Effects of management rules on pre-filling of stormwater detention facilities

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ABSTRACT
Detention ponds are important for stormwater control. Insufficient design of these facilities may have significant impact in terms of flood and environmental safety. Although continuous simulation is sometimes used, often design procedures are based on the single-event approach and pre-filling possibility is neglected. This can lead to underestimation of pond insufficiency risk. Pre-filling probability is here analyzed for different pond management rules and some direct relationships are proposed. An application to a real case is also presented.

KEYWORDS
Detention facilities; stormwater management; pre-filling probability.

INTRODUCTION
Detention tanks and ponds are often used for downstream control in stormwater conveyance systems to reduce the risk of both flooding and environment pollution. Although proper probabilistic design of these facilities should be based on the stochastic process of flood events, often an event-based approach is adopted for design. This is often due to lack of hydrological data, in most cases limited to the knowledge of rainfall intensity-duration-frequency curves only, but sometimes also to the need of a fast “first-order” estimation of the control volume.
In the event-based approach, the detention facility is assumed to be always empty at the beginning of the storm event, neglecting the possibility of carryover from prior events. This carryover is related to the possibility that two successive storm events may be so close that the water volume stored at the end of the first one can’t be completely discharged before the beginning of the second one.
Although in most cases this possibility is low, sometimes insufficient design may result by neglecting it and an erroneous level of risk may be assumed. In literature, several methodologies have been presented to take into account this possibility and to estimate the corresponding volume, most of them based on semi-probabilistic analytical modeling (Di Toro and Small, 1979; Loganathan and Delleur, 1984; Adams and Papa, 1999). However, results are not completely satisfactory from an engineering point of view. The possibility of pre-filling and the size of carryover by prior events, in fact, is dependent not only on the nature of the storm stochastic process, particularly on the probability distribution of interevent time, but also on the way in which the facility is managed.
Relevance of the management rules of detention facilities on carryover probability is here investigated, using an analytical probabilistic methodology. Three rules have been identified, according to usual engineering practice. For each of them explicit relationships for pre-filling probability are derived and compared.

Reliability of the proposed approach and effects of management rules have been tested comparing results from application of theoretical relationships and from continuous simulation of a 21-years long series of rainfall intensities recorded in Milano. Continuous simulation of a synthetic storm series, generated through a Monte-Carlo procedure, was also performed, in order to compare results and to highlight the effects of simplified hypothesis used in the probabilistic approach.

MANAGEMENT RULES OF DETENTION FACILITIES

Although they may vary according to system setup (i.e. on-line or off-line) and to constrains on discharges, management rules are generally aimed to make operation of detention facilities more reliable and efficient. This means not only that the risk of uncontrolled overflows must be minimized, but also that the effect of water detention, i.e. flood peak attenuation and pollutant retention, must be maximized. Then, conflicts among different needs may arise and a unique "optimal" management rule cannot be identified. In order to consider different options, but always among the more common strategies, the following three management rules have been considered in the analysis, all with a constant outflow:

- Rule A: constant outflow q_u starts with the facility filling. If rectangular inflow hydrographs are considered (see the following chapter), this means that outflow starts at the beginning of each storm event and carryover from prior event is minimized (Figure 1a). However, this rule may be not feasible, e.g. due to temporary limited conveyance of downstream system.
- Rule B: constant outflow q_u starts only when the storm event is ended (Figure 1b). In this case outflow happens when inflow rates are low and limits due to effective conveyance of downstream system are overcome. A limit of this rule is the difficulty in the identification of storm end.
- Rule C: constant outflow q_u starts when the stored volume reaches a fixed value $\alpha\cdot \overline{w}$ less than or equal to the facility capacity $\overline{w}$ (Figure 1c). For $\alpha = 0$ this rule is the same than rule A. With this rule the number of outflows is minimized and water detention times are maximized, but the risk of carryover from prior events increases with coefficient α.

