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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ABSTRACT

This exploratory study is a contribution to the development of an objective method to design flood mitigation structures distributed over the catchment. Its main issue is to analyse the influence of the input (rainfall scenarios), on the choice of a technical solution (here, the best location for 1 or 3 dry dams). To take into account the spatial variability of the rainfall, we used a simulator of stochastic distributed rainfall fields. A very simple rainfall-runoff model was then implemented on a test case, a 150 km² catchment near Lyon. It was divided into only 63 computation units, following subcatchments delineation. A dry dam can be placed at the outlet of any unit. Such a simple model has short computation times, allowing to run numerous tests and optimization procedures. This study illustrates frequent flaws in operational studies, such as the subjectivity of the definition of an indicator, the ignorance of the exact pattern of the rainfall and of rainfall variability. The main results are summed up in this paper through six didactic remarks. Important issues arising from this study are (i) how to include extreme events in the set of input scenarios, and (ii) how to define efficiency indicators - relying on hydrological variables alone is clearly insufficient. The efficiency indicator should be based on economic terms ; our suggestion is to use a cost-benefit approach. Indeed, it implies annualizing the cost of damages, and so the estimated damages for each flood event are weighted by the range of frequency it represents, and thus the problem of the weight of extreme events is at least partly solved.

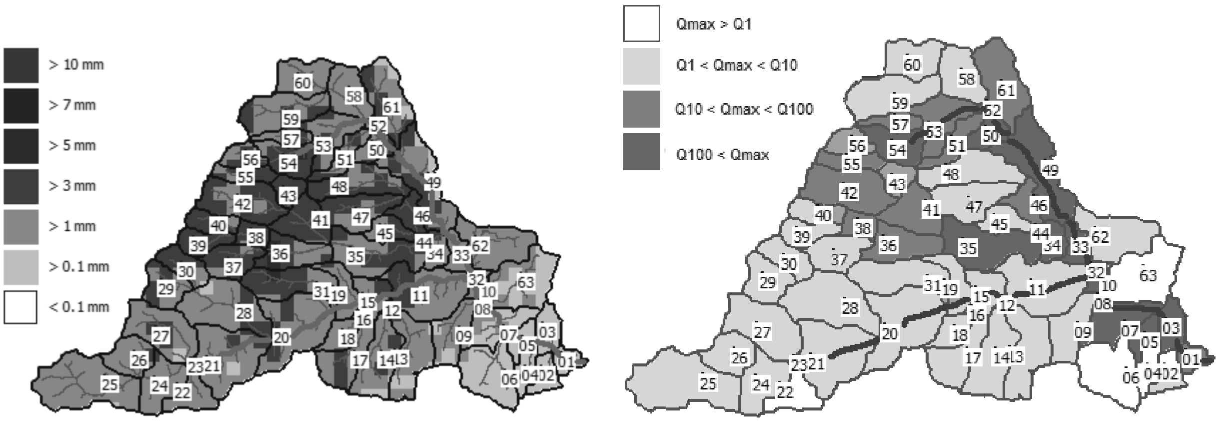
Keywords: dry dams, flood mitigation, flood regime, stochastic distributed rainfall fields

INTRODUCTION

Structural measures for flood mitigation must be designed at the right spatial scale, to avoid transferring 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. Besides, mitigation structures should be designed in a coordinated manner, to assess the overall effect. The aim of this study is to test a methodology to design dams distributed over the catchment. The effect must be quantified through a comparison of the consequences with and without mitigation structures over the whole flood regime. The main difficulty is to define the input at catchment scale. We chose a rainfall-runoff approach, using stochastic distributed rainfall fields fed into a simple rainfall-runoff model developed for the study, called MHYSTER. As computation time is very short, numerous sensitivity analyses can be easily carried out to study and improve assessment methodologies. The tests highlighted significant differences in calculated hydrographs when using distributed fields or homogenous fields obtained by spatial averaging. The second question addressed is how to define a set of distributed rainfall events representative of the flood regime, knowing that the return period of flood generated by a distributed rainfall event varies in space. 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 inputs. We chose the other approach, *i.e.* to feed rainfall fields, obtained from a spatially distributed rainfall field generator, into a distributed hydrologic model. Our rainfall generator is based on the turning bands method, according to the perspective presented in Ramos *et al.* (2006). Our test case is a 150 km² catchment near Lyons. First, the temporal and spatial characteristics of the rainfall regime over the catchment were estimated using data from 5 raingauges (Chennu *et al.,* 2008). The model then generated 9000 72h-events of 3h time-step on a grid of 500mx500m (Fig. 1), assumed to represent 9 major events per year over 1000 years. The observed data used to calibrate the generator integrate various rainfall forms, but none of the observed events has an estimated return period over 100-year. The relevance of the simulated extreme events thus obtained is disputable, since climatic conditions leading to extreme events can be very different from the observed ones. This point is open for further studies.

