Reliability analysis of sustainable storm water drainage systems

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Abstract

The water balance of developed land is associated with reduced infiltration and large surface runoff leading to shorter concentration times, greater peak discharge, large total volume of runoff and minimum amount of water that infiltrates into the soil. Efforts to mitigate the negative impact of urbanization and manage storm water drainage in a more sustainable way could be achieved by increasing the storage capacity of the drainage system or by increasing the infiltration capacity of the urban catchment. Climate, the soil properties, the catchment characteristics and the storage capacity of the drainage system determine the effectiveness of the storm water controls that are constructed to retain or infiltrate part of the runoff volume. A probabilistic model for the estimate of the reliability of sustainable drainage and reuse system in a Mediterranean type climate is proposed for evaluating the reliability of the combined sustainable drainage and irrigation system.

1 Introduction

Urbanization, with the creation of extended impervious areas to the detriment of vegetated zones has and impact on the water and the energy balance in urban environments [1]. Maintaining or restoring vegetated areas in urban environments is becoming a major concern since vegetation alters water and energy fluxes through evapotranspiration, the soil sheltering action, and the indirect impact of root growth on the soil structure and thus on the soil infiltration capacity.

The concern about restoring (at least partially) the pre-development water balance is growing among urban hydrologist. Realizing infiltration systems and storage capacities is one way to enhance groundwater recharge, delay and reduce surface runoff and thus protect receiving water bodies and sewer system and prevent overflow. Detention basins are effective controls that attenuate peak

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discharge. When they act as infiltration system or in series with an infiltration system may help restoring the pre-development water balance. Plants growing on infiltration systems, increase their infiltration capacity by altering the vadose zone soil structure. Furthermore, plants by transpiration and soil sheltering, reduce the rise of urban temperature and increase the liveability of cities.

Many studies already focussed on the design criteria, performance and reliability of stormwater best management practices, such as bioretention facilities, rain gardens, vegetated rooftops, rain barrels, and permeable pavements (e.g. [2]), that preserve natural landscape features, minimize effective imperviousness and treat stormwater as a resource rather than a waste product. The probability approach [3] provides analytical equations for the estimate of the risk of failure of retention facilities and other elements of the urban drainage system and results in agreement with many physically based methods if applied to the study of low impact development.

Mediterranean type climate is characterized by winter rains alternating with summer drought and high temperature, that are often exacerbated by urbanization. In order to sustain vegetated infiltration systems, providing sufficient water for urban irrigation may be a challenging task. The shortage of water for irrigation during the dry season may be mitigated by rainwater reuse. Contextually, rainwater reuse may have a positive impact on the increasing demand for drinking water and the need for groundwater recharge, that are additional problems to deal with in expanding urban areas (e.g. [4]).

Stormwater harvesting structures reduce stormwater flows from a catchment and provide reuse volume for the irrigation of public vegetated areas, rainwater tanks reduce flows from roofs and supply water for irrigation of private gardens but can have an impact on the catchment water balance if many rainwater tanks are realized within the catchment area. The reliability analysis of multipurpose storage capacity is discussed in the following Sections in a conceptual framework that can be adapted to urban drainage problems at different scales, to concentrated as well as distributed stormwater control systems.

Stormwater harvesting and reuse schemes for existing urban areas are suitable for non-potable purposes such as irrigating public areas. In the following just their hydraulic operation scheme is analyzed, even though the design of a drainage, storage, reuse and distribution system should incorporate the analysis of public health and environmental risks that are beyond the scope of this study.

According to a low impact development approach, at least two different objectives may be desirable: to realize a flood detention structure acting mainly during the rainy season and to have a reuse volume available for irrigation during the dry season. Whether the same structure may be able to satisfy both objectives at different times of the year depends on climate, hydrology and management strategy. In Section 2 the conceptual model of the drainage and reuse system is described. In Section 3, two closed form solutions have been derived for the estimate of the risk of flood and the risk of irrigation water shortage. The reliability analysis applied to reuse systems received so far less attention than the reliability analysis of storage systems and the closed form equation for the risk of water shortage during the growing season was never considered before. The reliability analysis has been performed for different development levels, irrigation strategy and size of detention structure. In Section 4 the twofold problem of stormwater runoff management during the rainy season and green water reuse during the dry growing season by the use of the same detention structure is addressed with a probabilistic approach.

