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Design of dry dams at watershed scale : lessons learnt from sensitivity analyses using a simple but consistent rainfall-runoff model

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Abstract

We investigate the assessment of the overall efficiency of a set of dry dams on flood mitigation. To ensure the spatial consistence of our flood scenarios, we used a stochastic rainfall simulator to generate rainfall fields representative of the climatology of a 150 km² catchment near Lyon. The influence of the variability and spatial structure of the rainfall on the choice of the best locations for a set of dams was previously studied using a simplistic rainfall-runoff model. The estimated optimum is highly dependent to the choice of the sub-sets of events, confirming that assessments based on a limited number of scenarios are heavily flawed. A large set of events, representative of the regime, is indispensable. For further investigations of this approach, a cascade-of-reservoirs conceptual model now computes the rainfall-runoff transformation and can optionally be chained to a 1D-hydraulic models. This increases both results consistence and computation-time, however sensitivity analyses remain accessible. We studied optimisation of outlet dimensions in addition to dam location. The effect of a given solution at a given point is represented over a wide range of flood probability, versus peak flood return period, but also versus peak volume return period, which strongly influences the mitigation potential.

Keywords: dry dams; flood management assessment; stochastic rainfall scenarios

Introduction

Flood retention structures appear an interesting solution for mitigation because they act upstream the places to protect instead of evacuating the flow and transferring the flood hazard downstream. Besides, they are potentially less perturbing for the ecosystems than dikes or river training (e.g. Poulard et al., 2010). To take advantage of all the reasonable retention opportunities, a project can include several structures spread over the catchment. Figure 1a presents such an example with three series of off-line flood storage basins in the Savoureuse catchment (Eastern France). From a hydrological point of view, the design consists in defining the characteristics of the outlet and inlet (for off-line structures) to obtain the required mitigation effect. When several structures are projected, the design should be coordinated at catchment scale, considering the whole regime (e.g. Poulard et al., 2009a and b). Modelling is a good tool to compare hydrographs and flooded surfaces with and without the projected structures, but when working a catchment's scale the difficult point is to define consistent input scenarios. One solution is to use observed time-series, whether discharge or rainfall time-series. Observed time-series are also important to calibrate the models. However, to cover a wider range of return-periods, it is necessary to build-up scenarios, including rare events, with a plausible spatial repartition of the input in the sub-catchments.

There are two main types of approaches to define scenarios : discharge scenarios or rainfall scenarios. Figure 1a illustrate how discharges scenarios can be built by combining hydrographs corresponding each to a return period : one hydrograph is highlighted in orange for each branch. Taking into account the space correlations is more and more difficult when the number of branches increases. This is why we investigate here the other approach, with distributed rainfall scenarios generated by a stochastic method, and fed into a simple but consistent rainfall-runoff model.

We have two objectives. The first one is short-term : illustrate how the variability of rainfall, intra-event (spatial heterogeneity) and inter-event, impact the diagnosis of mitigation efficiency. The second objective is to contribute to the development of a diagnosis methodology using this approach, in parallel to the current developments of the rainfall generator.

A first series of tests using a simplistic hydrological model already yielded much information and pointed out some errors that can be made when the diagnosis is based on too few events (Poulard et

al., 2009c). We carried on using another hydrological model, and completed the tests by new simulations, and in particular sensitivity analyses.