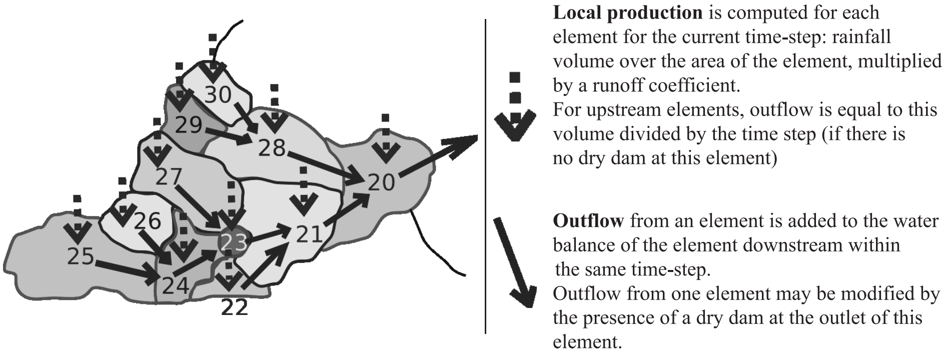


a) Map of the rainfall on the catchment for event #1 (500m x 500m grid) and main river network

b) Map of resulting peak flood Qmax (without dams) compared to the local flood quantiles on each element

Fig.1: Representations of input and output of the MHYSTER model for distributed rainfall event #1.

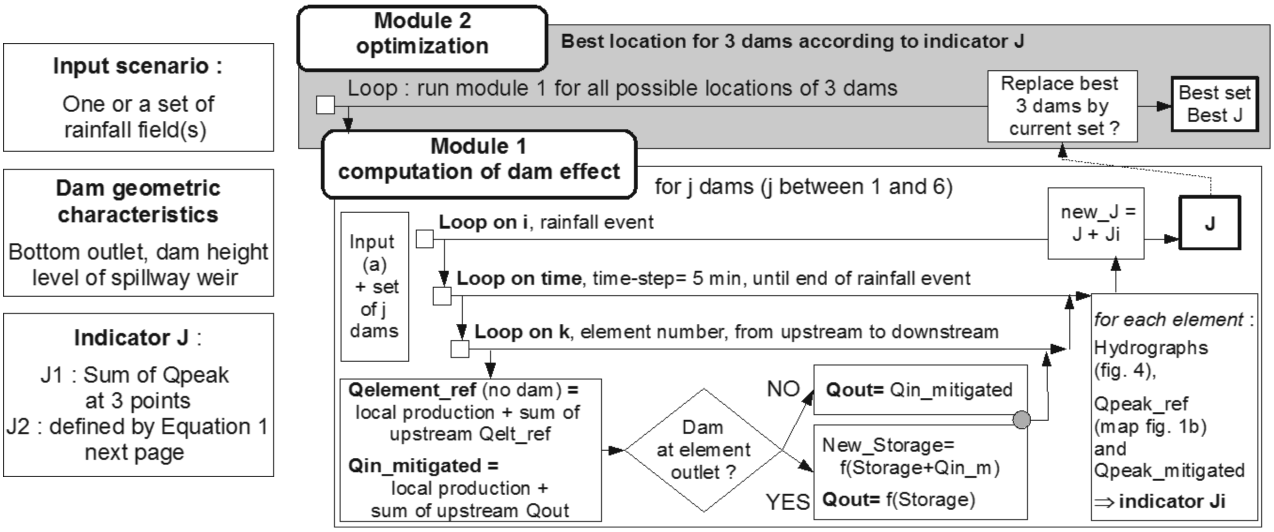
A physically-based chain of models was already implemented on this catchment and calibrated against observed events (Chennu *et al,.* 2008). It is composed of MARINE, an event-based distributed rainfall-runoff model simulating infiltration with the Green-Ampt model (Estupina–Borrell, 2004) and MAGE, a 1-D hydraulic model based on St-Venant equations (Giraud, 1997). We wanted a simpler, easy-to-use distributed model on the same test-case to allow quicker exploratory computations and carry out numerous sensitivity analyses. We therefore developed MHYSTER to meet the minimum requirements to reproduce hydrographs all over the watershed. The computation units are 63 subcatchments elements (Fig. 1 and Fig. 2). Hydrographs are computed by adding upstream contributions to local rainfall; Fig. 3 presents the algorithm. The main module in MHYSTER, Module 1 (Fig. 3), computes hydrographs at each element's outlet (Fig. 4). Outflow from one



