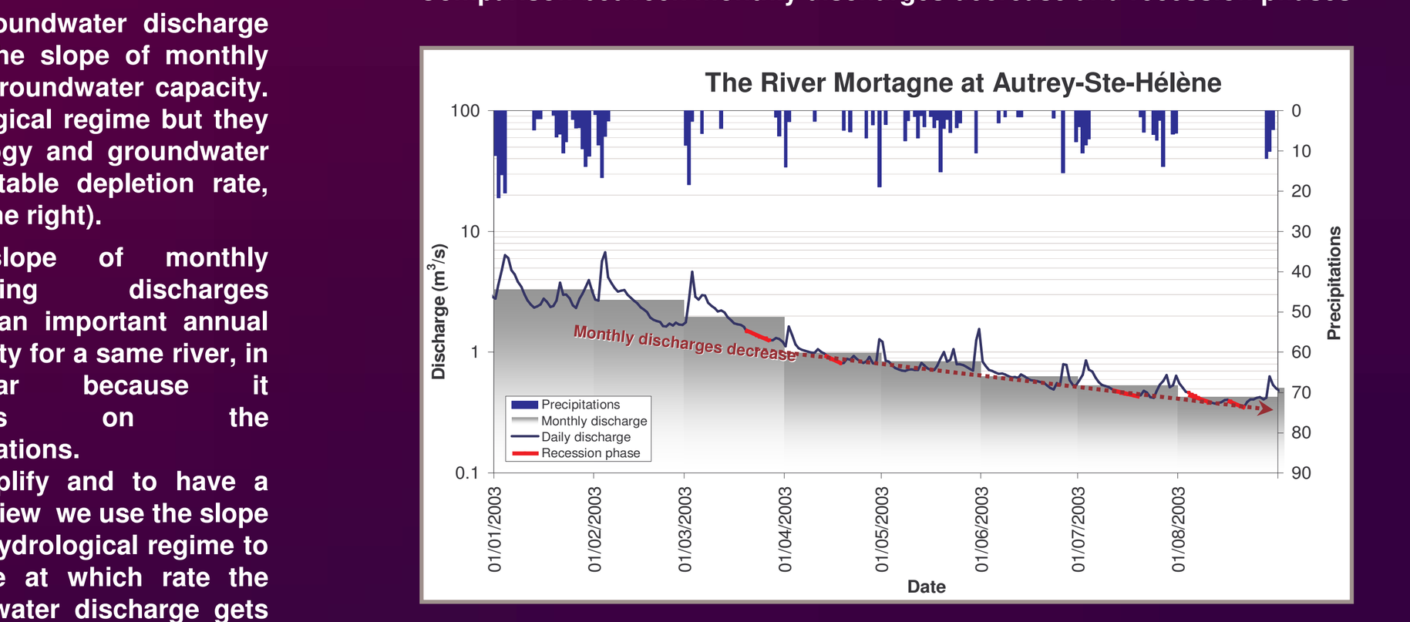
Monthly basis of groundwater discharge

Monthly river discharges could in no case be liken to groundwater discharge because it is always mixed with overland flow. However, the slope of monthly discharge decrease during the low flow period is related to groundwater capacity. Indeed, all the basins in this study present the same hydrological regime but they are more or less moderate. This can be explained by geology and groundwater capacity. Thus, we propose to estimate the groundwater table depletion rate, starting from the decrease of monthly river discharge (see on the right).



The slope of monthly decreasing discharges shows an important annual variability for a same river, in particular because it depends on the precipitations.
To simplify and to have a global view we use the slope of the hydrological regime to estimate at which rate the groundwater discharge gets empty (see on the left).