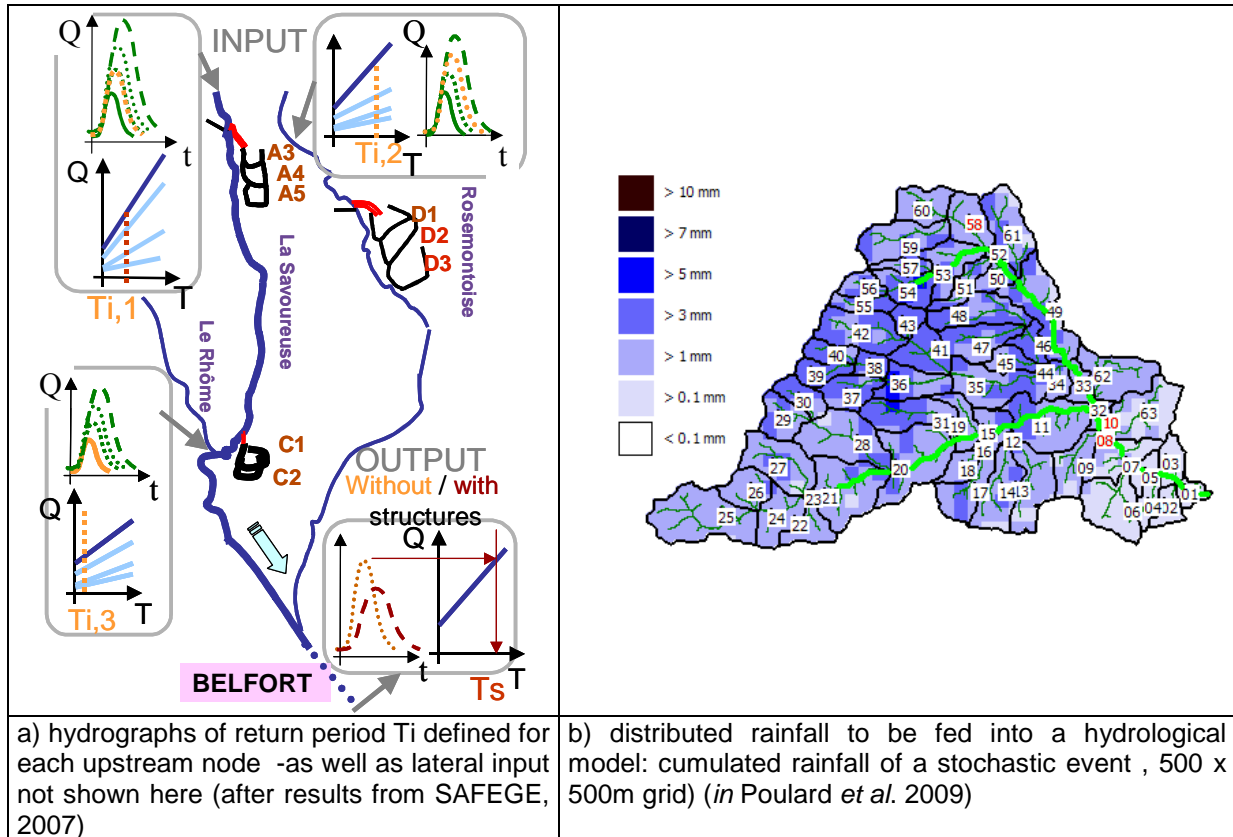


Figure 1. illustration of two approaches to define an input scenario over a catchment

Methodology applied: the chain of models

Our approach is based on three modules (Figure 2) :

- A stochastic rainfall generator calibrated with respect to the available local rainfall data, produces rainfall fields respecting the space-time properties of local rainfall ;
- A semi-distributed hydrological module takes as input these rainfall fields and converts them into runoff, until the main river network ;
- A hydraulic module takes as input the runoff, computes the hydrographs in the absence of structure and in the presence of projected structures to quantify the effect of these structures.

