Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 70 (2014) 1391 – 1400

Procedia Engineering

www.elsevier.com/locate/procedia

12th International Conference on Computing and Control for the Water Industry, CCWI2013

Probabilistic design of multi-use rainwater tanks

A. Raimondi[a,]*, G. Becciu[a]

[a] *Politecnico di Milano, P.zza L. da Vinci 32, 20133 Milano, Italy*

Abstract

Many studies have revealed that traditional approaches in urban stormwater drainage may sometimes be insufficient to manage properly the unbalance of water cycle due to urbanization. In response to these increasing concerns, many cities have encouraged the applications of local disposal of rainwater. In particular multi-use rainwater tanks, combine the advantages of infiltration basins and tanks for rainwater use.

This paper proposes a procedure for their design based on an analytical probabilistic approach. Finally, an application to a case study is presented.

Keywords: Multi-use rainwater tanks; probabilistic approach; pre-filling

1. Introduction

One of the main consequences of urbanization is the increase of impermeable surfaces and the intensification of flood events. In some cases the only downstream control of runoffs has caused insufficiencies of the urban drainage system and its management is often complex and expensive. Moreover the rapid population growth, especially in developing countries and the climate changes impose to pay more attention to water saving.

In last decades the interest for the use of multi-use rainwater tanks is increased due to the great flexibility of operation modes they allow. They can have different configurations; often they are composed of different

* Corresponding author. Tel.: +39-02-2399-6208; fax: +39-02-2399-6207.
E-mail address: anita.raimondi@polimi.it

doi:10.1016/j.proeng.2014.02.154

compartments each of them with a specific function. The coupling of a rainwater use tank with an infiltration basin allows to meet both the need of water saving and of local control of runoffs which would otherwise be handled by the urban drainage system. Rainwater collected from roof is generally not much polluted and can be used for different purposes representing, especially during dry periods, a precious source for water supply. On the other hand infiltration basins temporarily store rainwater volumes and then infiltrate it into the soil even under conditions of low permeability.

A multi-use rainwater tank can satisfy these different requirements. The issue in the design of this kind of facilities is to find a balance between the need of a water volume for the desired use and of a storage volume for minimizing uncontrolled spills. That is, infiltration basins should empty as quickly as possible between two consecutive rainfall events to guarantee the maximum storage volume, while to satisfy the desired water supply a residual volume should be stored in the facility.

In literature many authors (Camnasio and Becciu, 2011; Ahmed and Sarma, 2005; Karamouz and Araghinejad, 2008; Mehta and Jain, 2009) have proposed methods for the optimization of multi-purpose reservoirs, most based on genetic algorithms, fuzzy logic or continuous simulation of long-term series of data. These studies have been mainly made on large basins where effects of single events are less evident and issues are different.

On small scale, as in the case of multi-use rainwater tanks for buildings, the stochastic process of rainfall events should be closely considered, to make a reliable design of the facility. Although in literature several methods are proposed to take into account this process, mainly based on simulation techniques, the temporal interconnection among events is often disregarded when direct approaches are considered. Traditional design storm approaches consider a critical rainfall, isolated from the temporal sequence of events, neglecting the probability of pre-filling from the previous events with consequent underestimation of the storage volume. This aspect is particularly relevant for infiltration basins often characterized by low infiltration rates (Becciu and Raimondi, 2012). In this case, storage volume can no completely empty even for more than two consecutive rainfall events especially when clogging occurs.

Modern analytical probabilistic approaches combine the simplicity of the event-based methods and the probabilistic reliability of the continuous simulations. Their application to detention facilities was first investigated by Adams and Papa (2000). These methods are based on the probabilistic analysis of functions of random variables, aimed to the analytical derivation of their probability distributions, eased by some simplifying hypotheses. The use of analytical probabilistic approaches for the design of both infiltration basins and storage units in green buildings has been applied with good results by some authors (J.C.Y. Guo, 2001; Y. Guo, 2007).

In this paper an analytical probabilistic approach to size multi-use rainwater tanks is proposed, aimed to find an optimal trade-off between the risk of water shortage and the risk of overflow.