2 Model

2.1 Rainfall distribution

Small urban catchments have response times typically less that one hour. The assessment of rainfall at time scales from 1 to 10 minutes is a prerequisite for urban rainfall-runoff prediction [1]. Following the approach proposed by [5] rainfall depth (h), duration (t) and interevent time (b) are modelled as three independent random variables with exponential probability density function, in order to simplify the mathematical tractability. The distribution parameters are:

$\zeta =$ the inverse of the expected value of the rainfall depth;
$\lambda =$ the inverse of the expected value of rainfall duration; and
$\psi =$ the inverse of the expected value of the duration and inter-arrival respectively.

In a Mediterranean type climate ζ, λ and ψ assume different values during the rainy season and during the vegetation growing season [6].

2.2 Irrigation volume and channel protection storage capacity

An urban catchment is subdivided into two sub-catchments: a vegetated pervious sub-catchment and an impervious sub-catchment where infiltration is impeded (Figure 1). The percentage of the area that is impervious at a given stage of development is p, and $\frac{p}{1-p}$ is the development ratio at that time.

In the post development scenario, infiltration decreases and the peak discharge and the discharge volume increase. Assuming that the concentration time of the urban catchment does not change substantially with development and the hydrograph is triangular $V_s \approx pft$, where

$t =$ rainfall time and
$f =$ infiltration capacity of the pervious sub-catchment.

In a Mediterranean type climate the growing season of many vegetation species coincides with the dry season. Rainfed vegetation often suffers water stress due to the long inter-arrival time between successive rainfall events. In order to avoid vegetation water stress, the soil layers where the vegetation roots are established, must be maintained above the wilting point. Multipurpose storage capacities are designed to store the rainfall volume falling on the impervious surface to be reused for the irrigation of the vegetated part of the catchment (the pervious sub-catchment) in the inter-event time.

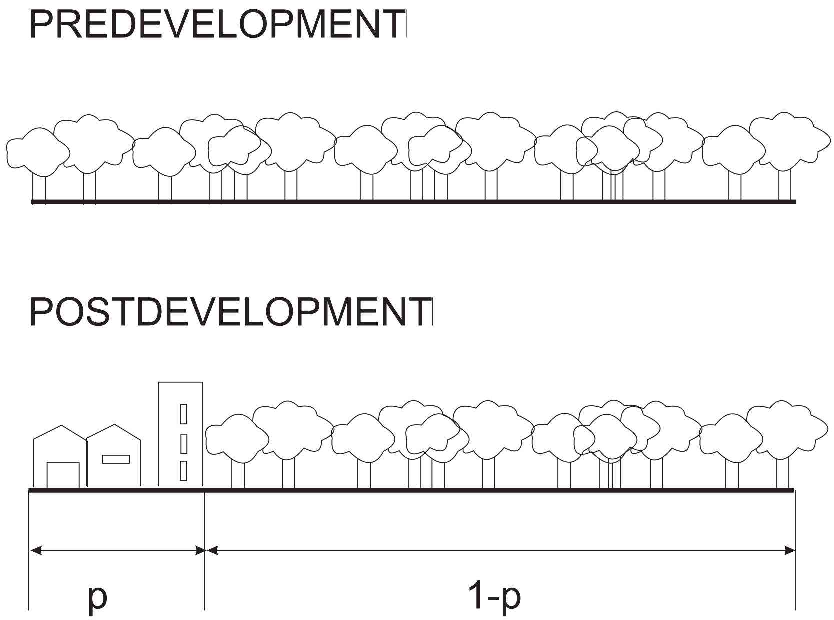

Figure 1: Subcatchment conceptual model.