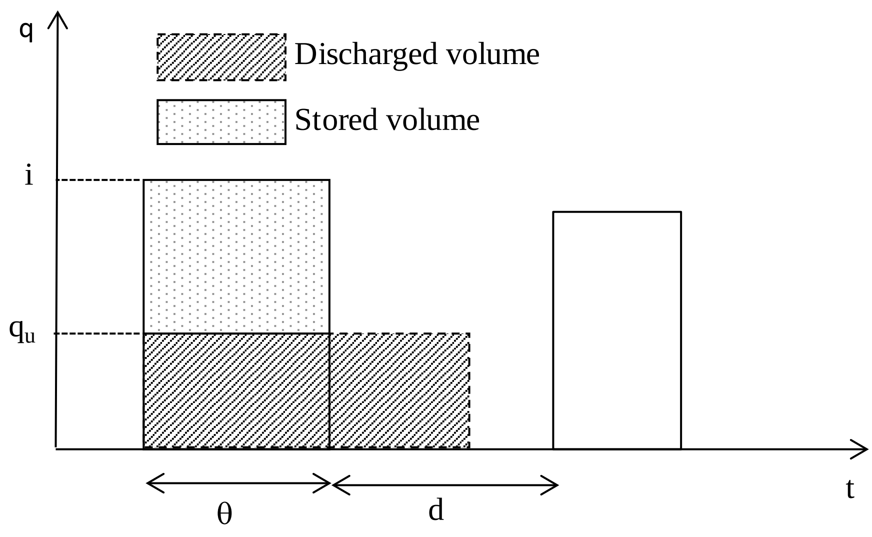

Figure 1a. Detention facility management rule A.

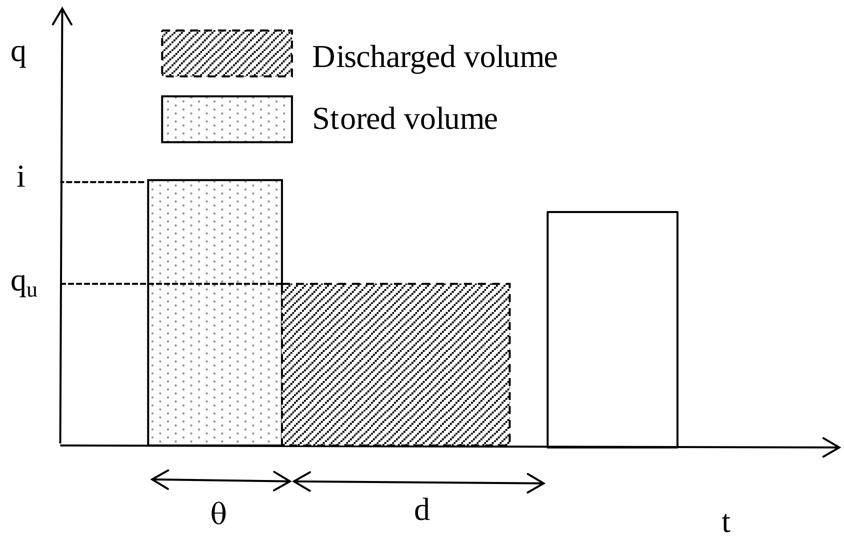

Figure 1b. Detention facility management rule B.

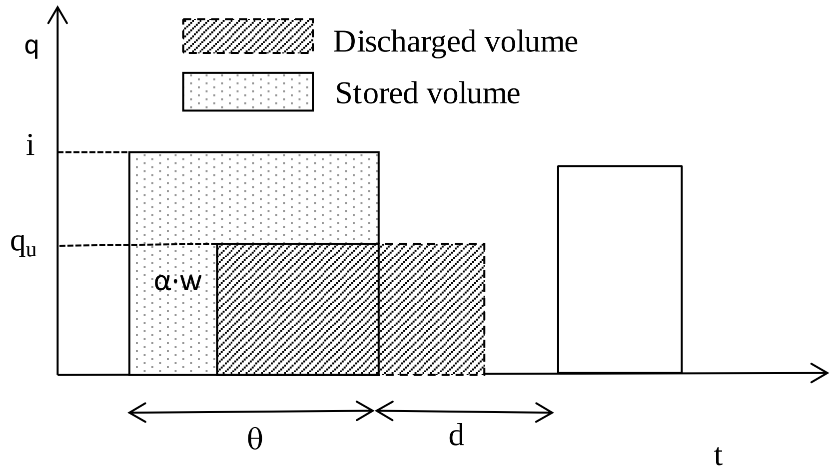

Figure 1c. Detention facility management rule C.