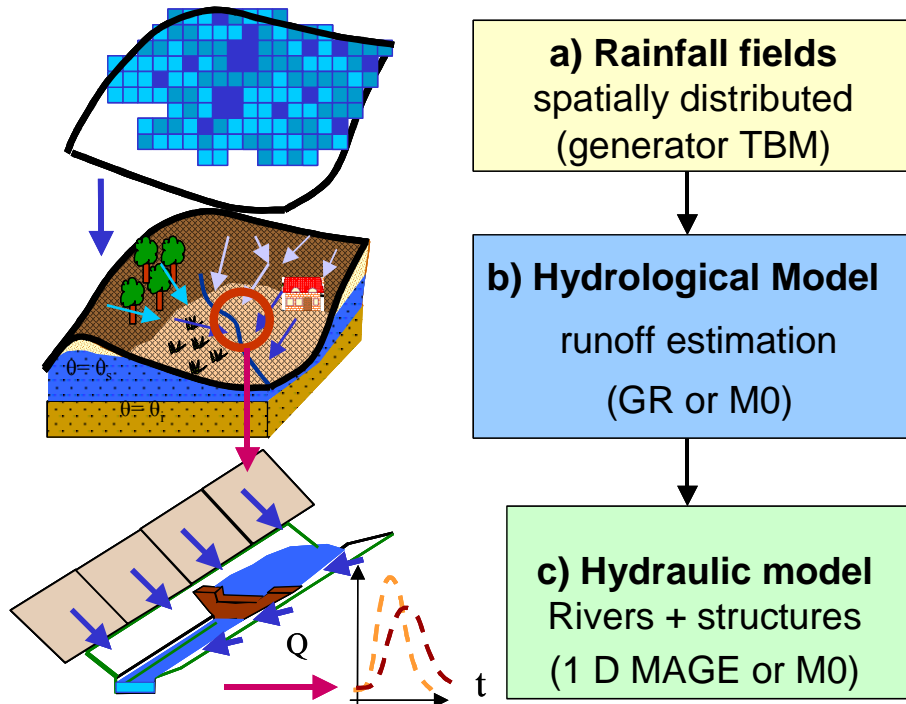


Figure 2. principle of our chain of models

a) The rainfall generator

The rainfall generator is based on the turning bands method, according to the perspective presented in Ramos *et al.* (2006). First, the model is calibrated on the case-study using the available local rainfall time-series. The major drawback of this present version is the representativity of rare events, well-above the intensity of observed ones. Climatic conditions leading to extreme events can be very different from the observed ones. And yet, extreme events are absolutely necessary for dam efficiency assessment. Thus, generation of extreme events is to be improved, for instance by integrating additional information in the model.

The advantage of this approach is to produce events reproducing the natural variability :

- within a event : the space-time variability properties are guaranteed by the calibration phase.
- between events : the model can simulate as many rainfall fields as requested, thus producing a large sample of events

The module also allows conditioned simulations : stochastic rainfall fields with given values in a given set of points, corresponding for instance to observed values.

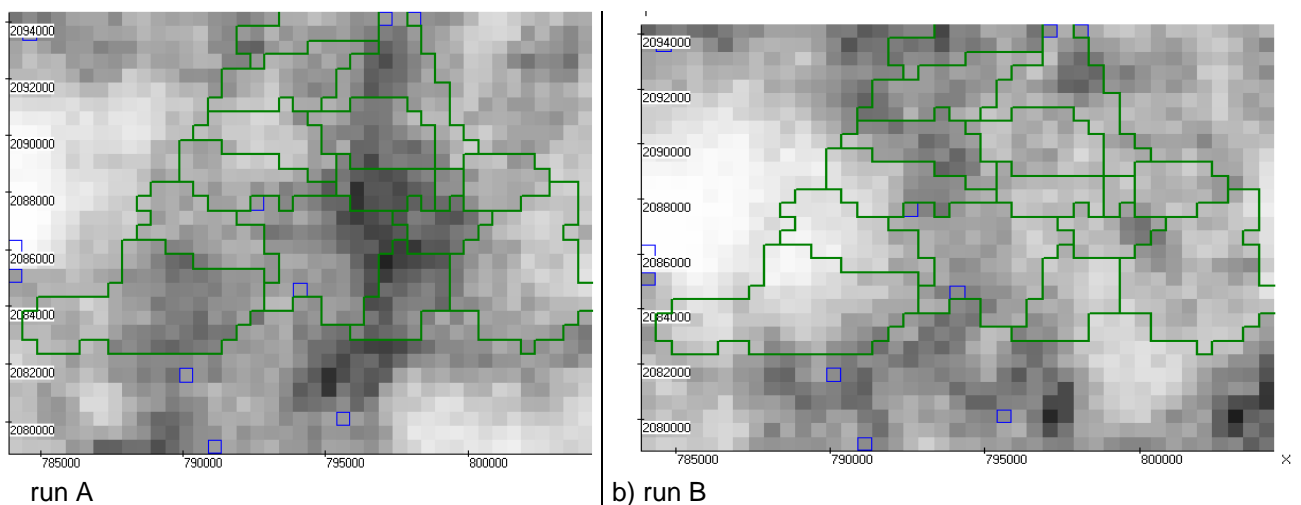


Figure 3. examples of rainfall generator outputs– two different conditioned simulations for the same conditions at a given time-step (grid elements with imposed values are in blue)

b) Hydrological models

Since our objective was to test a methodology, and not to obtain precise results for a given project, and moreover to carry out sensitivity analyses, we needed an easy-to-use model meeting the minimum requirements to reproduce hydrographs all over the watershed, with a minimum computational time (Figure 4). In the M0 version, described in Poulard et al., 2009, we implemented a very simple model, mainly based on a mass-budget. The computation units are 63 subcatchments elements (Figure 1b). In version M1 we now use a semi-distributed conceptual reservoir model, GR (Javelle et al., 2008), which allows to better reproduce the hydrographs.

c) Hydraulic models

Dry dams can be added at any of the elements outlets ; the parameters are dam height, bottom outlet dimensions and the geometrical shape of the bowl. In version M0, there is no routing delay ; outflow is computed from water stage behind the dam with a standard. In version M1, we can use the same module as in M0 or MAGE, a 1D hydraulic model based on the shallow-water equations (Giraud et al., 1997).