A case study to test the reliability of the resulting formulas has been finally discussed.

2. Modeling of the stochastic rainfall process

To isolate independent rainfall events a minimum interevent time (IETD) has to be defined. If the interevent time (d) is greater the $IETD$, two consecutive rainfall events are considered independent otherwise they are joined together into a single rainfall event.

In the modeling of storage volumes the three main variables characterizing the stochastic process of rainfall are rainfall depth (h), rainfall duration (θ) and interevent time (d). For many basins (e.g. in the U.S.A.) their probability function can be assumed exponential distributed:

$$f_h = \xi \cdot e^{-\xi \cdot h} \tag{1}$$

$$f_\theta = \lambda \cdot e^{-\lambda \cdot \theta} \tag{2}$$

$$f_d = \psi \cdot e^{-\psi \cdot d} \tag{3}$$

$\xi = 1/\mu_h$, μ_h : average rainfall depth
$\lambda = 1/\mu_\theta$, μ_θ : average rainfall duration
$\psi = 1/\mu_d$, μ_d : average interevent time

Studies on Italian basins have shown that the Weibull probability distribution function (Bacchi, 2008) and the double-exponential probability distribution function (Raimondi and Becciu, 2013) better fit to the frequency distribution of observed data. In particular, the effects of the bias due to the use of the exponential distribution has been deeply discussed by Raimondi and Becciu (2013).

For simplification, net rainfall intensities have been used as inflow rates in the basin neglecting the rainfall-runoff transformation. This hypothesis can be reliable for small catchments (e.g. roofs) where runoffs can be assumed approximately proportional to rainfall intensities. As consequence, runoff duration has been considered equal to rainfall duration although in reality the duration of a runoff event is usually longer than that of a rainfall event.

The schematization of the multi-use rainwater tank is shown in Figure 1. Rainwater harvested on the roof is collected by gutters into the multi-use rainwater tank. It is composed of two compartment: the first one is completely impermeable and stores water that is then used for different purposes. The second one has a permeable bottom from which stored rainwater is infiltrated into the soil.

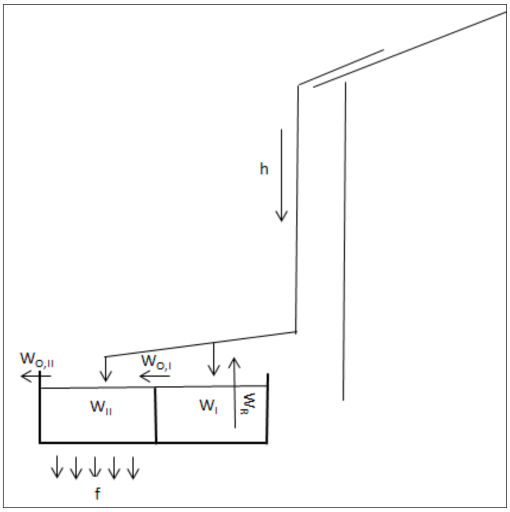

Figure 1. Multi-use rainwater tank schematization

W_R : volume of rainwater use
W_I : volume of the first compartment (rainwater use tank)
W_{II} : volume of the second compartment (infiltration basin)
f : infiltration rate at saturation
$W_{O,I}$: overflow volume from the first compartment to the second one
$W_{O,II}$: overflow volume from the second compartment to the urban drainage system

Two different operation modes have been considered:

- Rainwater use system on
- Rainwater use system off

When the rainwater use system is on (Figure 2), all rainwater is stored into the first compartment. If the inflow volume exceeds the storage volume, the surplus is discharged into the second compartment and then infiltrated into the soil.

