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Risk analysis of sustainable urban drainage and irrigation

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ABSTRACT

Urbanization, by creating extended impervious areas, to the detriment of vegetated ones, may have an undesirable influence on the water and energy balances of urban environments. The storage and infiltration capacity of the drainage system lessens the negative influence of urbanization, and vegetated areas help to re-establish pre-development environmental conditions. Resource limitation, climate, leading to increasing water scarcity, demographic and socio-institutional shifts promote more integrated water management. Storm-water harvesting for landscape irrigation mitigates possible water restrictions for the urban population in drought scenarios. A new probabilistic model for sustainable rainfall drainage, storage and re-use systems was implemented in this study. Risk analysis of multipurpose storage capacities was generalized by the use of only a few dimensionless parameters and applied to a case study in a Mediterranean-type climate, although the applicability of the model is not restricted to any particular climatic type.

1. Introduction

Flood and drought have social, economic and environmental consequences which are exacerbated by urban development and climate change [28]. Urbanization, by creating extended impervious areas, to the detriment of vegetated ones, has an undesirable influence on the water and energy balances of urban environments [15], increasing peak discharge and total volume of surface runoff and reducing groundwater recharge. An important concern of urban hydrologists is thus to restore (at least partially) the pre-development water balance, thus, managing urban water in a more sustainable way. Nevertheless, since the increasing scarcity of clean water in many urban areas leads to intense competition for its use [4], the aim of sustainable urban water management cannot be restricted simply to restoring pre-development runoff conditions: rather, it should continue to evolve as urbanization increases and aim at better integrating urban, environmental, agricultural and industrial water use. There is a need to ascertain whether integrated strategies can achieve social and economic goals as well as good-quality ecosystem service and maintenance [22].

When rainfall falls over impervious land and does not infiltrate, it runs off becoming storm-water. Storm-water best management practices (BMP) preserve natural landscape features, minimize effective imperviousness, and treat storm-water as a resource rather than simply letting it go to waste [33]. The design criteria and performance of BMP have gained much coverage in the technical literature [8,9,37]. Detention basins are effective controls which can attenuate peak discharge [31]. When they act as infiltration systems, or in series with such systems, they can help to restore the pre-development water balance, enhance groundwater recharge, delay and reduce surface runoff, and thus protect receiving water bodies, and sewer systems [11,38]. Plants growing on natural or artificial soils increase their infiltration capacity by altering the soil structure of the vadose zone [26]. Bioretention area must be sufficiently permeable to infiltrate storm-water and have adequate retention capacity to support healthy vegetation growth. Engineered soil mix may achieve both objectives.

Vegetation is a crucial element in the mass and energy flux locally at the soil-vegetation-atmosphere interface, and in the earth's climate in general [27,34]. Maintaining or restoring vegetated areas in urban environments may further help to re-establish the pre-development water and energy balances. Plants can control the urban microclimate through transpiration and soil sheltering, reducing rises in urban temperatures and increasing the "liveability" of cities [12]. Nevertheless, vegetated urban landscapes consume water and are drought-sensitive, and thus pose the problem of water saving in landscape irrigation [13]. Frequency of irrigation depends on soil properties, climate and vegetation type. Applied water should never exceed the water holding capacity of the soil. Typically, deep and infrequent irrigation favors root elongation, health and vigor of turfgrass. Irrigation of vegetated bioretention area must minimize water use and avoid underdrain flow during dry weather. Although storm-water harvesting and landscape irrigation systems may require pumping stations, the additional cost of energy

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distribution is expected to be offset by energy savings on cooling systems [30].

Storm-water harvesting and re-use schemes for non-potable purposes (such as landscape irrigation) may mitigate the risk of water restrictions for urban populations. Treated waste-water may also be used for landscape irrigation according to many local regulation, although the re-use of storm-water collected from impervious land, which is discussed here, have higher public acceptance than alternative water supplies such as waste-water recycling [7]. For example, swale adjacent to impervious areas can support grass growth on golf courses in arid areas [35], and properly designed, maintained, and treated storm-water harvested from roofs is low-cost, often less polluted than other sources of water in urban catchments, and may integrate existing water supplies [29].

Storm-water harvesting reduces growers' dependence on the municipal water supply [6], however, storm-water re-use may meet water requirements for urban horticulture, if a sufficient volume is available during the growing season of the vegetation. It is not clear if, in climates of Mediterranean type, characterized by winter rains alternating with summer drought and high temperatures, which are often exacerbated by urbanization [25], landscape irrigation with reuse storm-water could be successful. In climates of Mediterranean type, due to the fact that rainfall and air temperature are out of phase and that the end of the rainy season corresponds to the beginning of the growing season, rain-fed vegetation often suffers water stress due to the long inter-storm interval between successive rainfall events in the dry-warm period. Collecting and reusing sufficient quantities of water of the required quality when the demand for irrigation is high is expected to be a problem, due to rainfall scarcity and variability [14].