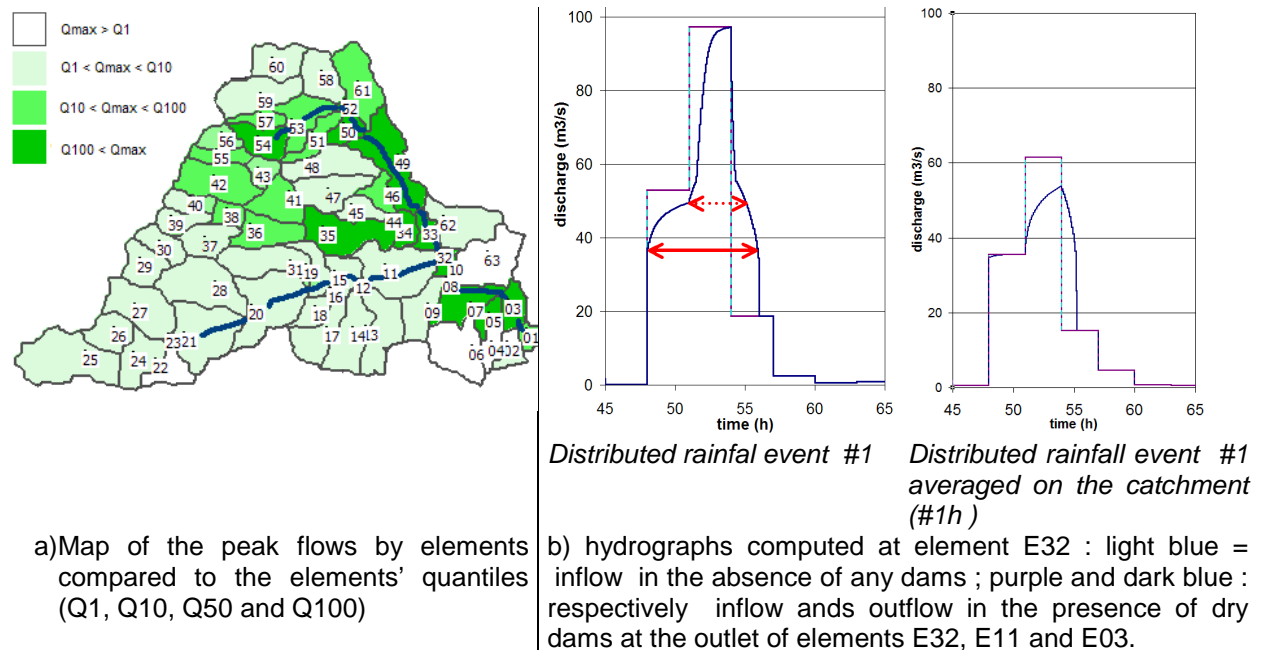


Figure 4. outputs of the model (M0 version) for one distributed rainfall event

The model M0 may seem too simplistic, nevertheless it provides the required information : cumulative rainfall maps, peak floods maps and hydrographs at each element's outlet (Figure 4) ; the trends are correct and this is satisfactory for our purposes. To avoid that the extreme simplicity cast doubts on our results, we decided to use in a parallel more precise modules, M1. However, we insist that the focus of our study is the definition of the input, and how flaws in the definition of this input will inevitably lead to erroneous conclusions, however excellent the rainfall-runoff transformation modules.

d) Computation of an indicator and optimisation procedure

Whether with M0 or M1, the chain of models can estimate the hydrographs in the present state and in the presence of 1 to 6 dry dams.

To compare solutions, or to carry out optimization procedures, a quantitative indicator is needed. Investigation of possible formulas highlighted the necessity of for an indicator to be defined at catchment scale but also at the scale of the regime. Choosing the best solution for one given event is absurd. Moreover, since the M0 version runs very fast, we implemented an optimization procedure based on this indicator, to identify the set of 3 dams leading to the maximum for one rainfall scenario or a set of several rainfall scenarios.

In this communication, we will present results obtained by an indicator representing the reduction of flooded area, weighted in some cases by a coefficient depending on land-use.