PROBABILITY OF CARRYOVER FROM PRIOR EVENTS

To analyze the dynamics of stored volume in a detention facility, a simplified scheme was adopted, based on the following hypothesis:

- outflow from facility has been considered constant (in this case the efficiency of the detention facility, in terms of inflow peak attenuation, is maximized);
- rainfall-runoff transformation has been neglected, considering rainfall intensities instead of water discharges (if the catchment upstream the detention facility is small, discharges may be considered approximately proportional to rainfall intensities);
- rainfall intensities have been considered constant in time (if inflow are always greater than the constant outflow for all the storm duration, the final stored volumes are independent from hydrograph pattern and rectangular events may be used);
- carryover have been assumed to be due to the previous storm only, so that a couple of storms at a time are considered.

To identify independent rainfall events, a minimum dry period, the so called InterEvent Time Definition (*IETD*) (USEPA 1986), is defined. To take into account effective storms only, an initial abstraction *IA* is assumed. In the following the (net) rainfall depth $h = h_{TOT} - IA$ will be considered. Rainfall depth h, rainfall duration θ and interevent time d, are considered as independent random variables with the following exponential PDFs (Chow, 1964; Howard, 1976; Adams and Bontje,1984; Adams *et al.*, 1986):

$$f_h = \xi e^{-\xi h}$$
$$f_\theta = \lambda e^{-\lambda\theta}$$
$$f_d = \psi e^{-\psi(d-IETD)}$$

with $\xi = \frac{1}{\mu_h},\ \lambda = \frac{1}{\mu_\theta},\ \psi = \frac{1}{\mu_d - IETD}$,

being μ_x= expected value of random variable x. Although the observed distributions of rainfall characteristics are in most cases different from the exponential one (generally the Weibull or the Gamma distribution are more suitable), this hypothesis is considered acceptable if an $IETD$ of more than 4 hours is considered (Eagleson, 1972; Wenzel and Vorhees, 1981; Hvitved-Jacobsen and Yousef, 1987).
By means of analytical functions, the carryover probability is calculated for a couple of chained storm events from the probability distribution function of the three rainfall parameters (rainfall depth h, rainfall duration θ, interevent time d) for the three management rules. The following auxiliary dimensionless variables are introduced:

$$q^* = q_u \frac{\mu_\theta}{\mu_h} = q_u \frac{\xi}{\lambda}$$

$$\beta = \frac{q_u \xi}{\psi + q_u \xi} = \frac{q^*}{\frac{\psi}{\lambda} + q^*}$$

$$\delta = 1 - \xi\alpha\bar{w}.$$

Probabilities have been calculated considering the two possible states of the detention facility at the end of the first storm: stored volume smaller than facility capacity ($w_i < \bar{w}$) or equal to capacity ($w_i = \bar{w}$). The general condition $\frac{\bar{W}}{q_u} > IETD$ for the possibility of pre-filling has also to be taken into account.

