URBAN WATER JOURNAL, 2016
http://dx.doi.org/10.1080/1573062X.2016.1223324

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Risk analysis of combined rainwater detention and pumping systems

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ABSTRACT

Storm sewer systems (SSSs) are complex, with many hydraulic, mechanical and electrical components which may fail during natural extreme events, changing environmental conditions (including urban development), or simply due to poor maintenance. System complexity and management are important and still debated concepts within the framework of SSS risk analysis. A new probabilistic model for a conceptualized urban SSS, including a storage unit (SU) and a pumping station (PS), shows how single-component risk analysis can be extended to complex SSSs and demonstrates the combined effect of key design parameters (SU volume, detention time, prescribed outflow discharge) and management strategy on the overall SSS risk of failure. The risk of failure evaluated in a typical case study, demonstrates that economic restrictions leading to the loss of reliability of PS elements and the lack of redundant mechanical elements represent a major threat to SSSs and suggests a new risk-based definition of 'extended' SU.

ARTICLE HISTORY
Received 20 November 2015
Accepted 11 July 2016

KEYWORDS
Sustainability; risk assessment; Best Management Practices

1. Introduction

As the population increases around urban areas and land use gives rise to changes in the disturbed water cycle in newly developed and developing areas, undesirable effects are produced on surface and subsurface water bodies (Salas and Obeysekera, 2014; Fletcher et al., 2008): increasing imperviousness may reduce water-table recharge whereas run-off volumes and peak flows increase. As a consequence, urban subcatchments and streams are more prone to flooding (Villarini et al., 2009; Vogel et al., 2011; Leopold, 1986). Urban water systems dynamically co-evolve with society, enabling rapid growth and adaptation to environmental changes (Urich and Rauch, 2014). Among structural technologies, best management practices (BMPs) help to restore pre-development run-off conditions. BMPs detain run-off volume and release it at a slower rate into downstream water drainage systems or water bodies, allowing for water quality control (Salas and Obeysekera, 2014; Villarini et al., 2009; Hejazi and Markus, 2012). As decentralized BMPs are currently implemented on a local scale, their ability to provide water quality and quantity control is limited by the amount of water managed in a "non-sustainable" way (Roy et al., 2008).

Development commonly reduces land availability in urban areas, so storage units (SUs) must be constructed below ground, and pumping stations (PSs) must ensure that rainfall volumes are delivered above ground for treatment, sent to an already existing body of water, or to the downward drainage system. The capability of combined SU and PS systems to deliver a service to customers (i.e. releasing at sufficiently slow rates volumes of water from SU during a storm event with no overflow, and improving water quality) typically depends on hydrology and good management. The latter is influenced by human decisions in response to changes in the economy, innovation technology, and non-stationary environmental conditions. Poor management may be a consequence of changing economic conditions and political actions leading to cuts in technical personnel and lowering of the priority for repairs in cases of failure of repairable mechanical and electrical parts.

A wide range of urban stormwater models is available for designing storm sewer systems (SSSs) and predicting the effects of low impact structural measures, including ponds, stormwater tanks and bio-retention devices, which are typical BMPs with SU. Their potential uses cluster around planning or preliminary design, when sustainability principles start to be converted to solutions (Elliott and Trowsdale, 2007). Uncertainty is not systematically included in problem solving as neither risk within the society is well understood (Hlavinek et al., 2009). The interplay of human and technical systems is rarely taken into account by conventional stormwater models, even though technical, socio-economic and ecological issues need joint consideration and integration (Rauch et al., 2005). "*There is need for better methods to address the complex interactions of urban infrastructure systems, physical environment, level of services and social factors*" (Hlavinek et al., 2009).

Models of sewer pumping stations which assess the deterioration (Wirahadikusumah et al., 2001; Korving et al., 2006) and risk of failure of system components (Jin and Mukherjee, 2010; Chughtai and Zayed, 2008; Hahn et al., 2006), such as parallel pumping units (Ursino and Salandin, 2014; Ursino et al., 1996), or others which examine the hydraulic functioning of the system (Bennis et al., 2003; Ermolin et al., 2002) rarely take into due account random flow rates resulting from urban rainfall drainage and detention.

The probability approach (Adams and Papa, 2000) provides analytical equations to estimate the risk of failure of components of the urban drainage system based on continuum rainfall records (Guo and Adams, 1999, 1998). Although many studies have applied a probabilistic approach to BMP overflow risk

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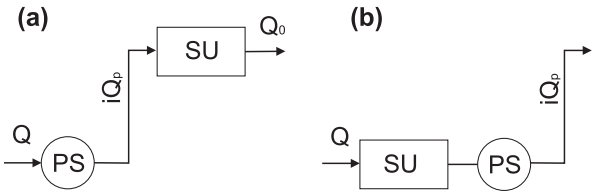

Figure 1. Conceptual model of low impact structural measures for storm sewer system (SSS). SU = storage unit, PS = pumping station.

analysis (Zhang and Guo, 2014, 2013; Guo et al., 2012; Balistrocchi et al., 2009; Guo and Baetz, 2007; Guo, 2001), and to insufficient treatment risk analysis (Park et al., 2015; Park and Roesner, 2012), failure-prone PS and SUs, which are parts of complex SSSs, have not yet been considered in the same context.

A new probabilistic model was formulated for a conceptualized urban SSS. Risk analysis focuses on the risk of failure of both SU and PS, so that the complexity of the SSS involves the interplay of two failure-prone elements on a local scale. The simple model described here represents a first step toward (1) the definition of risk models for complex SSS systems, which is an important and still unresolved task in sustainable water management (Urich and Rauch, 2014) and (2) the quantitative evaluation of socio-hydrological systems, which is a new topic, currently under debate (Montanari, 2015; Sivapalan, 2015).The effects of PS management policies are analyzed here in a range of cases based on literature data. Gathering data from a variety of sources and adapting socio-hydrological models to what is available and communicating and using model outcomes in policy applications are challenging and worth exploring aspects in water resources research and management (Sivapalan, 2015; Sivapalan et al., 2012).