The total rainfall volume that may be collected from the impervious area per unit surface is given by the product between the average rainfall volume and the average number of rainfall events during the growing season

$$V_i = p\,\frac{1}{\zeta} \cdot \frac{T_g}{\frac{1}{\lambda} + \frac{1}{\psi}} = p\,\frac{T_g}{\zeta}\,\frac{\lambda\,\psi}{\lambda + \psi} \tag{1}$$

When it rains, irrigation is not necessary, thus the average duration of the irrigation time during the growing season depends on the vegetation growing season T_g.

$$T_i = Tg\,\frac{\frac{1}{\psi}}{\frac{1}{\lambda} + \frac{1}{\psi}} = T_g\,\frac{\lambda}{\lambda + \psi} \tag{2}$$

The amount of water that must be supplied to the vegetation (the irrigation demand) depends on the vegetation physiology, the soil properties and climate. The maximum achievable irrigation rate is

$$\frac{V_i}{(1-p)\,T_i} = \frac{p}{1-p}\,\frac{\psi}{\zeta} \tag{3}$$

If the rainfall volume falling during the growing season is not enough to fulfill the irrigation demand additional drinking water must be provided for irrigation to ensure the vegetation survival.

The irrigation rate i may be the amount of water i' required to fulfill the transpiration losses and avoid that the soil moisture drops below the wilting point, or a lower rate, depending on the rainfall volume that may be effectively collected and reused during the irrigation time: $i = \min\left[i'; p\,\psi \cdot \zeta^{-1}\right]$.

3 Reliability analysis

3.1 Risk of flood

During the rainy season the probability that the rainfall volume exceeds the available storage capacity per unit surface, is given by the probability that the storage volume of a storm water retention capacity V_s is empty when the rainfall event occurs and the rainfall volume is $p\,h > V_s$ and by the probability that two consecutive rainfall events occur in a short time, at the beginning of the second rainfall event the storage capacity is $V_s' < V_s$ and the rainfall volume is $p\,h > V_s'$ [7]. V_s may eventually comprehend the capacity volume per unit surface of the storm water drainage system in addition to the capacity volume per unit surface of a constructed retention structure.

In the time between two consecutive rainfall events, the storage capacity is slowly emptied by gravity or by a pumping station in order to have $Q \leq Q_0$, where Q_0 is the maximum peak discharge for channel protection or overbank flood protection or extreme flood protection according to the prescribed return period of Q_0.

In order to accelerate the draw down of V_s, part of the outflow discharge may be conveyed to the pervious sub-catchment that functions as an infiltration system during the rainy season. Consequently, $Q = Q_0 + (1-p)\cdot f$, where f is the infiltration capacity of the pervious sub-catchment.

It is well known that the vegetation even if it is dormant, with its root apparatus alters the soil structure creating macropore flow and enhancing the soil infiltration capacity. As a consequence maintaining a vegetation cover on the pervious subcatchment may reduce the drawdown time of V_s and increase the reliability of the drainage system, even when it is not actively involved in the water balance.

The risk of flood due to the insufficient storage capacity of the stormwater retention basin is evaluated using derived probability distribution theory [5, 8].

$$R_f = \frac{\zeta\,Q}{\zeta\,Q + p\,\psi}\,e^{-V_s\left(\frac{\zeta}{p}+\frac{\psi}{Q}\right)} + \frac{\psi\,p}{\zeta\,Q + \psi\,p} \tag{4}$$

During the growing season the risk of flood is still given by equation (4) where the rainfall distribution parameters are characteristics of the dry season and Q equals the irrigation rate i.

3.2 Risk of water shortage (during growing season)

During the dry season the risk of overflow is expected to be lower than during the rainy season, and drawing down the storage capacity as soon as possible may be not so urgent as it is during the rainy season. During the growing season, the precipitation falling on the impervious area is conveyed into the storage tank with capacity and from there, in the time lag between subsequent precipitation events, is transported by a water irrigation system to the pervious subcatchment for irrigation at a rate $i < Q$. After each rainfall event the reservoir is full if $p\,h \geq V_s$.