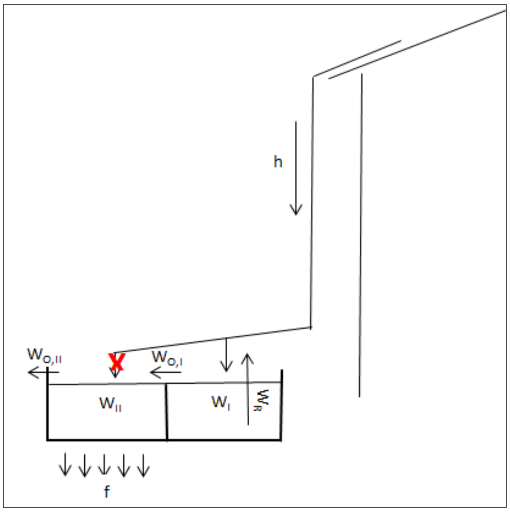

Figure 2. Operating mode with the system for rainwater use on

If the rainwater use system is off (Figure 3), all rainwater is directly collected to the second compartment and then infiltrated into the soil. Infiltration rate into the soil is conservatively assumed equal to the infiltration rate at saturation. When the storage volume is full, spills into the urban drainage system occur.

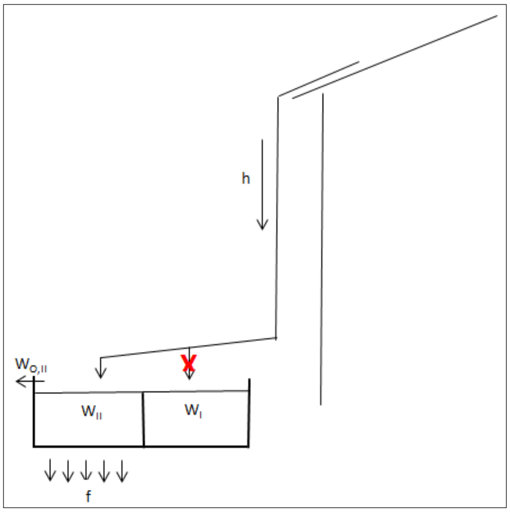

Figure 3. Operating mode with the system for rainwater use off

3. Multi-use rainwater tank design

Each of the two compartments of the multi-use rainwater tank has been sized separately.

For the design of the first compartment (tank for rainwater use) the scheme shown in Figure 2 has been considered. Generally, the system for rainwater use is activated at constant time intervals. In a generic period, the probability of complete rainwater use (P_R) can be expressed by:

$$P_R = \sum_{n=1}^{N} P_n(n) \cdot P\left(h \geq \frac{W_R}{A_D \cdot n}\right) \tag{4}$$

$P_n(n)$: probability that n rainfall events occur in the considered period
n : number of rainfall events in the considered period
N : maximum number of rainfall events in the considered period
A_D: catchment area

If a Poisson probability distribution function is assumed for $P_n(n)$, the solution of equation (4) is:

$$P_R = \sum_{n=1}^{N} e^{-\mu_{nx}} \cdot \frac{\mu_{nx}^n}{n!} \cdot \int_{h=\frac{W_R}{A_D \cdot n}}^{\infty} f_h \cdot dh = \sum_{n=1}^{N} \frac{\mu_{nx}^n}{n!} \cdot e^{-\left(\frac{\xi \cdot W_R}{n \cdot A_D} + \mu_{nx}\right)} \tag{5}$$

μ_{nx} : average number of rainfall events in the considered period

By means of the relation between the probability of success and the return period (T):

$$P(x \geq X) = 1 - \frac{1}{T} \tag{6}$$

and posed $W_R = W_I$, the volume of the first compartment of the multi-use rainwater tank (W_I) can be estimated.

The surplus of rainwater stored in the first compartment of the multi-use rainwater tank (tank for rainwater use) is spilled into the second compartment (infiltration basin). To size its storage volume, the second operation mode (system for rainwater use off) should be considered (see Figure 3), since it involves the maximum storage volume. In this case, all rainwater is collected to the second compartment and then infiltrated into the soil. As discussed by Guo, (2001) for the design of this kind of facilities the probability of overflow has to be considered. Due to the low outflow rates, often the infiltration volume can no empty completely between two consecutive rainfall events. This aspect influences the storage capacity and cannot be neglected in the estimation of the storage volume (Becciu and Raimondi, 2012). Two possible operating conditions can occur at the beginning of each rainfall event:

- Storage volume completely available, that is interevent time (d) sufficient to completely drain the infiltration basin
- Storage volume partially filled, that is interevent time (d) less than the drainage time ($\bar{d}$)

If the drainage time ($\bar{d}$) to completely empty the infiltration basin is less than the minimum interevent time ($IETD$), the whole capacity is available at the beginning of the following rainfall event. Considering m consecutive rainfall events this condition can be expressed by:

$$\frac{W_{II}}{f \cdot A_F} < m \cdot IETD \leq m \cdot d \tag{7}$$

A_F : infiltration area

The probability of overflow from the second compartment of a multi-use rainwater tank (P_o), results:

$$P_O = \int_{d=\frac{m\cdot W_{II}}{f\cdot A_F}}^{\infty} f_d \cdot dd \cdot \int_{\theta=0}^{\infty} f_\theta \cdot d\theta \cdot \int_{h=\frac{W_{II}+f\cdot A_F\cdot\theta}{A_D}}^{\infty} f_h \cdot dh = \frac{\lambda\cdot A_D}{\xi\cdot f\cdot A_F+\lambda\cdot A_D} \cdot e^{-W_{II}\cdot\left(\frac{m\cdot\psi}{f\cdot A_F}+\frac{\xi}{A_D}\right)} \qquad (8)$$

If the time to completely drain the infiltration basin is greater than the minimum interevent time ($IETD$) two possible conditions can occur:

- Interevent time (d) greater than the drainage time ($\bar{d}$)
- Interevent time (d) less than the drainage time ($\bar{d}$)

Considering m consecutive rainfall events, this condition can be expressed by:

$$\begin{cases} m\cdot IETD \le \frac{W_{II}}{f\cdot A_F} \le m\cdot d \\ m\cdot IETD \le m\cdot d \le \frac{W_{II}}{f\cdot A_F} \end{cases} \qquad (9)$$

In this case, pre-filling between consecutive rainfall events can occur. To consider this possibility, the probability of overflow is expressed by:

$$\begin{aligned} P_O &= \int_{d=\frac{m\cdot W_{II}}{f\cdot A_F}}^{\infty} f_d \cdot dd \cdot \int_{\theta=0}^{\infty} f_\theta \cdot d\theta \cdot \int_{h=\frac{W_{II}+f\cdot A_F\cdot\theta}{A_D}}^{\infty} f_h \cdot dh + \qquad (10) \\ &+ \int_{d=IETD}^{\frac{m\cdot W_{II}}{f\cdot A_F}} f_d \cdot dd \cdot \int_{\theta=0}^{\infty} f_\theta \cdot d\theta \cdot \int_{h=\frac{W_{II}+f\cdot A_F\cdot[m\cdot\theta+(m-1)\cdot d]}{m\cdot A_D}}^{\infty} f_h \cdot dh = \\ &= \frac{\lambda\cdot A_D}{\xi\cdot f\cdot A_F+\lambda\cdot A_D}\cdot e^{-W_{II}\cdot\left(\frac{m\cdot\psi}{f\cdot A_F}+\frac{\xi}{A_D}\right)} + \frac{m\cdot A_D^2\cdot\lambda\cdot\psi}{(f\cdot A_F\cdot\xi+\lambda\cdot A_D)\cdot[A_F\cdot f\cdot\xi\cdot(m-1)+m\cdot\psi\cdot A_D]} \\ &\quad \cdot\left[e^{-\frac{f\cdot A_F\cdot\xi\cdot IETD}{A_D}\cdot\left(1-\frac{1}{m}\right)-\psi\cdot IETD-\frac{\xi\cdot W_{II}}{m\cdot A_D}} - e^{-\frac{m\cdot\psi\cdot W_{II}}{f\cdot A_F}-\frac{\xi\cdot W_{II}}{A_D}}\right] \end{aligned}$$

4. Case study

For the application of the derived formulas to a case study, the series of rainfall data recorded at Milano-Monviso station during the period 1971-2005 has been used.

For small catchments (i.e. roofs), $IETD = 1\ hour$ can be adequate since concentration times are small.