<u>*Rule A*</u>

The carryover from prior storm can be expressed as:

$$w_{pr} = \begin{cases} h - q_u\theta - q_u d & if \quad h - q_u\theta < \bar{w}; h - q_u\theta - q_u d > 0 \\ \bar{w} - q_u d & if \quad h - q_u\theta \geq \bar{w};\ \bar{w} - q_u d > 0 \\ 0 & otherwise \end{cases}$$

Combining the above relationships with the associated conditional probabilities, the carryover probability for rule A is:

$$P\left(w_{pr} > 0\right) =$$

$$= \int_{\theta=0}^{\infty} f_\theta \, d\theta \int_{h=q_u(\theta+IETD)}^{\overline{w}+q_u\theta} f_h dh \int_{d=IETD}^{\frac{h}{q_u}-\theta} f_d dd$$

$$+ \int_{\theta=0}^{\infty} f_\theta \, d\theta \int_{h=\overline{w}+q_u\theta}^{\infty} f_h dh \int_{d=IETD}^{\frac{\overline{w}}{q_u}} f_d dd =$$

$$= \frac{(1-\beta)}{(1+q^*)}\left(e^{-\lambda q*IETD} - e^{\psi IETD - \frac{\xi \overline{W}}{\beta}}\right)$$

Analogously, for the other rules the resulting relationships are:

Rule B

$$w_{pr} = \begin{cases} h - q_u d & if \quad h < \overline{w};\ h_n - q_u d > 0 \\ \overline{w} - q_u d & if \quad h \geq \overline{w};\ \overline{w} - q_u d > 0 \\ 0 & otherwise \end{cases}$$

$$P\left(w_{pr} > 0\right) = \int_{h=q_u IETD}^{\overline{w}} f_h dh \int_{d=IETD}^{\frac{h}{q_u}} f_d dd + \int_{h=\overline{w}}^{\infty} f_h dh \int_{d=IETD}^{\frac{\overline{w}}{q_u}} f_d dd =$$

$$= (1-\beta)\left(e^{-\lambda q*IETD} - e^{\psi IETD - \frac{\xi \overline{W}}{\beta}}\right)$$

Rule C

$$w_{pr} = \begin{cases} h_n & if \quad h < \alpha\overline{w} \\ h - q_u\theta\left(1 - \dfrac{\alpha\overline{w}}{\mu_{h_n}}\right) - q_u d & if \quad h \geq \alpha\overline{w};\ h - q_u\theta\left(1 - \dfrac{\alpha\overline{w}}{\mu_{h_n}}\right) < \overline{w}; \\ & \qquad h - q_u\theta\left(1 - \dfrac{\alpha\overline{w}}{\mu_{h_n}}\right) - q_u d > 0 \\ \overline{w} - q_u d & if \quad h \geq \alpha\overline{w}; h - q_u\theta\left(1 - \dfrac{\alpha\overline{w}}{\mu_{h_n}}\right) \geq \overline{w}; \overline{w} - q_u d > 0 \\ 0 & otherwise \end{cases}$$

$$P\left(w_{pr} > 0\right) = \int_{h=0}^{\alpha\overline{w}} f_h dh +$$

$$
+ \int_{\theta=0}^{\infty} f_\theta \, d\theta \int_{h=q_u IETD+q_u\theta(1-\xi\alpha\bar{w})}^{\bar{W}+q_u\theta(1-\xi\alpha\bar{w})} f_h dh \int_{d=IETD}^{\frac{h}{q_u}-\theta(1-\xi\alpha\bar{w})} f_d dd
$$

$$
+ \int_{\theta=0}^{\infty} f_\theta \, d\theta \int_{h=\bar{w}+q_u\theta(1-\xi\alpha\bar{w})}^{\infty} f_h dh \int_{d=IETD}^{\frac{\bar{w}}{q_u}} f_d dd =
$$

$$
= \left(1 - e^{\delta-1}\right) + \frac{1+\beta}{1+\delta q *}\left(e^{-\lambda q * IETD} - e^{\psi IETD - \frac{\xi \bar{W}}{\beta}}\right)
$$

Relationships for carryover probability are similar in the three cases. As expected, this probability is minimum for rule A and maximum for rule C with $\alpha = 1$.

