Stochastic generation and disaggregation of hourly rainfall series for continuous hydrological modelling and flood control reservoir design

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Abstract In the urban environment, stormwater detention basins are a powerful means to limit the frequency of sewer system failures and consecutive urban flooding. To design such waterworks or to check their efficiency, it is possible to carry out continuous rainfall-runoff modelling. A long-term discharge series obtained from a long-term rainfall series is used as input for a storage model describing the detention basin behaviour: the basin behaviour may be consequently studied over a long period. The provided statistical information on the working state frequency, failure frequency, ... of the detention basin is of high interest for the basin diagnostic or for its design. This paper presents the whole methodology which leads to production of such statistical information and especially: the models used to generate long term rainfall series with a short time step, the rainfall-runoff model used to transform the later series into a long term discharge series, and the model used to describe the behaviour of the detention basin. This methodology was applied to evaluate the efficiency of 4 detention basins built for stormwater control and flood mitigation. They are situated on a Swiss urban catchment (Chamberonne catchment – 40 km^2) collecting water from the Mèbre and Sorge rivers.

Keywords Rainfall disaggregation; rainfall modelling; rainfall series; reservoir design; stochastic generation

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Introduction

To design or check the efficiency of stormwater detention basins, an interesting alternative to well known design rainfall based methods is to use a long-term chronological record of rainfall to simulate long-term discharge series. Such simulations have a lot of advantages when compared to classical approaches: there is no more an arbitrary choice for the shape of the design rainfall and/or for the resulting flood event and it is no more of use to suppose correspondence between rainfall and discharge return periods (ASCE, 1996). Furthermore, the statistical study may be based on the behaviour of the detention basin. It is possible to characterise the working state frequency and the filling rates of the reservoir, two important factors needed to define what sort of use may be made of the land situated in the detention area (parking area, sport field, green pleasure area,...). Moreover, it is possible to characterise the failures of the system, in terms of failure frequency, failure duration, failure intensity, failure impacts and especially damage to the urban environment. This approach also allows us to get rid of the determination of the antecedent condition of the watershed. It is finally possible to simulate two or more floods following each other in time and thus to take account of different possible initial filling states of the drainage system and different storage rates of the retention basins.

In the urban context, the response times of catchments are usually short, which implies describing the rainfall events with a good time resolution: a 10 mn time step is often necessary. Furthermore, as the protection targets of the urban environment are usually high, the detention basins have to be effective for floods with a rare frequency: this implies to work with very long term series (50 to 100 years records). For the case presented in the following sections, if the length of the available 10 mn-rainfall series was already unusual (17 years at the Pully rainfall measurement station), it was nevertheless insufficient. More generally, the currently available series of observed rainfall with such a time resolution are always too short. A long-term and continuous simulation approach therefore implies the production of long-term 10 mn-rainfall scenarios. The EPFL Soil Water Management Institute recently developed such a long-term and continuous simulation approach for the efficiency evaluation of 4 detention basins situated in the Chamberonne catchment, Switzerland (Monbaron *et al.*, 1999). It led to considerable improvements to the study of the whole drainage system, when compared to a simple single-event approach.

Rainfall series generation

The generation of fictitious long term rainfall series (100 years) with a short time step (10 mn) may be done using different methods. The chosen methodology (Monbaron *et al.*, 1999), has the 2 following steps: (1) production of long term rainfall scenarios with an hourly time step and next (2) disaggregation of each hourly rainfall amount to produce a 10 mn-long term rainfall series.

Hourly rainfall series generation

The generation of rainfall scenarios with an hourly time step is quite well controlled. Stochastic cluster rainfall models are for example well suited for this type of work. The selected stochastic generator of rainfall is the Neyman Scott Rectangular Pulses Model (NSRPM) (Rodriguez-Iturbe *et al.*, 1987; Figure 1) : it describes the rainfall processes as a combination of rectangular cells. The parameters of NSRPM can be calibrated so that the main statistical properties of the simulated precipitation scenarios are similar for different time steps t to those of the observed rainfall process (t = 1 hour or 1 day). The calibration of the five NSRPM parameters is based on the first and second order moments of the rainfall process (mean and variance of rainfall amounts over time step t) and on the autocorrelation coefficients between consecutive rainfall amounts (statistical variables calculated for rainfall amounts relative to both hourly and daily time steps). Twelve sets of 5 parameters (one per month) were adjusted to take into account the seasonal variability of the rainfall process. Favre (1998) proposed a robust calibration method. Here, NSRPM was used to generate 10 rainfall series of 100 years with an hourly time step. The last validation of the model consisted in controlling its ability to reproduce the occurrence probability of maximal rainfall intensity for various time spans (1 hour and 1 day) (Figures 2 and 3).

