

TOWARDS OBJECTIVE DESIGN OF DRY DAMS AT WATERSHED SCALE : HOW TO TAKE INTO ACCOUNT THE SPATIAL STRUCTURE OF THE RAINFALL AND ITS VARIABILITY

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Introduction

Structural measures must be designed at the right spatial scale, lest the works simply transfer the problems from one area to another. In this light, upstream retention by dry dams has many advantages compared to river training or levees ; moreover, they do not hinder the river natural dynamics.

The aim of this study is to test and improve a methodology to design dams distributed on the catchment. The first difficulty is to define the input at catchment scale. We chose to use a rainfall-runoff approach, and investigated whether it was acceptable to use homogenous rainfall fields, and if not how to define distributed fields. The second key question is how to define a set of distributed rainfall events to ensure an appropriate knowledge of the flood regime, knowing that the return period of flood generated by a distributed rainfall event varies in space. To design dams, we need to compare objectively the flood regime with and without mitigation structures.

We chose to develop a simple rainfall-runoff model, using as input stochastic distributed rainfall fields. As computation time is very short, sensitivity analyses can be easily carried out to investigate the above questions and help define an objective methodology. We also discussed the definition of a quantified efficiency indicator, necessary to compare several sets of dams.

Models : from rainfall fields to hydrographs

With retention structures dispersed throughout the catchment, input scenarios have to be built at catchment scale. One approach is to define hydrographs at each upstream node and lateral input. We chose the other approach, *i.e.* to feed rainfall fields into a distributed hydrologic model. We used a spatially distributed rainfall field generator. Our test case is a 150km² catchment near Lyons.

Rainfall fields generator

Our rainfall generator is based on the turning bands method (Ramos, Leblois, Creutin, 2006). First, the temporal and spatial characteristics of the catchment were estimated using the data of 5 raingauges (Chennu *et al.* 2007).

In accordance to the catchment properties, each rainfall event lasts from 12 to 72 hr. The model then generated 9000 events of 3hr time-step on a grid of 500mx500m (Figure 1a), representing 9 major events per year over 1000 years.

Hydrologic models : MARINE+MAGE chain and MHYSTER.1 simplified model

A physically-based chain of models was already implemented in this catchment and calibrated against observed events (Chennu *et al.* 2007). It is composed of MARINE, an event-based distributed rainfall-runoff model simulating infiltration with the Green-Ampt model (Estupina – Borrell, 2004), and MAGE, a 1D hydraulic model based on St-Venant equations (Giraud, 1997). To allow quicker computations, we also developed MHYSTER. The computation units are 63 subcatchments elements (Figure 1). In the current version, MHYSTER.1, rainfall feeds the hydrographs at the outlet of each element for computation time steps of 5 minutes (Figure 2). Routing simply consists in summing up the hydrographs at each confluence. In its present state, this easy-to-use distributed model meets the minimum requirements to reproduce hydrograph all over the watershed, and allow to carry out quickly sensitivity analyses. Dams can be added at any of the elements outlets ; outflow is computed from water stage behind the dam with the same laws as in MAGE.

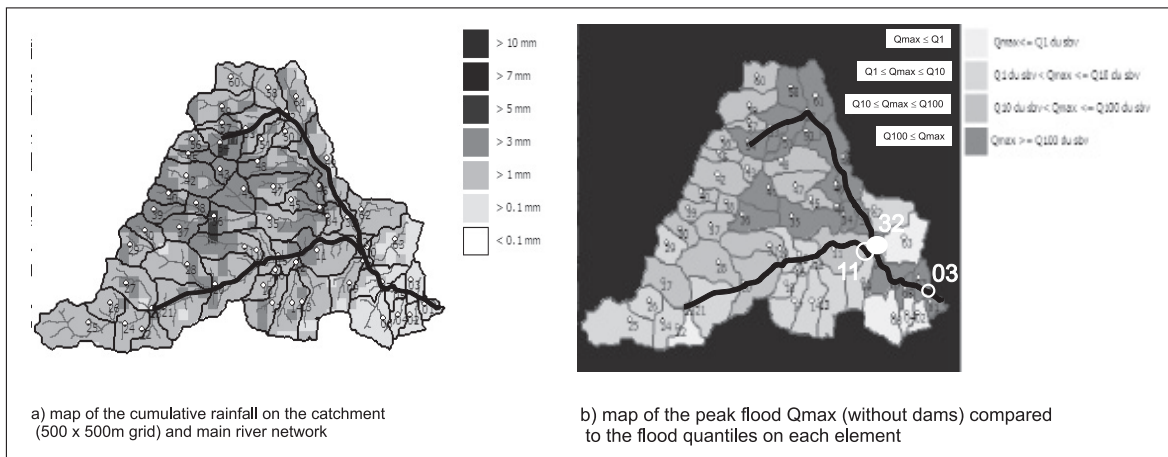


Figure 1 :representations of input and output of the MHYSTER.1 model for a distributed rainfall event