Comparison between monthly discharges decrease and recession phases



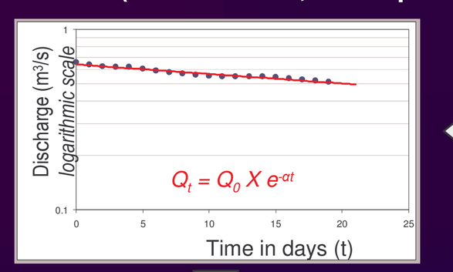
Daily basis of groundwater discharge : Recession analysis

With a daily basis it is possible to determine precisely the groundwater depletion rate by making a recession analysis. However, to avoid the selection of overland flow the choice of the recession discharges must be managed by rigorous criterions. The selection follows three steps:

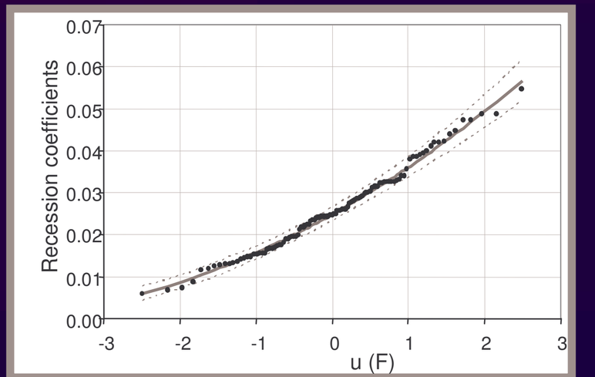
- Step 1: First selection of the decreasing discharges during a period of at least 5 days with no precipitations.
- Step 2: Suppression of overland flow according to the following formula: $T=A^{0.2}$ (*T: overland flow time in days & A: basin area;* Rutledge[2], 1994). Discharges which are higher than normal annual discharge are also removed.
- Step 3: Suppression of the last doubtful discharges (overland flow, anthropic influence, etc.)

Recession discharge data base

Determination of the recession parameter of the depletion curves according to Maillet form

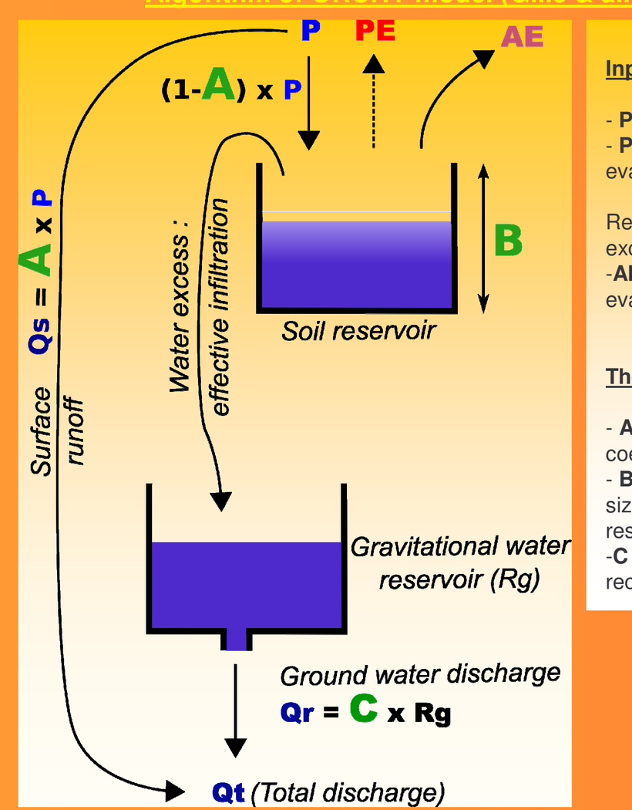


Depending on the episodes, the recession parameters are variables for a same river. For this research the main objective is to determine the average depletion curve for each river, in order to make forecasts by extrapolation of this curve. A lot of methods such as «master recession curve…» etc. have been developed to determine an average value.
The good quality recession parameters adjustments allows a statistical analysis for each river. The statistical analysis has advantages because it makes it possible to calculate frequency recession parameters which are used in forecasts to draw enveloping curves.