$N_{tot} = 4161$ independent rainfall events have been identified and the values of ξ, λ, ψ are shown in Table 1.

Table 1. Values of ξ, λ and ψ

ξ [1/mm]	0,13
λ [1/hour]	0,23
ψ [1/hour]	0,01

Formulas (5) and (8) have been applied with reference to volume for unit of area [mm].

With regard to the first compartment of the multi-use rainwater tank (tank for rainwater use), two different regulations have been considered:

- Daily regulation

- Weekly regulation

To calculate the probability of complete rainwater use (P_R), the average and maximum number of rainfall events in the considered period (respectively μ_{xn} and N_x) have to be estimated.

Generally, the average number of rainfall events (μ_{nx}) in the considered period, can be expressed by:

$$\mu_{nx} = \frac{N_{tot}}{nx} \tag{11}$$

N_{tot} : total number of recorded rainfall events in the considered period
nx : number of weeks/days in the considered period

With reference to a weekly regulation the average number of rainfall events (μ_{nw}) results:

$$\mu_{nw} = \frac{N_{tot}}{nw} = \frac{4161}{15 \cdot 52} = 5{,}33\ events/week$$

While considering a daily regulation, it is:

$$\mu_{nd} = \frac{N_{tot}}{nd} = \frac{4161}{15 \cdot 365} = 0{,}76\ events/day$$

The maximum number of rainfall events (N_x) in the considered period (d_R), can be estimated by:

$$N_x = \frac{d_R}{IETD} \tag{12}$$

For weekly and daily regulation it respectively results:

$$N_w = \frac{d_R}{IETD} = \frac{7*24}{1} = 168\ events$$
$$N_d = \frac{d_R}{IETD} = \frac{24}{1} = 24\ events$$

The probability distribution of complete rainwater use (P_R), varying the storage volume of the first compartment (w_I) is shown in Figure 4.

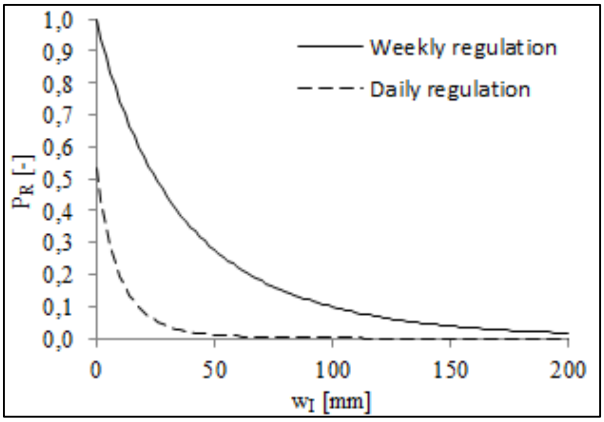

Figure 4. Probability of complete rainwater use (P_R) for weekly and daily regulation varying the volume of the first compartment (w_I)

Since the volume of the first compartment (w_I) has been assumed equal to the volume for rainwater use (w_R), the probability of complete rainwater use decreases with increasing volume. Obviously, the probability of complete rainwater use is higher if a weekly regulation is considered. With reference to a daily regulation, the probability of complete rainwater use is different of one even if the storage volume is null (see Figure 4); this because for the considered rainfall series there is less than one event per day.

The probability of overflow from the second compartment (infiltration basin) of a multi-use rainwater tank, has been estimated for different infiltration rates at saturation . Equation (10) considers the possibility that the basin not drains completely before the next rainfall event occurs. Theoretically, an infiltration basin could never empty completely. It has been demonstrated (Raimondi and Becciu, 2013) that the effects of the pre-filling from previous rainfall events are significant up to $m = 3$. The application of equation (10) to the case study has been presented in Figures 5-6-7. Figures 5 and 7 show the probability of overflow from the second compartment of a multi-use rainwater tank varying its volume (w_{II}) and the number of considered consecutive rainfall events (m) for infiltration rates at saturation (f) respectively equal to 1 $mm/hour$ and 0,01 $mm/hour$. Figure 6 shows the probability of overflow from the second compartment of a multi-use rainwater tank (P_o) varying its volume (w_{II}) for infiltration ratse $f = 2 - 5 - 10\ mm/hour$, assumed the number of considered consecutive rainfall events (m) equal to 1.