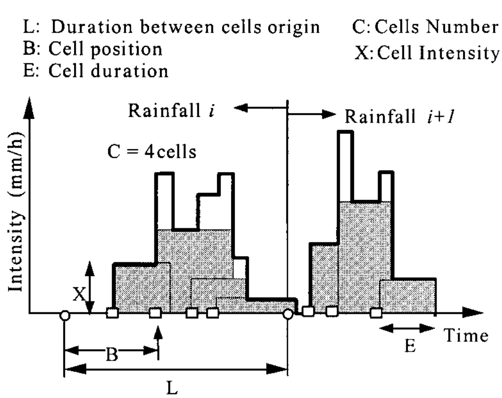


Figure 1 NSRPM model

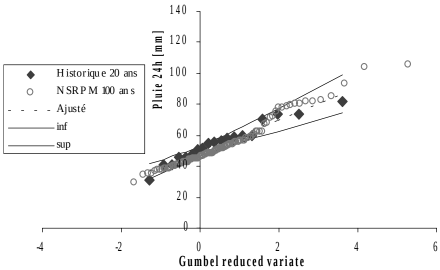


Figure 2 Comparison of maximal daily rainfall heights between simulated (NSRPM) and observed data

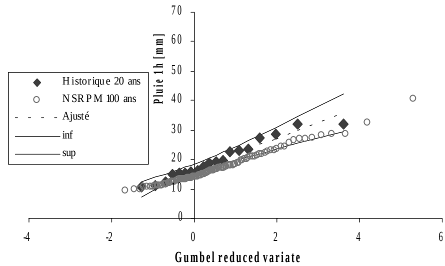


Figure 3 Comparison of maximal hourly rainfall heights between simulated (NSRPM) and observed data

Rainfall series disaggregation

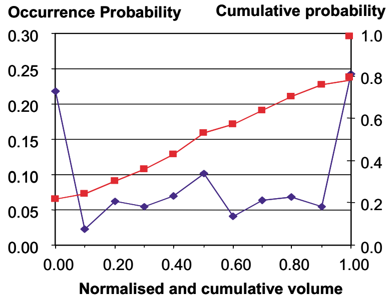
If hourly rainfall generation is a rather well mastered operation, it is not really the case for generation of rainfall series with a 10 mn time step. A possibility is to produce a 10 mn rainfall series by disaggregating an hourly rainfall series (observed or generated by a stochastic model). The major difficulty is to derive from hourly rainfall series 10 mn rainfall series with satisfying temporal structures without modifying the overall statistical characteristics relative to hourly and daily rainfall amounts. Moreover, the model should theoretically take into account the external temporal structure, of rainfall i.e. depths of rainfall in the rainy hours that precede and follow the rainy hour to disaggregate (said central rainy hour). Different types of models have been previously presented in that sense. Two of the models developed to achieve that purpose use the rainfall amount trends observed between first the preceding and the central rainy hours and next between the central and the following ones (Ormsbee, 1989; Burckhardt-Gammeter and Frankhauser, 1998). The artificial neural network technique was also tested for this task (Burian *et al.*, 2000): the relationships between the external rainfall structure and the internal rainfall distribution are learned from a given training data set and next used for disaggregation. The stochastic disaggregation model developed for this study is an alternative one: it makes the simplifying hypothesis that the internal distribution of rainfall is independent of the external rainfall amount pattern. It is simply based on the statistical analysis of the normalised temporal rainfall structures within a rainy hour for all rainy hours of the 17-years observed rainfall series (available with a 10 mn time step) (Monbaron *et al.*, 1999).