3.3. MONTHLY WATER BALANCE MODEL FOR LONG-TERM FORECASTING

Algorithm of ORCHY model (Gille & al.[3], 2003)



Input data :
- P : precipitations
- PE : potential evapotranspiration

Results (discharges excepted) :
- AE : actual evapotranspiration

The parameters:
- A : a runoff coefficient
- B : a maximum size of the soil reservoir (in mm)
- C : a monthly recession parameter

Calibration and validation of the model

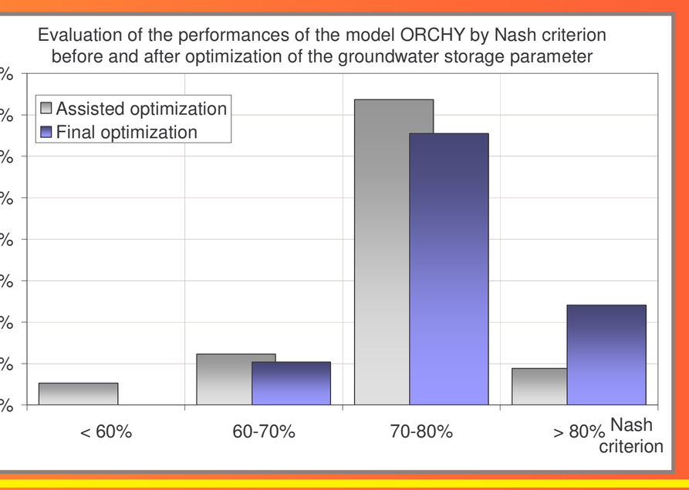
The previous analysis of monthly groundwater discharge is used to help the optimization of the gravitational water reservoir parameter. This approach is included in what we call the "assisted optimization" (Gille & al.[3], 2003).

After an optimization the parameters lose their representativeness. That's why we choose to use values directly resulting from a previous hydrological analysis. The purpose of the prior estimation of some parameters is to preserve some representativeness of the model's results. The objective is to avoid as much as possible the iterative processes which are frequently used. As the step of optimization is not given up, we call that "the assisted optimization".

Values calculated from the slope of the regime are introduced in the monthly model in order to initialize the C parameter. In certain cases this value has been a little modified (in fact the slope of the regime do not correspond exactly to groundwater discharge).

-« Assisted optimization » means that the model parameters are optimized except for C which keeps the value estimated from the regime slope (we can see that the results are not so bad; the estimation of the gravitational water reservoir parameter is not so far from reality).

-« Final optimization » means that all the parameters are now optimized.



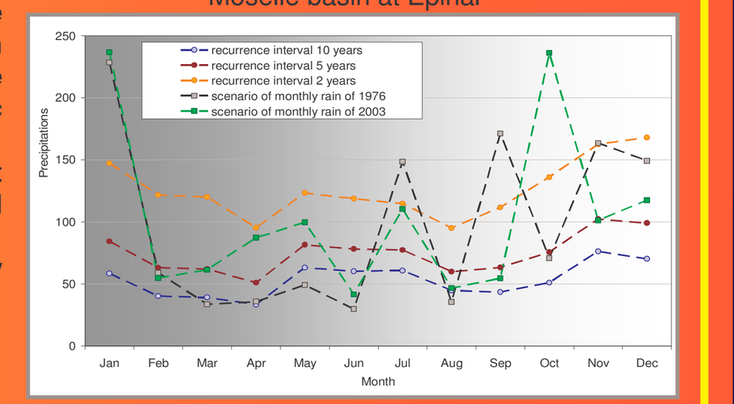
The performance of the model is evaluated by using the Nash criterion (from the logarithm of the values). The figures show the repartition of the Nash criterion for the 60 stations.

Let's note that stations which present a Nash criterion inferior to 60% are generally rivers which are influenced by anthropic activities.