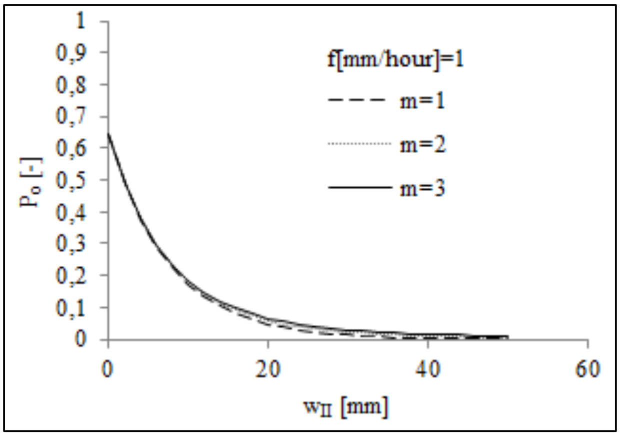

Figure 5. Probability of overflow from the second compartment of the multi-use rainwater tank (P_o) varying its volume (w_{II}) and the number of considered consecutive rainfall events (m), with infiltration rate at saturation (f) equal to 1 $mm/hour$

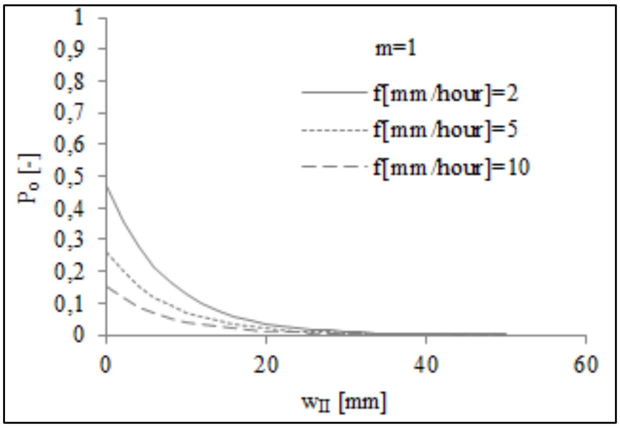

Figure 6. Probability of overflow from the second compartment of the multi-use rainwater tank (P_o) varying its volume (w_{II}) and the infiltration rate at saturation (f), assumed the number of considered consecutive rainfall events (m) equal to 1

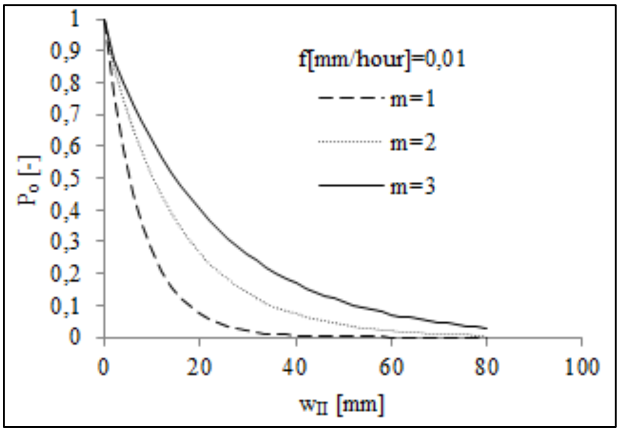

Figure 7. Probability of overflow from the second compartment of the multi-use rainwater tank (P_o) varying its volume (w_{II}) and the number of considered consecutive rainfall events (m), with infiltration rate (f) equal to 0,01 $mm/hour$