APPLICATION

The above relationships have been tested comparing their estimates of carryover probability with the sample values obtained by continuous simulation of the rainfall series recorded in Milano, Italy, from 1971 to 1991. This series was recorded with a time resolution of 1 minute and a depth resolution of 0.2 mm. Two different IETD have been used to identify independent rainfall events, 1 hour and 10 hours, the first one smaller and the second greater than standard value of 4 hours (Wanielista, 1990). A initial abstraction IA = 2 mm was applied to recorded depths. The number of storms in the series is 1453 for IETD=1 hour and 979 for IETD=10 hours. Mean and standard deviation of rainfall characteristics are shown in table 1, while the correlation coefficients among them are shown in table 2.

Table 1. Mean and variance of rainfall characteristics in the Milano series.

	IETD =1h		IETD =10h	
	μ	σ	μ	σ
h [mm]	11.50	15.38	16.49	21.33
θ [hour]	6.78	7.31	14.37	14.81
d [hour]	119.33	183.96	172.81	223.89

Table 2. Correlation coefficient among rainfall characteristics in the Milano series.

	IETD =1h	IETD =10h
$\rho_{h,\theta}$	0.66	0.62
$\rho_{h,d}$	0.03	0.11
$\rho_{d,\theta}$	0.04	0.11

As can be observed, while the other characteristics are only weakly correlated, rainfall depths and durations are not independent random variables as assumed. More, also the hypothesis of exponential CDFs for all three rainfall characteristic is not well suited to the samples of recorded values. Both results are not unexpected, since they were observed for rainfall in the Alpine catchments in previous studies (see e.g., Bacchi *et al.*, 1994, 2008), but these hypotheses has been held anyway to avoid a considerable increase in the complexity of relationships.

To test the effects on results of these inconsistencies between the real storm series and the adopted probabilistic model, a second storm series, consistent with the above hypotheses, was generated with a Monte Carlo procedure. This synthetic series has the same number of events of the original recorded one, but rainfall characteristics are independent and exponentially distributed with the observed means. In figure 2 the probabilities of carryover estimated by the proposed relationships for the three management rules are compared with the cumulated frequencies calculated by continuous simulation of both the recorded and the synthetic storm series. Results are reported versus the detention facility capacity $\bar{w}$ and for q^* = 0.5, 1.0, 2.0 for the two cases of IETD=1hour and IETD=10 hours.