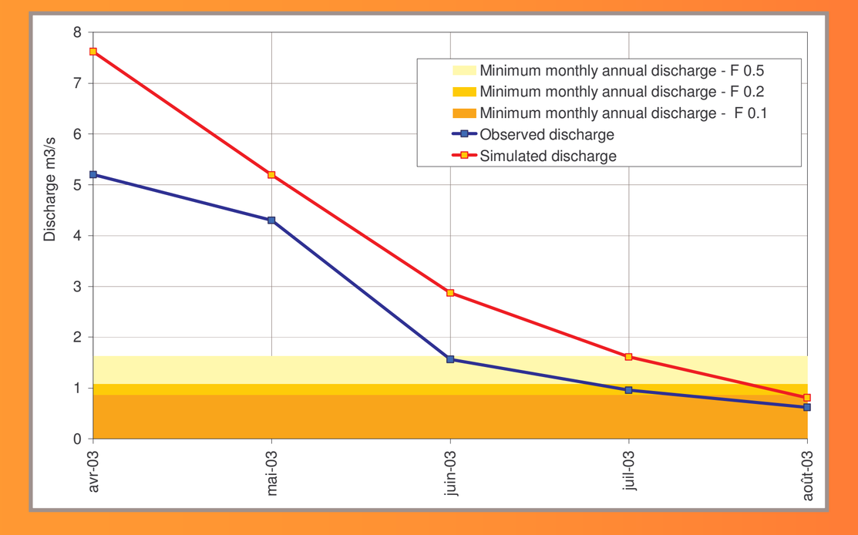
Long-term forecasting

The hydrological forecast depends wholly on weather forecast. The particularly long genesis of low water allows long-term forecasting, in the term of several months. As seasonal forecasts don't propose quantified precipitations, the models must be supplied by stochastic scenarios.
The monthly model functions in continuous in the course of the year. It is supplied by observed precipitations and evapotranspiration until April and after then stochastic scenarios are introduced.
For each catchment, we dispose of a data base with monthly frequency precipitations and mean evapotranspiration.

Example of frequencies monthly precipitations: The Moselle basin at Epinal



Example of long term forecast : The River Moselotte at Zainvillers (2003)



Generally 2 years recurrence interval precipitations are used to make the first forecasts. Indeed, if with these "normal" values the simulated discharges have been proved very low, the risk in sever low water level must be taken seriously (see on the left the case of 2003).

If severe low flows may occur, short-range forecasts from a daily model are proposed for the summer period. It means thus that the daily conceptual model do not functions in continuous in the course of the year, but just if an hydrological drought may occur.

The gravitational water reservoir of the daily model can be initialized from the level of the monthly gravitational water reservoir.

3.4. DAILY HYDROLOGICAL MODEL FOR SHORT-RANGE FORECASTING

Calibration and validation of the model

For the daily conceptual model the "assissted optimization" approach presents a bigger interest than the monthly model. In fact the daily basis recession analysis allows the precise determination of the recession parameter. This one can directly be introduced in the model. So the recession parameters emerging from the previous recession analysis are directly introduced into the daily hydrological model after using this formula:

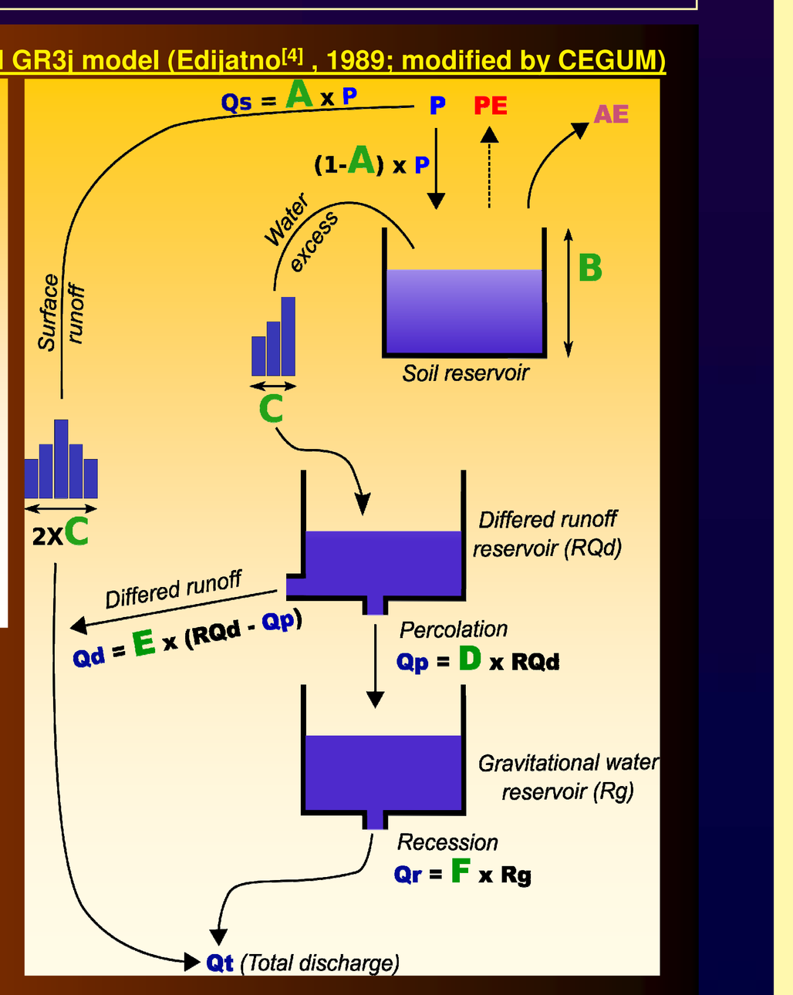
$F = 1 - e^{-\alpha}$ *(which α is the Maillet's recession coefficient)*

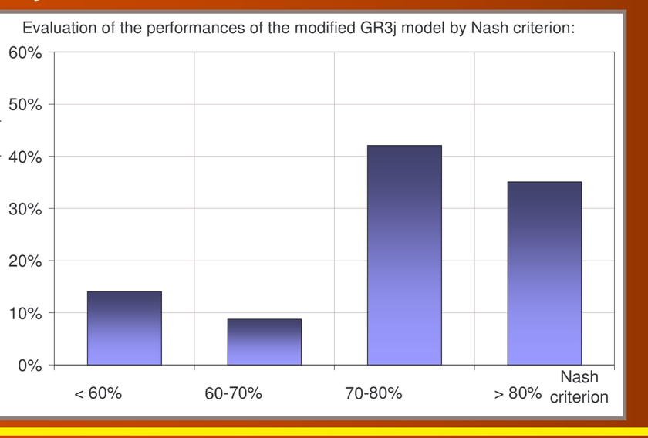
The model uses in fact a linear equation to calculate the groundwater discharge coming out of the groundwater storage (modification of GR3j which initially uses a quadratic equation). The other modification of GR3j concerns the addition of a reservoir of differed runoff. So F, calculated from the recession analysis, is directly introduced to manage the gravitational water reservoir parameter without any future modification.

Algorithm of modified GR3j model (Edijatno[4], 1989; modified by CEGUM)

Input data (the same one as for the monthly model)

The parameters :
- A : runoff coefficient
- B : maximum size of the soil reservoir (in mm)
- C : unit hydrograph duration
- D : percolation coefficient
- E : emptying coefficient of the differed runoff reservoir
- F : recession parameter





Short-term forecasting

Public authorities are interested by the most critical situation, this is why daily forecasts are made assuming that no precipitation should arise.

Estimation of dry-spell risk

To forecast the discharges in *d* days, we make the assumption of *d* consecutive days without rainfall or significant rainfall. It is so necessary to know the probability of occurrence of *d*. There are 2 ways to calculate it (Sharma[5], 1996 ; Bernier[6], 1963).