Statistical analysis. For each rainy hour of the 17-years observed rainfall series, the dimensionless and cumulated hyetograph is built (intensities are normalised by the hourly rainfall amount). It is described by a set of 7 values $H(t_i)$ corresponding to the dimensionless cumulated rainfall amounts fallen between the beginning of the rainy hour and the time $t_i = i$ 10 mn:

$$H(t_i) = \sum_{k=1}^{i} (t_{k-1},t_k) \Big/ \sum_{k=1}^{6} (t_{k-1},t_k)$$

with (t_{k-1}, t_k): rainfall amount fallen between times t_{k-1} and t_k and with $0=H(t_0)$ $H(t_i)$ $H(t_6)=1$.

As $H(t_i)$ varies between 0 and 1, it would be possible to adjust a continuous density function on this interval. Garcia-Guzman and Aranda-Oliver (1993) propose to adjust a beta distribution. We have used an empirical distribution (Figure 4) derived from the 17-years series of observed rainfall.



Application of the disaggregation model:

1) Random drawing of 5 numbers p_i in the [0,1] interval;
2) Sorting in increasing order of the precedent p_i values: obtaining of a sorted set of 5 values p^*_i;
3) For each random number p^*_i, $H(p^*_i)$ determination thanks to the distribution function of the corresponding normalised and cumulated volumes (Figure 4);
4) Determination of the normalised rainfall increments between time t_{i+1}: $V_i = H(p^*_{i+1}) - H(p^*_i)$;
5) Determination of rainfall height increments (t_{i+1}, t_i) thanks to the precedent normalised increments and to the total rainfall amount fallen during the studied rainy hour.

Figure 4 Occurrence probabilities for cumulated and normalised rainfall amounts within a rainy hour

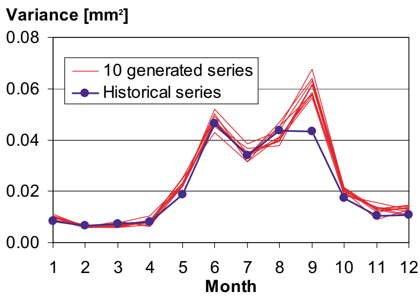


Figure 5 Monthly variances (10 minutes)

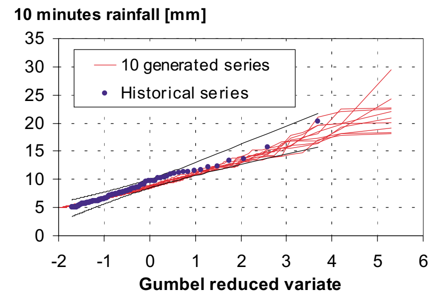


Figure 6 Maximal rainfall heights over 10 minutes

Results. This empirical time distribution of rainfall depth for each interval can be used to randomly determine a dimensionless hyetograph, which will allow the redistribution of the hourly rainfall volume between the six 10 mn time steps of the hour. As a result, 10 long-term rainfall series (100 years) at short time steps (10 mn) whose statistics are similar to the original series (and especially monthly variance and maximal intensities over a 10 mn time duration), are available (Figures 5 and 6).

Modelling the rainfall-runoff transformation

The modelling used for rainfall-runoff transformation is based on a semi-distributed representation of the watershed which is intended to describe all sub-catchments (10 for the present case) with a deterministic, conceptual and "storage oriented" model (Jarrar and Consuegra, 1996). For each rural sub-catchment, two reservoirs are used to describe separately the soil hydrological behaviour and the catchment overland behaviour. These reservoirs are fed by a certain fraction of the total rainfall and their draining leads to flow formation (respectively base flow and runoff components). The storage-discharge relations are respectively linear for the soil reservoir ($Q_{base} = K.S$ where K is the recession parameter and S the storage in the soil reservoir) and non linear for the overland reservoir ($Q_{quick} =\ \ p^{1/2}H^{5/3}$ where is the reservoir parameter, p the mean catchment slope and H the reservoir water level). The model finally connects effective and total rainfall (P_{net} and P_{tot}), as well as actual and potential evapotranspiration (ET and PET), through the filling rate of the soil reservoir: S/A where A is the maximum storage capacity of the soil reservoir.