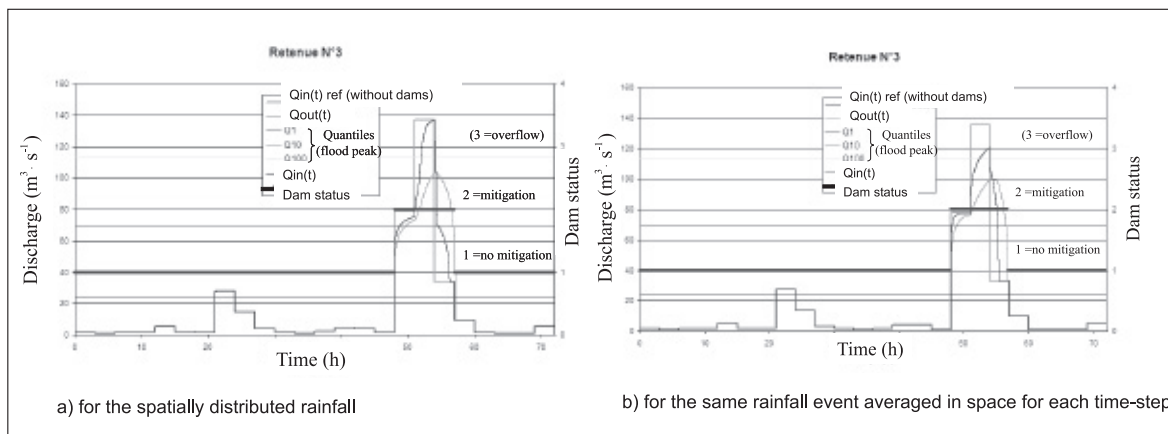


Figure 2. hydrographs computed by MHYSTER.1 for one given stochastic rainfall event (#1) at element 03

MHYSTER.1 produces cumulative rainfall maps and peak floods maps (Figure 1) as well as hydrographs at each element's outlet (Figure 2). The reference hydrograph without dams $Q_{in}(t)_{ref}$ follows the 3hr-time step of the rainfall event because of the computation method. When 3 dams are placed in elements 03, 11 and 32 (fig.2b), the hydrograph is already mitigated upstream element 03 ($Q_{in}(t)$). The dam at the outlet of element 03 further diminishes the peak ($Q_{out}(t)$). A dam status indicator points out when mitigation occur (value rises from 1 to 2) and also overflows 3 (not shown in figure 3).

Rationale to test a set of dams and quantify their efficiency

We first decided which variables could be adjusted and which are fixed, and then we defined an quantified indicator to compare solutions, which was then used in optimization procedures.

Choice of degrees of freedom

Although the possible dam locations are generally limited, we decided to allow 63 possible locations for the dams, one at each element's outlet, in order to investigate thoroughly the effect of spatial rainfall distribution. In order to limit the degrees of freedom, dams outlets and dam height were fixed in the present study with respect to the local 10- and 100-years return period flood at the element outlets. These quantiles were derived from flood peak quantiles calculated at one gauging stations, assuming a proportionality with the catchment area to a power 0.8 (Myers formula).

Definition of an efficiency indicator

To compare solutions and to carry out optimisation procedures a quantified indicator has to be defined. In a real study, it should take into account damages reduction and the costs of the dams.

However, MHYSTER.1 does not produce flood maps and forbids realistic damage assessment. So, we devised a simplified benefit function J . The reduction of damages in an element i is proportional to peak discharge decrease ΔQ_i and to element reach length l_i . A cost coefficient c_i accounts for the land uses. The benefit function J is the sum of the benefits of each rainfall event k :

$$J = \frac{1}{k} \sum_{k=1}^N w_k \sum_{i=1}^{63} f(\Delta Q_i; l_i) c_i \quad (1)$$

For the time being all the weight coefficient w_k were left equal to 1.