With version M0, the flooded area cannot be estimated, so we used a simple formula to mimick this value, assuming the flooded area in each element was proportional to the peak flood reduction and length of the element.

$$J2 = \frac{1}{N} \sum_{i=1}^N w_i \sum_{k=1}^{63} f(\Delta Q_k; l_k) c_k \quad (\text{Eq. 1})$$

Where : w_i are weight coefficients for each of the N rainfall events ;

c_k are weight coefficients for each of the 63 elements, depending on the land-use.

The test-case

The test-case is the 144 km² Yzeron catchment (France) ; the river flows into the Rhône just South of Lyons (Figure 1b, Figure 4a). This catchment was already used for previous studies, and in particular for the calibration of a hydrological distributed model, Marine (Estupina-Borell, 2004) coupled with MAGE. The existing results (e.g. Chennu, 2008) were useful to analyze and validate our results.

Rainfall data

To calibrate the stochastic rainfall model, we selected raingauges, in or nearby the catchment, which provided the longest simultaneous time-series. This reduced the data to 5 continuous time-series from 1985 to 1997, with an hourly time-step. The analysis of the discharge time-series concluded that the most important events regarding flood hazards were 72h-events, and that a time-step of 3hr on a grid of 500mx500m (Figure 1b) were sufficient to reproduce flood hydrographs. The generator then simulated 9000 events, representing 9 major events per year over 1000 years.

Discharge data

The 2 gauging stations on the main river are respectively Craponne, operating since 1969 (48 km²) and Taffignon, since 1988 (129 km²).

From a hydrologic analysis, we estimated the flood quantiles at Craponne and Taffignon. The comparison of the time-series at both gauging stations shows that the main tributary, which flows into the Yzeron between Craponne and Taffignon, has a different specific discharge. However, in the present study, we estimated the quantiles all over the catchment from the quantiles at Craponne by a Myers formula,

$$Q_{Yo}(BV_j) = Q_{Ti}(Craponne) \left(\frac{S_{BVj}}{S_{Craponne}} \right)^{0,8} \quad (\text{Eq. 2})$$

where S are the catchments' surfaces.

If the real catchment, only a limited locations are suitable for dry-dams ; however, since our purpose was to investigate the spatial effects we allowed to place dry dams at any of the elements outlet. Conversely, to limit the number of degrees of freedom, we chose to fix once and for all the dimensions of all the bottom outlets of the dry dam, to allow an outflow proportional to the annual quantile of the peak flood subcatchment.

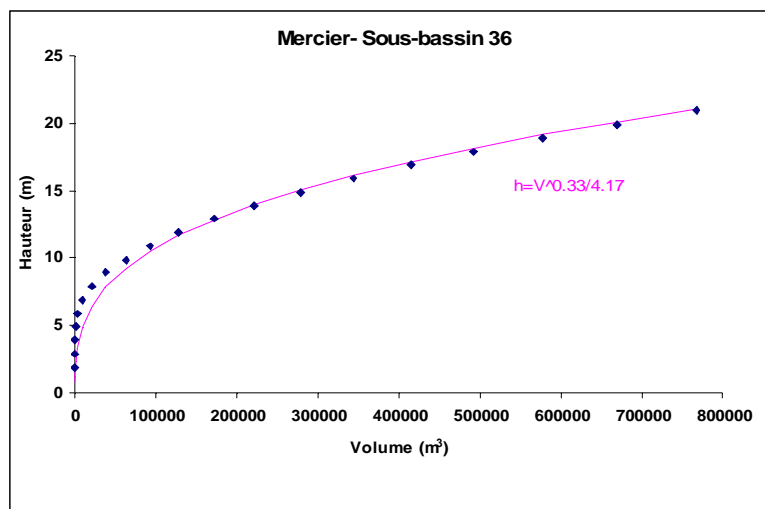
Topographical data

For the previous studies, we had collected topographical information, and a model of the river network built with the MAGE software was available.