Generally, the probability of overflow (P_o) decreases with increasing the volume of the infiltration basin (w_{II}) and the infiltration rate at saturation (f). Since the average rainfall intensity (λ/ξ) is very low (1,79 $mm/hour$), already for infiltration rate equal to 1 $mm/hour$, the infiltration basin empties at the end of each rainfall event, especially for small volumes (see Figure 1). For null storage volume ($w_{II} = 0$), the probability of overflow (P_0) represents the probability that rainfall intensity is greater than infiltration rate. Considering a single rainfall event (see Figure 6), the probability of overflow decreases fastest with increasing the basin volume for low infiltration rates. Anyway for specific volume $w_{II} > 200\ m^3/ha_{imp}$, the probability of overflow results lower than 10%. Only when the basin clogs ($f = 0{,}01\ mm/hour$), the probability of overflow drops below 10% for specific volume $w_{II} > 600\ m^3/ha_{imp}$. In this case, the effects of pre-filling from previous rainfall events can not be neglected and strongly influences the probability of overflow.

5. Conclusion

Multi-use rainwater tanks can be effective tools for the localized control of urban runoffs. The division of the whole capacity in two compartments whit different functions allows a better operation efficiency of the facility and a rationed usage according to the requirements. For example, during spring and summer months, the system for rainwater use can be on and all rainwater can be stored in the first compartment of the multi-use rainwater tank while only the spills into the second compartment are infiltrated; during dry periods stored rainwater can be pumped out and used for irrigation. During autumn and winter months, the system for rainwater use can be off and rainwater collected from the roof can be directly stored in the second compartment (infiltration basin) and then infiltrated into the soil.

The design of multi-use rainwater tanks should meet the different needs of the two compartments. For the first compartment (tank for rainwater use), the probability of complete rainwater use at constant (weekly and daily) intervals has been estimated. For the second compartment (infiltration basin) the probability of overflow in the urban drainage system has been considered. In this case, formulas take into account the possibility of pre-filling from previous rainfall events, especially for low infiltration rates.

Results of the application of resulting equations to a case study in Milan (Italy), show that the probability of complete rainwater use strongly depends on the period of regulation. If a weekly regulation is considered, the probability of complete rainwater use is good for small storage volumes, that is for small volumes of rainwater use.

On the contrary, in case of daily regulation, the probability of complete rainwater use is always below to the fifty percent, since the recorded series presents less than one rainfall event per day.

With the reference to the second compartment of the multi-use rainwater tank (infiltration basin), the probability of overflow is significant only for small storage volumes and low infiltration rates. In particular, for the considered rainfall data, the effects of pre-filling can be neglected in most cases, except when the basin clogs and infiltration rate falls near to zero. This underlines the importance of regular maintenance that guarantees the efficiency of this kind of facilities in the control of urban runoffs.

Reference

B.J. Adams and F. Papa, Urban Stormwater Management Planning with analytical probabilistic models, New York, USA: John Wiley & Sons, 2000.

J.A. Ahmed, A.K. Sarma, “Genetic algorithm for optimal operating policy of a multipurpose reservoir”, Water Resources Management, Springer, 2005.

B. Bacchi, M. Balistrocchi, G. Grossi, “Proposal of a semi-probabilistic approach for storage facility design”, Urban Water Journal, Vol. 5, No 3, pp. 195 – 208, 2008.

G. Becciu and A. Raimondi, “Factors affecting the pre-filling probability of water storage tanks”, in WIT Transactions: Ecology and the Environment, volume 164 (Water Pollution XI), WIT, 2012, pp. 12.

Camnasio, E., Becciu, G., 2011. Evaluation of the Feasibility of Irrigation Storage in a Flood Detention Pond in an Agricultural Catchment in Northern Italy, Water Resour. Manage., 25, 1489–1508.q

J. C. Y. Guo, “Storage Volume and Overflow Risk for Infiltration Basin Design”, Journal of Irrigation and Drainage Engineering, vol. 127, no. 3, 2001, pp. 170–175.

Y. Guo, B.W. Baetz, “Sizing of Rainwater Storage Units for Green Building Applications”, Journal of Hydrologic Engineering, 2007.

M. Karamouz, S. Araghinejad, “ Drought mitigation through long-term operation of reservoirs: case study”, J Irrig Drain Eng 124(4):471–478, 2008.

R. Mehta, S.K. Jain, “Optimal operation of a multi-purpose reservoir using neuro-fuzzy technique”, Water Resources Management, Springer, 2009.