Local production is computed for each element for the current time-step: rainfall volume over the area of the element, multiplied by a runoff coefficient.
For upstream elements, outflow is equal to this volume divided by the time step (if there is no dry dam at this element)

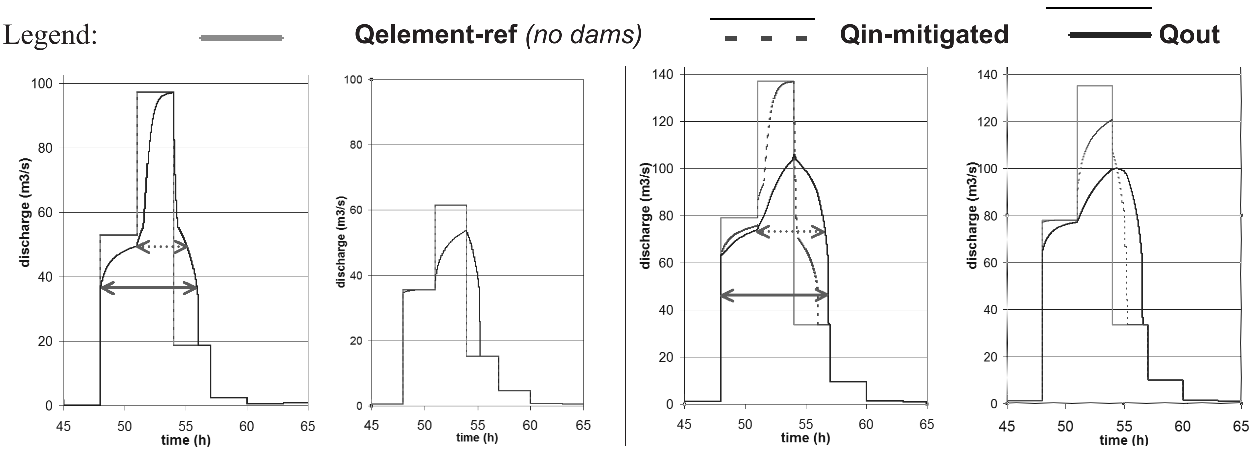
Outflow from an element is added to the water balance of the element downstream within the same time-step.
Outflow from one element may be modified by the presence of a dry dam at the outlet of this element.

Fig. 2: Principle of discharge computation along the drainage system (subcatchment down to element #20).



a) User's main choices b) Algorithm – modules 1 and 2

Fig. 3: Structure of MHYSTER.



hydrographs at element 32 hydrographs at element 03

a) distributed event #1 *b) averaged in space (#1h)* *c) distributed event* *d) averaged in space (#1h)*

Fig. 4: Peak of hydrographs computed by Module 1 for rainfall event #1, with dams at outlets of elements 32, 11 and 03. *Aarrow: duration of mitigation by the element's dam; dotted arrow: overflow.*

element is immediately transferred to the element downstream within the same time-step. Because there is no routing delay, the reference hydrographs without any dam-denoted **Qelement_ref** in Fig. 4 – follow the rainfall 3h-pattern. Although possible dam locations are generally limited in real catchments, we allowed dams to be placed at the outlet of any of the 63 elements, in order to investigate thoroughly the effect of spatial rainfall distribution in this study. Hydrograph **Qin_mitigated** is computed using inflow already mitigated by upstream dams. If there is a dam at the outlet of the element, the outflow from element, denoted **Qout**, is further mitigated by this dam. Water stage behind the dam is obtained from the volume budget, assuming a simplified topography ; outflow is then deduced from the water stage, using the same standard formula as in MAGE. Cumulative rainfall maps and peak floods maps are also produced (Fig. 1). Module 1 also calculates a mitigation efficiency indicator J, that can be used in an optimization procedure, Module 2, to find the best set of three dams for a given set of rainfall scenarios.