For the M0 version, with no routing procedure, we used the following formula for the dams' bowls :

$$h = \frac{V^{0,33}}{k} \quad (\text{Eq. 3})$$

where h is the stage, V the volume and k is a form parameter,. The parameter was set at 4, and we tested on real topographical data at 8 sites that is was a satisfactory value, except for the last downstream reach.



blue dots : topographical data

red line : best fit for Eq. 3

calibration result : $k = 4,17$

Figure 5. calibration of the shape parameter k for the stage-volume relationship (Eq. 3) for element #36

Other data : soil, land-use and previous flood damages

Soil data was available and used to calibrate a hydrological model including infiltration on this same catchment in (Chennu, 2008). However, they were not used in this present work. In M0 no infiltration is taken into account, and in M1 the model parameters are calibrated, not estimated from physical data. Very little information is available so far about flood damages, and economical assessment is therefore difficult to undertake. However, land-use maps are available, and we can at least implement weight coefficients to illustrate that some gains in terms of flooded areas are more interesting in some places than in others.

Results

The interface presented in Figure 6 gives an overview of the procedures. The operator chooses its modules (here, M0), selects one or a set of rainfall events (top left), chooses locations for up to six dry dams (top right) or chooses an optimization procedure. The screen shows an on-going optimization procedure, with the indicator being computed for each set of 3 dams and displayed if the new indicator value improves the current maximum.

A rationale was defined to answer our questions, and in particular :

- is it necessary to take into account the rainfall spatial heterogeneity to correctly assess the mitigation effect of a set of dams ;
- how many rainfall scenarios are needed to find a robust solution ;
- what is the sensitivity of the result to the subjective choices.

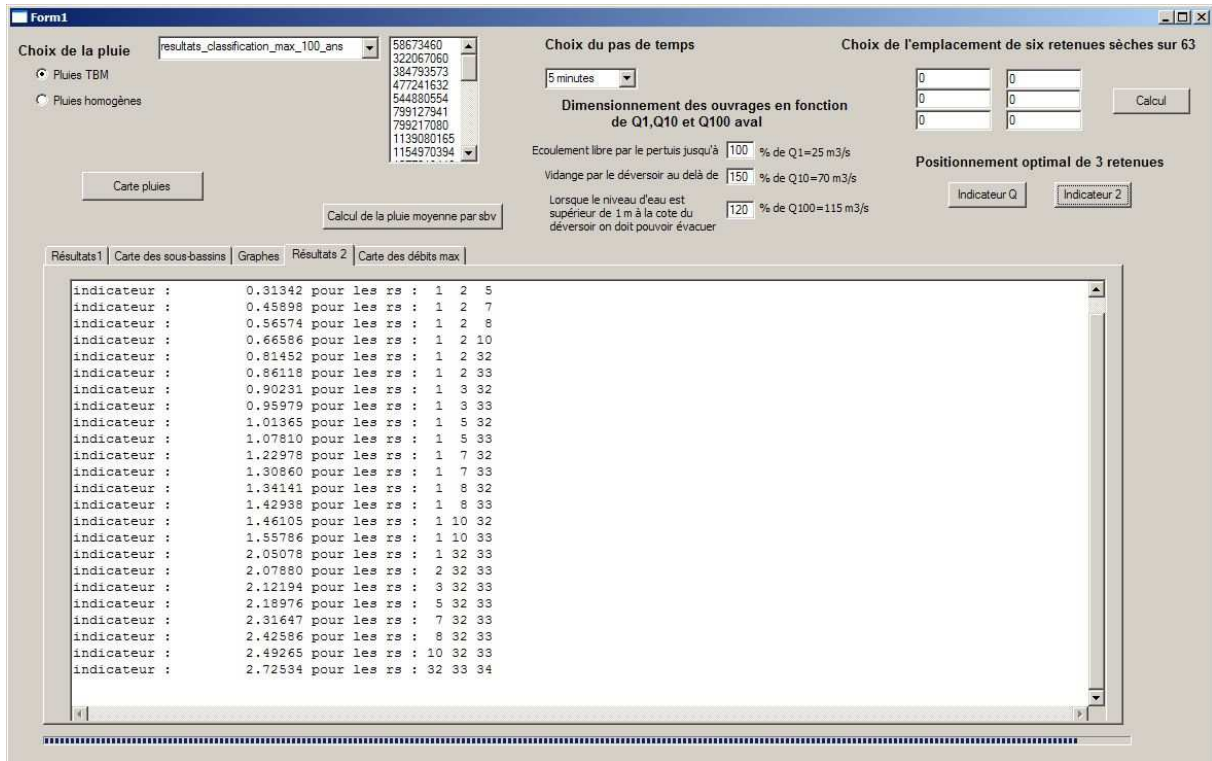


Figure 6. Model Interface (M0)

We shall present here only a summary of the main results.