$$ET = PET \lozenge \frac{S}{A}^{2} \quad \text{and} \quad P_{net} = P_{tot} \lozenge \frac{S}{A}$$

Three parameters are to be calibrated: K and A (influence the base flow reconstitution) and (determines the quick flow component). A similar modelling is used for urban parts of the

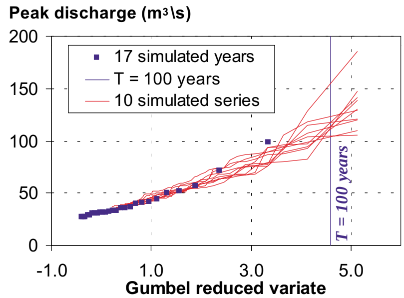


Figure 7 Comparison between simulated and observed discharge quantiles

modelled catchment. The rainfall-runoff model calibrated on a 4-years observed series (rainfall and discharges at the outlet of different sub-catchments) was used to produce ten 100-years simulated discharge series from the ten 100-years generated rainfall series. For each of the 10 simulated discharge series, the discharge quantiles were derived from a frequential analysis of the maximal annual peak discharges. They fit quite well with the observed (Figure 7). This shows for this case the suitability of the disaggregation model and suggests that it is not absolutely necessary to take into account for the disaggregation process depths of rain relative to the preceding and following hours.

Modelling the detention reservoir behaviour

To model the retention reservoirs behaviour, the method of the Storage Indication Curve was used. The simulation of the reservoirs behaviour was made for the 10 long-term generated discharge series. Two important characteristics were extracted from these simulations: the frequency of working state and the frequency of failure (frequency of reservoir overloading). A detention reservoir was considered to be in working state (resp. to fail) as soon as its filling rate was greater than or equal to 10% (resp. 100%). The occurrence probabilities of the different filling rates presented in the following table correspond to the average occurrence probabilities calculated from the 10 series of 100-years each.

Results: (1) the target Average Recurrence Interval (ARI) for the design of the retention basins system was initially 100 years. The first important result is that the retention system is unable to reduce the peak flow discharge for such a return period (Figure 8 – see Qp100). As there was no more free surface to increase the storage capacity of the retention basins, the project manager could have concluded that the basins implantation was useless because of the system inefficiency. Such a decision would have been wrong because the retention basins are particularly efficient for lower return periods (varying between 10 and 50 years). This information is only available thanks to an analysis of all return periods (and not with a single event approach using only one design hydrograph) (Figure 8).

(2) Furthermore, some in-going flood events (an average of 0.8 to 2.4 events per 100 years according to the basin) produce important overloading fluxes, which may cause great damage to the riparian urban zones. But it is impossible to define a relation between the event peak flow ARI and the basins failures: for example, the two following in-going floods have the same peak flow ARI (100 years) but because of its shape, the second one (b) produces a severe overloading contrary to the first one (a) which is entirely dumped by the detention reservoirs system (Figure 9). If the first event (a) had been chosen as the design hydrograph for the basins design in a single event approach, the size of the basins (apparently too efficient) could even have been reduced (that would have considerably increased residual flooding risks!...). More generally, in-going flood events with lower peak flow ARIs can also lead to basin overloading: such events are often critical because of their

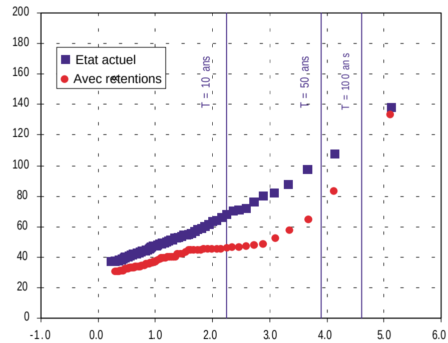


Figure 8 Effect of the retention basin on peak discharges at the outlet of the Mebres-Sorge Catchment