The hydraulic design of a multipurpose storage tank aims at two contrasting goals: (i) to provide detention capacity and peak discharge reduction and (ii) to ensure a sufficient re-use water for irrigation. The first aim demands empty tanks at the beginning of each rain event. The second is to have the largest possible amount of water stored in the tanks during the inter-storm interval. If the system fails, this is due to overflow, when the volume of rainfall exceeds available storage capacity, or to water scarcity, when the stored rainfall volume is drawn before the next rainfall event. The probability of system failure is called *risk*.

The main aim of this study is to examine if multipurpose tanks can store and provide sufficient storm-water volumes for landscape irrigation when required, whether this implies a significant increase in the risk of overflow, and to what extent the risk of drought or, conversely, overflow depends on climate, hydrology and/or management strategies. The probability approach [1] provides analytical equations to estimate the risk of failure of detention facilities and other elements of the urban drainage system in question [17,18]. Several studies have applied a probabilistic approach to BMP failure risk analysis and demonstrate that it matches many physically based methods [16,19,20,38,39]. The risk analysis of water-saving systems has so far received less attention than that of storage systems. Whether the storage capacity of a detention basin can also ensure a sufficient water supply for irrigation purposes, and whether multipurpose management strategies can affect the risk of overflow have not yet been studied on a probabilistic basis.

A new integrated risk model was implemented in this study. Section 2 describes the conceptual model of a drainage, detention and re-use system. In Section 3, closed-form solutions are derived. In Section 4 the risk analysis is generalized by expressing risk as a function of a few dimensionless groups, and the influence of tank management strategy is evaluated analytically and validated numerically. In Section 5 the results are discussed and problems in sustainable water management are discussed.

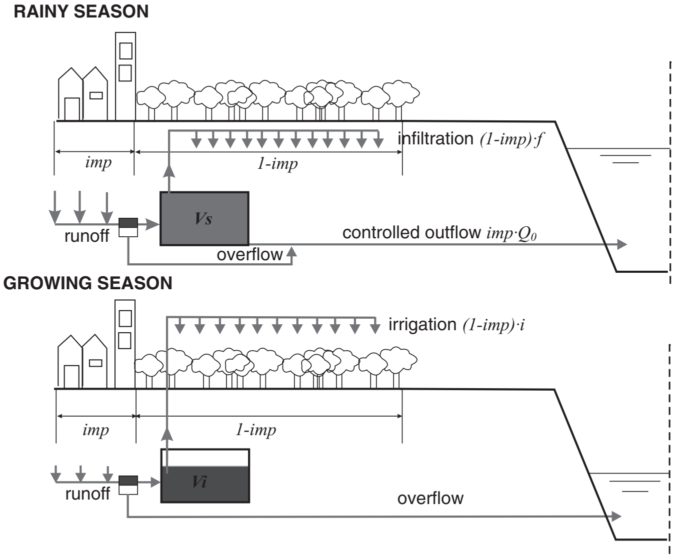

Fig. 1. Conceptual model of drainage system.

2. Model

2.1. Conceptual model of drainage system

A conceptual model is formulated for an urban catchment comprising one pervious (vegetated) and one completely impervious sub-catchment area (Fig. 1). Impermeability *imp* is the ratio between the impervious area and the whole catchment area and identifies the stage of development of the catchment.

The components of the drainage system (Fig. 1) are: (i) a network which transfers the rainfall volume falling on the impervious sub-catchment instantaneously to (ii) an overflow divider which diverts flow to storage or overflow discharge; (iii) a multipurpose tank; (iv) a distribution system drawing water from the tank to the pervious sub-catchment at a constant rate in the period of time between two rainfall events; (v) an outflow pipe taking water, at controlled rate, to discharge.

The network storage capacity should influence the rainfall-runoff transformation, which is kept as simple as possible, and indirectly the probability of overflow. However, the increasing storage capacity of the network with development, and thus *imp*, is neglected here for the sake of simplicity, possibly overestimating the risk of overflow. The tank is used for detention during the rainy season and for detention and landscape irrigation during the vegetation growing season. During the rainy season the pervious sub-catchment achieves in-place infiltration of storm water. The flow rate per unit surface in the infiltration system may reach soil infiltration capacity f during the rainy season, when the additional controlled outflow is Q and equals irrigation rate i during the growing season. The tank must be emptied as soon as possible after each rainfall event during the rainy season. Conversely, during the growing season, storm-water is stored for longer periods and re-used for irrigation at rate $i < f$. There is no controlled outflow during the growing season. This practice obviously increases the probability that storage capacity will not be available at the beginning of rare and intense showers during the growing season. Every time the rainfall volume exceeds the available storage capacity, the system fails. In this Section, the related probability of failure is called risk of overflow. The risk of water scarcity or drought is the probability of the tank being emptied during the irrigation season, before further rain falls (before the end of the inter-storm interval).