The dams effect is highly dependent on the rainfall scenario used to test them ; so finding the best solution is for one or several already observed events is by no means a satisfactory procedure.

Besides, working with distributed stochastic rainfall events and the same events averaged in space for each time step (Figure 4b) showed that both the indicators values and the “best set of dams” are different (table 1, Poulard et al., 2009). Further tests with simulations conditioned with the same observations (such as Figure 3) confirm that the raingauges do not give a sufficient knowledge of the actual rainfall, and so the usual efficiency assessment procedures using point data may lead to erroneous conclusions.

Table 1. cross-comparison of indicator values with respect to input and set of dams (all $c_k=1$) – in bold: optimum set of dams for this (set of) event(s) according to current indicator. (Poulard et al., 2009)

set of 3 dams	8 ; 10 ; 58	8 ; 10 ; 33	11 ; 14 ; 29	7 ; 8 ; 10	32 ; 33 ; 34
Rainfall (set of) event(s)					
#1 (Erreur ! Source du renvoi introuvable.)	0.88	0.85	0.003	0.858	0.150
#2 (Upstream)	0.28	0.40	0.06	0.32	0.32
#3 (South)	0.002	0.002	0.11	0.01	0.000
#3h (#3 averaged in space)	0.027	0.027	0.000	0.05	0.000
Set “Class 100”	0.04	0.06	0.015	0.04	0.10
Set “Class 1000”	0.19	0.24	0.04	0.24	0.12

Discussion

Choosing the best solution for one given event is absurd. Besides, one given event is very specific : intensity, duration, spatial extension, zones of maximum precipitations... Investigation of possible indicator formulas highlighted the necessity to define it at the scale of the catchment but also of the regime. Economical assessment, taking into account both benefit and cost of a given solution, assuredly gives the most pertinent indicator (e.g. Erlenbruch et al., 2009). It requires to estimate the probability of each studied event, and to work with a sample of events covering the whole range of floods in order to estimate the damages on average per year. It is quite easy to estimate a return

period for one input hydrograph, but far more difficult at the scale of the basin, where the hydrographs can have contrasted frequencies depending on the subcatchment.

Poulard et al. (2009) suggested to estimate the annualized benefit element by element, because estimating a return period makes sense only for a limited area (Figure 4a shows the variability of the spatial estimated return period for one event).

We followed this idea, and implemented a new function, which amounts to Equation 1 with weights w defined by the local frequency of the event. We are conscious of its limits and unsatisfactory character for any operational use, but kept it for this preliminary studies. The choice of the number of events to include into the set depends on the computation time : for a simple models such as M0, time is not a problem ; for more and more precise models, the number has to be limited and so a selection procedure has to be define (Chopart et al., 2007).

Results representation

We displayed results in the form of peak-flood vs estimated return period in each element, in the current situation and in the presence of dams. To compute the new indicator, the hydrologic representation has to be completed by the local component of the indicator, local damages for the element vs estimated return period.

These results show two already guessed features. First, in some cases, one given solution will worsen the flood situation on an element, for instance because a dam has delayed one contribution so that its peak now arrives at the same time as another peak, so the sum has now a higher peak. This kind of local anomaly is hidden when only one global indicator is used. Second, two hydrographs with the same peak value can have very different shapes and volumes. So, these hydrographs might be represented by close dots in the $Q(T)$ graph but the corresponding peak in the presence of dams can be very different.

So, we processed again the same sample of event using another criteria : the estimated return period of the event's volume.

Conclusions

The approach using stochastic distributed rainfall scenarios solves some of the mentioned problems : they guarantee realistic space and time correlation. However, our tests highlighted the difficulties. Some of the drawbacks of this approach (difficulty to build extreme-event scenarios, lack of data for economical assessment...) also exist for the other type of approach, with hydrographs. Others are linked to the tools : the approach requires a robust and reliable rainfall generator, valid also for extreme events which we are confident will be available within a couple of years. The generator calibration needs raingauges times-series but it has to be completed by any available data, radar maps containing information on spatial repartition, and regional climatology. In the meantime, we can nevertheless test the methodology for it to be available when the generator is released.

The tests also stress that all the comparison of solutions are worthless if the quantitative indicator is flawed. This is why it must be defined with the utmost care, and we recommend to use economical assessment. This required to estimate as precisely as possible the return period of the events.

Further tests will be carried out in a near future about simultaneous optimization of the outlet dimensions.

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