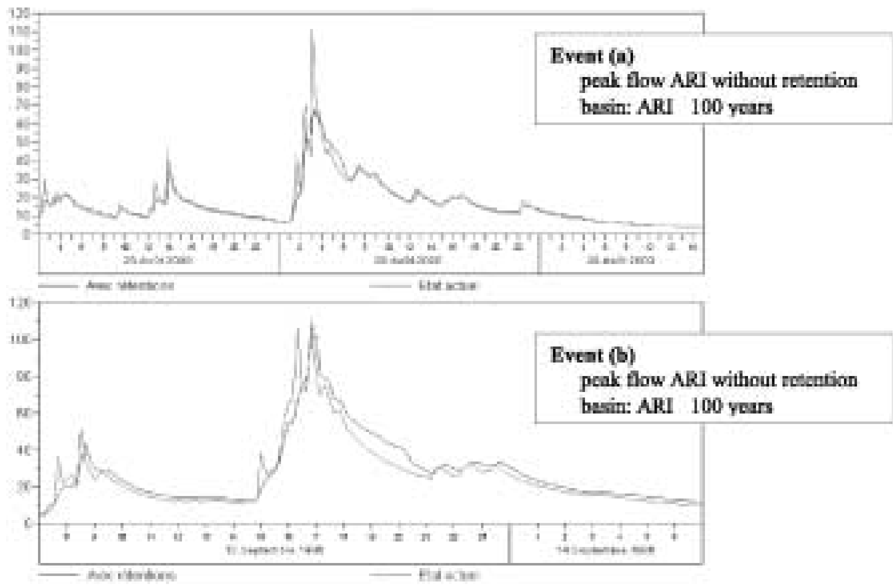


Figure 9 Simulated discharges (catchment outlet) with and without the retention basins system

shape or because they follow other in-going flood events which have already partially or entirely filled up the detention basins and/or the upstream sewer network.

(3) Finally, the working state frequencies are very different from one basin to another. The working state frequency of the R9 basin (125 times per century) is three times greater than the one of the R5 basin (42 times per century) whereas both of them have the same overloading frequency. If the land inside R9 basin could be used as a sport field it should not be the case for the R5 basin (Table 1).

Conclusions

This paper presents the methodology developed to design or to check the efficiency of stormwater retention basins. The major interests of this method are: (1) the production of long term rainfall series (100 years) with a short time step (10 mn) compatible with the rapid response times of urban catchments and representative of observed rainfall series, (2) the production of correlative long term discharge series thanks to an appropriate rainfall runoff model, (3) the simulation of the retention basin behaviour over a long term period and the consecutive characterisation of working-state and failure frequencies of the studied detention basins. The results obtained in terms of working-state and failure frequencies thanks to this continuous and long term approach are much more useful than simple results

Table 1 Average occurrence numbers (Av.Oc.Nb.) over 100 years for different filling rates and for the four detention basins

	Basin R2		Basin R5		Basin R8		Basin R9	
	V_{max}:	25,000 m^3	V_{max}:	15,000 m^3	V_{max}:	8,000 m^3	V_{max}:	30,000 m^3
Volume %	**Volume M^3**	**Av.Oc.Nb. / 100years**	**Volume m^3**	**Av.Oc.Nb. / 100years**	**Volume m^3**	**Av.Oc.Nb. / 100years**	**Volume m^3**	**Av.Oc.Nb. / 100years**
100	25,000	1.5	15,000	2.3	8,000	0.8	30,000	2.4
90	22,500	1.7	13,500	2.6	7,200	1.1	27,000	2.8
80	20,000	2.1	12,000	3.2	6,400	1.1	24,000	3.6
70	17,500	3.1	10,500	3.8	5,600	1.4	21,000	4.4
60	15,000	3.8	9,000	5.1	4,800	1.5	18,000	4.7
50	12,500	4.6	7,500	6.3	4,000	1.7	15,000	5.9
40	10,000	5.7	6,000	7.9	3,200	2.2	12,000	7.7
30	7,500	9.8	4,500	11.9	2,400	3.7	9,000	13.3
20	5,000	31.0	3,000	20.9	1,600	7.1	6,000	34.7
10	2,500	147.1	1,500	42.3	800	25.3	3,000	124.8

which could be obtained from single-event simulations. Such a continuous simulation actually takes into account the sequence of events and the inter-event times which are of most importance for detention projects. The case study presented in this paper is a good illustration for the high potential of such an approach for flood control reservoir design.

Acknowledgement

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