The simplicity of the rainfall-runoff model also serves didactic purposes. In operational studies, many efforts are generally made to fine-tune hydraulic models, while far less attention is given to the input. Very often, only one or two input scenarios are defined and tested ; flood reduction is optimised for these one or two events. The objective should be rather to obtain the best behaviour on average, with respect to flood probability. So, we explicitly shift the focus towards the definition of input scenarios. Wrong assumptions and choices in the model input lead to flawed conclusion – even if the hydraulic model is excellent.

RATIONALE TO TEST A SET OF DAMS AND QUANTIFY THEIR EFFICIENCY

Fig. 3a presents the three main choices the user has to make. The most important one is probably **to define the efficiency indicator**(s), denoted J, used to quantify the effect in order to compare solutions (Module 1), and necessary in optimization procedures (Module 2). In a real study, J should take into account the reduction of damages given by the dams, and also the costs of the dams. MHYSTER uses only one hydrological variable, the discharge ; it can estimate neither flood spatial extent nor water depths. So, a simplified benefit function J was proposed for this study. We assumed that reduction of damages in an element k is proportional to ΔQ_k, peak discharge decrease above an overflow threshold, and to element reach length l_k. All the weight coefficient w_i were left equal to 1 in this study. A cost coefficient c_k accounts for the land uses. The benefit function J is the average of the benefits of the N rainfall event:

$$J = \frac{1}{N} \sum_{i=1}^{N} \mathrm{W}i \sum_{k=1}^{\text{в}} f(\Delta Q_k; l_k) c_k \qquad \text{Eq. 1}$$

This definition suffices for this exploratory stage, but not for operational use. Moreover, damages are not necessarily proportional to flooded areas; submersion durations are also important. Futures versions should include damage evaluation tables, and account for building and maintenance costs. Besides, using the bowl area for water storage has a significant cost, whether through land purchase or indemnifying procedures.

Then**, dam outlets and height** must be defined. To limit the number of parameters, we define dam characteristics with respect to the local estimated 10- and 100-year return period floods at the element outlets, with the same ratio for all dams. The 10- and 100-year quantiles were derived from flood peak quantiles calculated at one gauging station, assuming a proportionality with the catchment area to a power 0.8 (Myers formula).

Finally, the user must choose the input ; he can work with **one or a set of rainfall event**(s). The methodology is to be implemented afterwards with accurate models, with long processing time, which will not be able to handle all 9000 produced by the stochastic generator. So, we tested procedures to extract automatically events sub-sets, in two stages (Chopart *et al.*, 2007):

- selecting the maximum rainfall events at 9 locations and for 6 durations (from 3 to 72h) ;
- reducing the sample size while keeping a fair intra-sample variability (almost uniform marginal distribution on all variables). The sub-set size was fixed at 30.

Two different sampling methods were applied twice: first on the set of 9000 events, representing 1000 years of data, and then on a subset representing 100 years of data. So, 4 sub-sets of 30 events were formed.

RESULTS AND DISCUSSION

The indicator defined by Eq. 1 was used to compare solutions and to carry out optimization procedures. This study allowed to test the sensitivity of the results to explicit or implicit choices made during the procedure. Some of the results only confirm what was logically expected, but are anyway presented and commented for didactic purposes, to point out flaws existing in too many operational studies (authors' experience).

a) Influence of the definition of the indicator

The influence of different damage coefficients was tested (Table 1), as well as other definitions for benefit function J (not shown here). Results are summarised in **Remark 1**: "Definition of the indicator strongly impacts the results of comparisons between dam locations."

Table 1: Results of the optimisation procedure for 6 input scenarios:
best set of 3 dams and indicator value (Eq1)
(indications 'Upstream' and 'South' refer to location of the area of maximum rainfall in the scenario).

Input scenario =		All damage coefficient $c_k = 1$		Different damage coefficient c_k	
		Best set of 3 dams	Indicator value	Best set of 3 dams	Indicator value
one single event	#1 (*see* Fig. 1)	**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 (#3 averaged in space)	7 ; **8 ; 10**	0.05	7 **; 8 ; 10**	5.29
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

Numerical values of the indicator should be interpreted carefully. Smaller values mean smaller mitigation and/or a smaller flood. So, comparisons are relevant only for a given set of events or for a given set of dams. Moreover, the global indicator may hide local peculiarities: the peak flood may locally increase if contributions are made concomitant. Mapping elementary indicators could be useful to identify these effects.

b) Influence of the pattern and choice of the (set of) rainfall scenario(s)