Due to the variability of rainfall the storage volume may be empty when water for irrigation is necessary. A water crisis is perceived any time the interarrival between two subsequent precipitation events is larger that the draw down time of the storage capacity, in this case, the water storage capacity is empty when the irrigation request is positive and it does not yet rains. Assuming that the storage capacity is empty at the beginning of the previous rainfall event, the risk of water shortage is overestimate by the following equation

$$R_i = \frac{(1-p)\,i\zeta}{(1-p)\,i\zeta + \psi\,p} + \frac{\psi\,p}{(1-p)\,i\zeta + \psi\,p} \cdot e^{-\frac{V_s}{p}\,\frac{(1-p)\,i\zeta + \psi\,p}{(1-p)\,i}} \tag{5}$$

where $i =$ irrigation request.

4 Results

The average storage volume V_s required to reduce the peak discharge from the pervious surface at values comparable with the pre-development situation is supposed to be proportional to the missed infiltration volume pf

$$Q_0 = \alpha\,p\,f \tag{6}$$

If the pervious surface is used as an infiltration system during the rainy season

$$Q = Q_0 + (1-p) \cdot f \tag{7}$$

The detention volume V_s depends on the acceptable risk of failure of the structural stormwater control and is expressed here as follows.

$$V_s = \beta\,\zeta^{-1} \tag{8}$$

The parameters α and β are design parameters that depend on the design objectives, jurisdiction and site characteristics.

Small impervious catchments with quick hydrological response are expected to have higher α and β. For an urban catchment with surface of few hundreds hectares, based on literature data [9] and with reference to return time up to 100 years, it can be set $\alpha = 0 \div 25$ and $\beta = 1 \div 3$.

According to Romano *et al.* [6] R_f and R_i have been estimated for $\zeta = 0.14\,\mathrm{mm}^{-1}$; $\phi = 0.02\,\mathrm{hr}^{-1}$; $\zeta_G = 0.16\,\mathrm{mm}^{-1}$; $\phi_G = 0.008\,\mathrm{hr}^{-1}$; $\lambda = \lambda_G = 0.23\,\mathrm{hr}^{-1}$.

In Figure 2 the results of the reliability analysis have been plotted for $\alpha = 20$; $\beta = 4$; $i' = 0.05 \cdot f$.

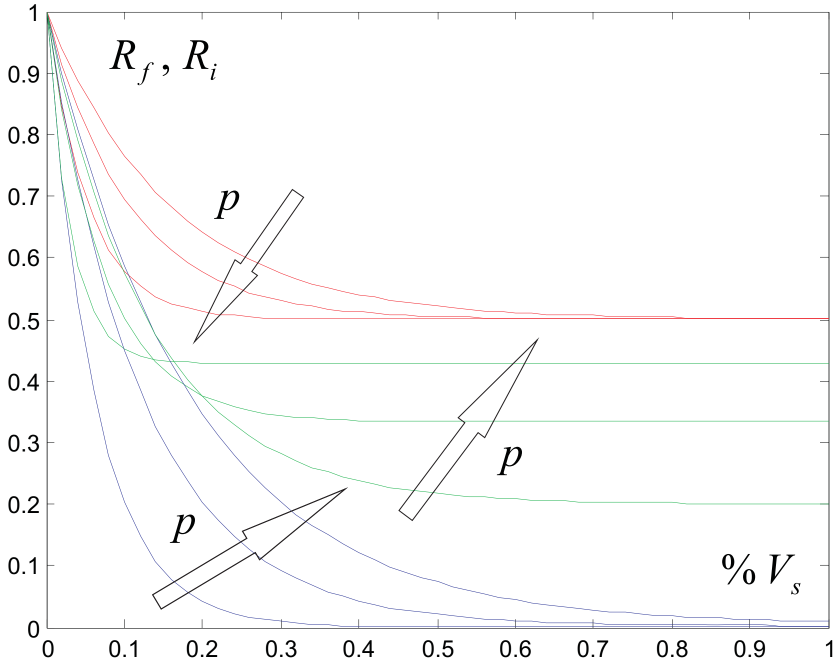

Figure 2: Results of reliability analysis risk of overflow during rainy season (blue lines); risk of drought (red lines) and risk of overflow (green lines) during dry growing season, as a function of the storage volume and for different developing stages ($p = 0.25$; 0.5; 0.75).