Dry dams reduce the peak floods, but they also delay the maximum and lengthen the flood. In some areas, lowering the water depth but increasing the inundation can increase the damages. However, the main drawback of this function is to omit costs. We assumed that dam building and maintenance costs were identical for sets composed of the same number of dams. However, the cost for the dam bowl area is not negligible and may vary very strongly in space ; so this will be corrected in the next version.

Choice of a set of rainfall events

The rainfall generator produced 9000 events. From the point of view of computational time, running the whole set with MHYSTER was possible. But the methodology is to be implemented afterwards with the chain MARINE+MAGE, which takes much longer processing time in its present form. Besides, we wanted to analyse the influence of the choice of a set of events. Furthermore, to analyse the results of an optimisation procedure, it is useful to look at hydrographs at several key points, which becomes unfeasible for a very large set of events. Our procedure to define events sub-sets is (Chopart, Leblois, El Kadi, 2007):

- selecting the maximum rainfall events at 9 locations and for 6 durations (from 3 to 72hr) ;
- reducing the sample size down to 30, while keeping the highest possible intra-sample variability.

This method was applied, with two variants for step 2, on the whole 9000 events representing 1000 year of data and also on a subset representing 100 years of data. In short, 4 sub-sets of 30 events were formed.

The user can choose to work with one event or a set of 30 events, distributed in space or averaged.

Results and discussion

Significant differences appear in our test-case between the hydrographs obtained for a rainfall scenario and the same averaged in space (Figure 2a and b, Table 1 event #3). This difference is even bigger with the MARINE+MAGE chain, where infiltration is taken into account (Chennu *et al.*, 2007). Therefore, a design fit for one homogenous scenario will give disappointing results for other rainfall patterns.

Table 1: Selected results of the optimisation procedure (best set of 3 dams)

Rainfall event		All damage coefficient $c_i = 1$		Distributed damage coefficient c_i	
		Best set of 3 dams	Indicator value	Best set of 3 dams	Indicator value
Optimisation with one single event (with location of the area of maximum rainfall)	#1 (See Figure 2)	8 ; 10 ; 58	0,88	10 ; 32 ; 33	87,42
	#2 (Upstream)	8 ; 10 ; 33	0,40	8 ; 10 ; 33	39,34
	#3 (South)	11 ; 14 ; 29	0,11	11 ; 15 ; 31	7,33
	#3h (same, but averaged in space)	7 ; 8 ; 10	0,05	7 ; 8 ; 10	5,29
Optimisation with a set of 30 events	Set "Class 100"	32 ; 33 ; 34	0,10	32 ; 33 ; 58	9,38
	Set "Class 1000"	7 ; 8 ; 10	0,24	7 ; 8 ; 10	24,35

Secondly, the results highlight the biases of optimisation. Table 1 shows that the results are very sensitive to the choice of the rainfall set. The set "Class1000", which includes extreme events strongly modifies the optimised solution. This is explained by the same weight w_i being attributed to all events in the optimisation function, including extreme events. Moreover, modifying the objective function (Equation 1) also modifies the results. MHYSTER.1 also helped demonstrate other effects. Peak delay is in general useful, but it can in some cases make the peak, albeit reduced, concomitant with the one of another branch at a confluence. This effect may vary from one event to another, because peak arrival time depends on the rainfall pattern.

Conclusion and perspectives

Dry dams are effective structures (*e.g.* Poulard *et al.*, 2005), but designing in a coordinate manner a set of several dams is a difficult task to-day. This study emphasizes the importance of taking into account the variability and spatial properties of rainfalls. It leads the way towards the development of an objective design method, to be adapted and used for design studies, for instance with the MARINE+MAGE chain of models.

In its present state, MHYSTER.1 is a very simple model, and yet it can carry out informative sensitivity analyses and help investigating the impacts of changes made to the methodology. MHYSTER.1 could easily be raised to the standards of a feasibility study for the hydrological computations. We also plan to use it as a pedagogical tool, for design exercises where students can test by themselves the consequences of their choices or constraints on the final result.

Choosing the set of events to be tested and taken into account in the objective function is the most difficult task. The method of sampling has to be refined, and a perspective is to adjust weight coefficients w_i in equation 1. It could allow to take into account the probability of occurrence of each event, although this is far from easy to define at catchment scale.

Another very interesting perspective is to investigate outlet dimensions optimisation.

The rainfall generator is still under development, in particular to take into account the movement of rainfall fields with wind. It is expected to offer many possibilities, for both research and operational purposes.

In any case, in a real study, the optimisation function should be defined to really quantify the economical benefit. This requires correct topographical and economical data, and to use state-of-the art economical analysis methods.

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