Probability distribution of duration of all the dry-spells [5]

Simple Markov process: $P(d \le i) = 1 - pp^{i-1}$
where:
- d is the duration of the period
- pp is the conditional probability of one dry day succeeds another dry day

Example of non-exceedance probality of the dry-spells durations

Duration (days)	Precipitation stations: Padoux	Precipitation stations: La Bresse
1	29%	27%
2	50%	47%
3	65%	61%
5	82%	79%
7	91%	89%
10	97%	96%
15	99%	99%
Proportion of dry days	45%	51%

Probability distribution of duration of the dry-spells (P < 3mm) higher than 5 days [6]

Exponential distribution: $P(d \le i) = 1 - e^{-\mu d}$
where:
- d is the duration of the period minus 5 days
- μ is the location parameter: $\mu = \frac{1}{d}$

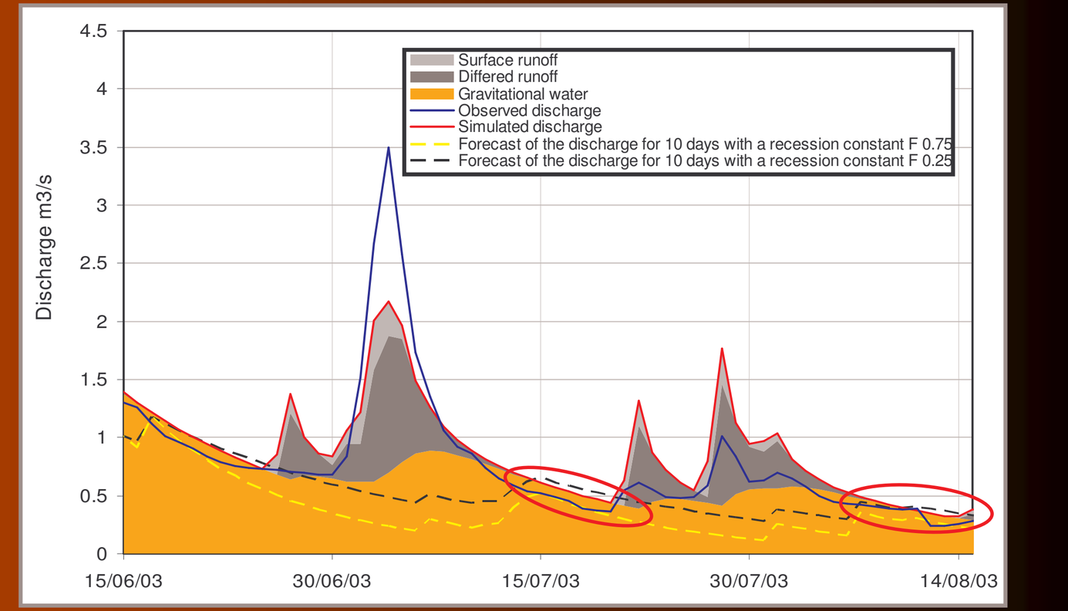
Example of non-exceedance probality of thedry-spells durations (P<3mm) higher than 5 days

Duration (days)	Precipitation stations: Padoux	Precipitation stations: La Bresse
6	14%	15%
7	27%	28%
8	37%	39%
9	46%	48%
10	54%	56%
15	79%	81%
20	90%	92%

Example of short term forecast : The River Moselotte at Zainvillers (2003)

The objective is to draw an interval defined by recession parameters of frequency 0.75 and 0.25. The chosen term of forecast is 10 days which is a long duration for a dry spell.

In this example the weaker observed discharges are in the interval.



SIMPLE INDICATOR
ASSESSMENT TOOLS
LONG TERM FORECASTING TOOLS
SHORT TERM FORECASTING TOOLS

FOOTNOTES & REFERENCES

Footnotes
- *PRESAGES : French acronym for « PREvision et Simulation pour l'Annonce et la Gestion des Etiages Sévères »
- *SEPAGES : French acronym for « SEuil de Précipitations pour l'Annonce et la Gestion des Etiages Sévères »

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