The risk of overflow during the rainy season (blue lines), the risk of drought (red lines) and the risk of overflow during the dry growing season (green lines) have been estimated as a function of the storage volume of the detention structure for different stage of urbanization, namely: $p = 0.25$; 0.5; 0.75.

Typical annual irrigation demand per unit surface of vegetated soil for open areas ranges between 300 and 800 mm, depending on climate, the vegetation physiology and the type of irrigation system used. The average rainfall volume falling during the rainy season is $V_r = p \cdot \frac{T_G \cdot \lambda_G \, \psi_G}{(\lambda_G + \psi_G) \cdot \zeta_G}$, according to equation (1). With $p = 1$ and $T_G = 5$ months, $V_r = 174$ mm, meaning that reused water cannot fulfill the irrigation demand and just a reduced irrigation rate may be provided instead of the irrigation demand. The risk of water shortage during the rainy season is high due to the low rainfall volume. More water must be provided from the distribution system and water reuse is not a reliable practice.

The risk of flood is almost the same during the dry and the rainy season for $V_s < 0.2\beta \, \zeta^{-1}$. The risk of flood decreases with increasing V_s, but it remains high during the growing season, meaning that if the detention capacity is used as storage capacity for irrigation purposes the drainage system lacks reliability.

By progressively increasing the storage capacity of the detention structure the risk of water shortage approaches its lower limit

$$R_{i,\,lim} = \frac{(1-p)\cdot\frac{i\,\zeta_G}{\psi_G}}{(1-p)\cdot\frac{i\,\zeta_G}{\psi_G}+p} \tag{9}$$

that, in general, depends on the dimensionless number $\frac{\psi_G}{i\,\zeta_G}$ and p, but it does not depend on p if the management strategy is dictated by equation (3).

Contextually, the risk of flood during the growing season approaches its lower limit

$$R_{f,G,\,lim} = \frac{p}{\frac{\zeta_G\,i}{\psi_G}+p} \tag{10}$$

Here $i = \frac{p}{1-p}\frac{\psi_G}{\zeta_G}$, according to equation (3). Thus $R_{i,\,lim} = 0.5$ and $R_{f,G,\,lim} = 0.42,\ 0.33,\ 0,2$ (Figure 2). Increasing i, that means adopting a different management strategy, would of course reduce $R_{f,G,\,lim}$. The actions that may be undertaken in order to reduce $R_{i,\,lim}$ are: (i) increasing the impervious surface that drains stormwater to the storage capacity (provided that R_f is still acceptable); and (ii) choose species that are more drought tolerant.

5 Conclusions

The probabilistic approach provides a useful analytical method to estimate the feasibility, the risk of failure and eventually support a cost benefits analysis of a multipurpose storage and reuse capacity. Closed form expression for the risk of overflow during the rainy season and during the growing season and the risk of water shortage during the dry season have been derived for a patchwork of pervious and impervious subcatchments corresponding to different development stage of an urban catchment. Connectivity and arrangement of the subcatchments have been ignored for the sake of simplicity, but its influence on the reliability analysis should be evaluate as well as the real size of the catchment.

Even though the model presented here is conceptual and simple, it evidences few important tenets. In Mediterranean climate the problem of peak flow reduction and reuse of rainwater could be decoupled, due to the fact that the rainy season and the time of the year when the irrigation demand is maximum are out of phase. The risk of water shortage is high during the growing season and the reliability of the drainage system is reduced by the reuse practice contextually, thus to fulfill the irrigation demand during the vegetation growing season and ensure that the drainage system is at the same time reliable may become a challenging task.

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