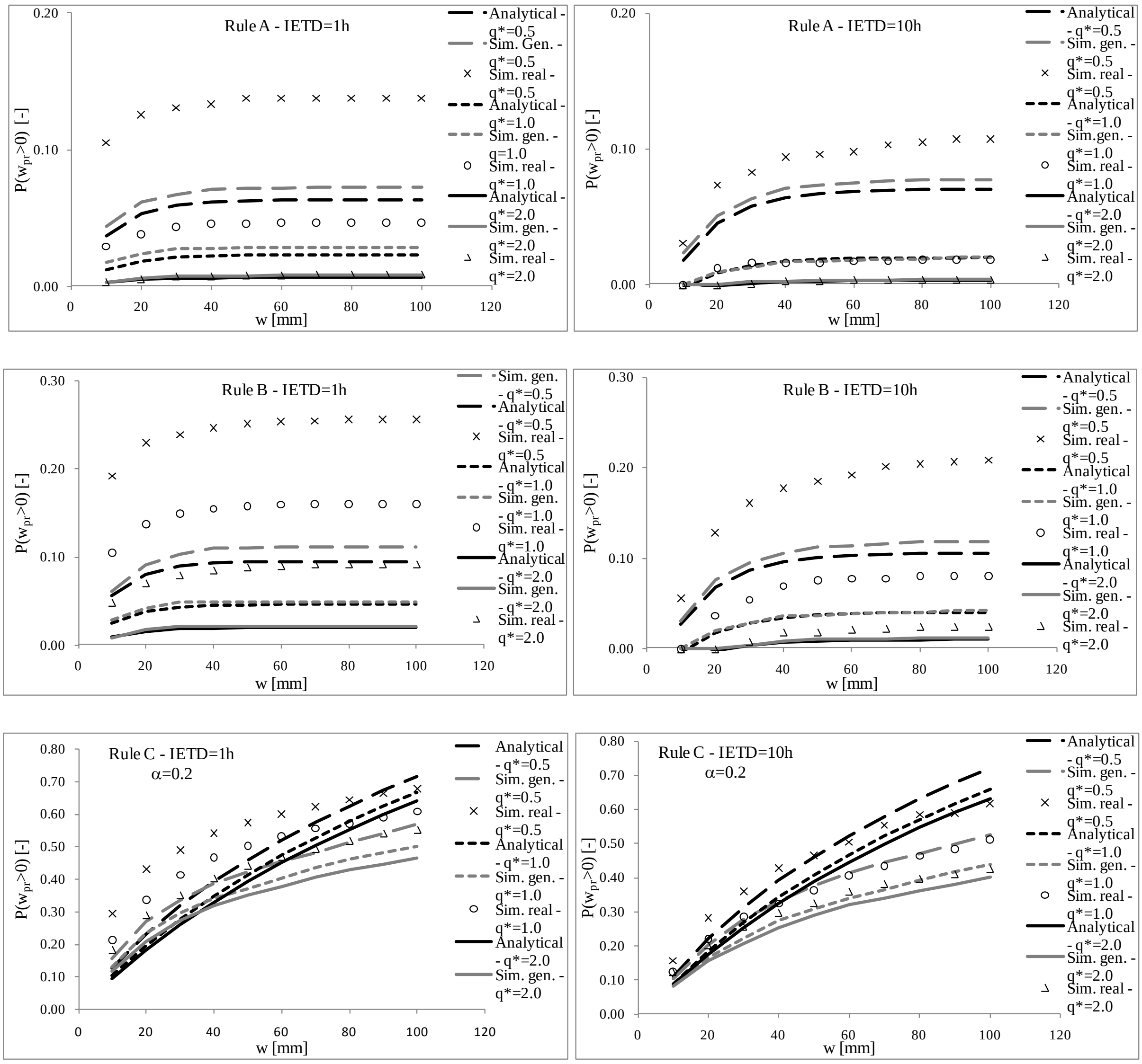

Figure 2. Comparison of carryover probability from analytical relationships and continuous simulation of real and synthetic storm series, for the three different management rules.

CONCLUSIONS

Simple relationships for the estimation of carryover probability in detention facilities have been developed for three different management rules. Results show that this probability is variable with the management rule of the facility and in some cases is not negligible as often

assumed. As expected, considering the same values for the other parameters, it increases with facility capacity and decreases with outflow rate.
For the case study, if a constant outflow equal to the ratio of rainfall depth and duration is considered (q*=1), this probability varies from few percent with the rule A to 50% and more with rule C with α=0.2.
Estimates given by the proposed relationships seem to be enough good if the comparison with the continuous simulation of the synthetic series is considered. A tendency to slightly underestimate the probability respect to continuous simulation results is observed for rules A and B. On the contrary, an overestimation is observed for rule C. In both cases, these differences are probably related to the fact that sometimes carryover is due to more than one prior event, as considered in the analytical approach.
Greater differences can be noticed with the results from the continuous simulation of the recorded series. In this case, the proposed relationships underestimate more significantly the carryover probability, especially when low outflows are assumed. The different results in the two cases, with the recorded and the synthetic series, show that the effect of the hypotheses of independency and exponential distribution of rainfall characteristics is significant.
Although it has to be noticed, however, that the differences in the estimates are more significant in percentage than in absolute terms, it will be worthwhile to try an improvement of the accuracy of proposed relationships, relaxing some of the simplifying hypotheses. Anyway, a trade-off between accuracy and simplicity of resulting equations should be found.
In conclusion, the presented analytical-probabilistic scheme seem suitable to reproduce, even in a simplified way, the stochastic process of successive fillings and emptying of a detention facility. The effect of different management rules on the carryover probability has been analyzed and simple relationships for its estimation were presented.

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