Major differences appear between the hydrographs obtained for a rainfall scenario and the same averaged in space for each time-step (Fig. 4). The hydrographs obtained from distributed and averaged events are even more different with the "MARINE+MAGE" chain, where infiltration is taken into account (Chennu *et al.*, 2008). Consequently, the difference in hydrographs has a strong impact on dam efficiency (example of event #1, Fig. 4). Differences are more acute in the upstream part and decrease in the downstream part. An example of optimization is shown for event #3: resulting dam locations are in the south part of the catchment, where the rainfall intensity is maximum (Table 1). Optimum indicator value is 0.11. For the same event averaged in space, event #3h, spatial contrast is obliterated and optimization favours dams in the downstream part, with an indicator of only 0.05. So, **Remark 2** is issued as follows: "Ignorance of the exact spatial pattern of the rainfall leads to errors in the hydrographs and in mitigation assessment".

Table 1 illustrates that each choice of set or sub-set of events leads to a different optimum solution, although some locations are selected more often that others in these cases (elements 8 and 10, in the lower part of the catchment). Optimization generally selects dams in the area of the most intense precipitations. Table 2 displays some cross-comparisons of rainfall scenarios and set of dams. The optimum solution obtained for each scenario selected in Table 1 was tested for the other events or sets of events, and showed contrasted efficiency. Hence **Remark 3**: "The optimum choice of dams for a rainfall scenario might give very poor results for other events". The results with sets of rainfall events lead to remarks 4 and 5.

Remark 4: "Solutions obtained for a set of events yield smaller values of the indicator. This value is an average, since the dams have a significant effect on some events and a much reduced one on other events".

Table2: 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.

Set of 3 dams Rainfall (set of) event(s)	**8; 10**; 58	**8; 10**; 33	11; 14; 29	7; **8; 10**	32; 33; 34
#1 (Fig. 1)	**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

c) Weight and representativity of extreme events

Remark 5: “The sub-set used to find the best solutions must be representative of the rainfall hazard regime”. Tests showed that this important requirement is not met in our tests, because of the reduced number of events in the set. Table 2 illustrates the variability of the indicator value depending on the set of events considered. Our present approach, with one or two extreme events in a set of 30 events and with all the weight coefficients equal to 1, is not satisfactory. Extreme events, such as existing in set “Class1000”, are too specific: events can be very strong on part of the catchment and rather moderate elsewhere. These individual peculiarities strongly impact the result. And yet, extreme events must be taken into account because they might account significantly in the damages.

This study highlights the danger to carry out an optimisation procedure based on flawed hypotheses and raises two key issues: how to define an objective and relevant benefit function J, and how to build a representative set of rainfall events.

CONCLUSION AND PERSPECTIVES

Dry dams are effective structures (*e.g.* Poulard *et al*., 2005), but designing a set of several dams to maximize their combined efficiency is a difficult task because it implies building rainfall scenarios at catchment scale. This study shows how a stochastic rainfall simulator can be efficiently used, and emphasizes the importance of taking into account the variability and spatial properties of rainfall. In its present state, MHYSTER is a very simple model, and yet it can carry out informative sensitivity analyses and investigate some recurrent flaws observed in operational studies. Our results clearly illustrates the main flaws, and MHYSTER could be used as a didactic tool: students could test the consequences of their choices or constraints on the final result.

This study also raised interesting questions, and in particular how to take into account extreme events. A promising solution is to define the cost function J according to a complete cost-benefit approach. This implies to estimate damages annualized values, once without and once with the dams. In this approach, extreme events are weighted by the range of frequency they represent. This partly solves the problem of assigning reasonable weights to extreme events. However, a given rainfall event has no intrinsic frequency at catchment scale; the estimated frequency of the resulting flood varies over the catchment (Fig. 1b). We therefore propose to estimate the annualized damages separately on each element. The overall benefits for a set of dams would be the sum of the annualized benefits of each element. Of course, the cost of dams construction and of maintenance should also be included into the cost function *J*, after being also annualized.

Remark 6: “*For an objective efficiency assessment, the indicator must account for both cost and benefits integrated over the regime, using a cost-benefit analysis*”. This implies that the set of events include enough diversity to estimate a comprehensive benefit/frequency rate on each element (*see* Remark 5).

This study leads the way towards the development of an objective assessment method, to be used afterwards with state-of-the-art models, such as the MARINE+MAGE chain of models. One very strong assumption is the ability of the rainfall fields simulator to yield sets of events representative of the rainfall hazard regime, including extreme events. Further research is needed to improve extreme events simulation, which is a necessary condition to consolidate this approach.

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