2. Model

2.1. Conceptual model of a storm sewer system (SSS) and failure scenarios

In a conceptualized SSS, detention is achieved by a storage capacity (SU) and a pumping station (PS) ensuring flow continuity to the final destination, because gravity drainage is not possible (Figure 1). The risk of SSS failure is expressed as a function of the risk of failure of the two key elements - SU and PS. These are connected in series and are thus both "necessary", so that, if the incoming rainfall volume exceeds the storage capacity of SU or if the peak inflow is greater than the capacity of the PS, the SSS fails. Two set-ups are examined here: above-ground SU downstream of the PS Figure 1(a) and SU upstream of it (Figure 1(b).

The storage capacities of the urban catchment, drainage network and PS are conservatively neglected. Therefore, the combined SU and PS systems may fail in the case of an exceptional storm event in which: (1) its flow rate exceeds the PS discharge capacity (situation of above-ground SU); (2) its volume exceeds the SU volume; (3) two exceptionally violent storm events occur with a short inter-arrival time and the volume of the second event exceeds the available SU volume. In addition, the SU, which provides flow control and water quality control, may also fail if the rainfall volume leaves the SU before treatment is complete, i.e. after a residence time shorter that the design detention time.

2.2. Rainfall probability distribution

The analytical expression for the risk of SSS failure is obtained under the assumption that the rainfall depth (h), the duration of the rainfall event (τ), and the length of the dry period in between two rainfall events (t) are three independent random variables with exponential probability density functions: $f(h)$, $f(\tau)$ and $f(t)$ according to Adams and Papa (2000).

$$f_h = \zeta\, e^{-\zeta h} \tag{1}$$

$$f_\tau = \lambda\, e^{-\lambda \tau} \tag{2}$$

$$f_t = \psi\, e^{-\psi t} \tag{3}$$

In equation (1) ζ is the inverse of the expected value of rainfall depth, in equation (2) λ is that of rainfall duration and in equation (3) ψ is that of the expected value of rainfall inter-arrival.

Characterizing the frequency distribution of rainfall is based on statistical analysis of rainfall records at gauge stations and on proper definition of inter-event time (IETD), which is required to isolate storm events from continuum time series (Adams and Papa, 2000).

2.3. Pump and PS reliability

The reliability of a pump is defined as the probability that it will not fail during time interval $[0, t]$. The probability that it will fail at time t, provided that it was operating in $[0, t]$, is $\alpha(t) \cdot dt$, where $\alpha(t)$ is the pump's failure rate. If the pump is not working at time $t = 0$, the probability that the component repairs are completed before time t is $\beta(t) \cdot dt$, where $\beta(t)$ is the pump repair rate (Mays and Cullinane, 1986). In general, the rates $\alpha(t)$ and $\beta(t)$ may vary during the lifetime of the PS.

However, when $\alpha(t)$ and $\beta(t)$ are assumed to be time-independent, mathematical tractability becomes much simpler, and the reliability a of each pump may be evaluated as the steady state solution of a Markov process with constant rates α and β (Henley and Kumamoto, 1992), according to the following equation expression:

$$a = \frac{\alpha}{\alpha + \beta} \tag{4}$$

Conversely, the risk of pump failure f is:

$$f = 1 - a = \frac{\beta}{\alpha + \beta} \tag{5}$$

The PS is modeled as a complex system with n identical components (pumps), which are connected in parallel, each pump having discharge capacity Q_p and reliability a, given by equation (4). Backup capacity is provided by r additional pumps with capacity Q_p and reliability a, which are redundant in standby. The probability that $n + r - i$ of $n + r$ pumps are not working at time t and thus, that the discharge capacity of the PS is i Q_p may be expressed by a binomial distribution (Ursino and Salandin, 2014), according to equation (6):

$$P_i = \binom{n+r}{i} a^i \cdot f^{n+r-i} \tag{6}$$

where $i = 0 \div n$.

Table 1. Risk model. Dimensionless groups.

Parameter	definition
k_ζ	$\frac{\zeta\ V_s}{\varphi\ S}$
k_λ	$\frac{\lambda\ V_s}{i\ Q_p}$
$k_{\psi,0}$	$\frac{\psi\ V_s}{Q_0}$
$k_{T,a}$	$\frac{IETD\ Q_0}{V_s}$
$k_{T,b}$	$\frac{IETD\ i\ Q_p}{V_s}$
k_ψ	$\frac{\psi\ V_s}{i\ Q_p}$
k_{λ,T_d}	$\frac{\lambda Q_0 T_d}{iQ_p}$
k_{ζ,T_d}	$\frac{\zeta iQ_p T_d}{\varphi S}$

2.4. Risk of SU overflow and risk of insufficient water treatment

The components of a conceptualized SSS with above-ground SU Figure 1(a) involve the following: (i) the network transferring flow Q to (ii) a PS equipped with $n + r$ pumps, each with discharge capacity Q_p and reliability a, and (iii) the SU with a regulated outlet to downward drainage, further treatment or a water body. The SU's maximum detention volume and detention time are V_s and T_d. Stormwater is released from the SU at prescribed rate Q_0 after each storm event, either for as long as it contains rainwater, or a new rain event occurs. Even though, in reality, run-off detained in the SU can be conveniently released also during run-off inflow, here the resulting additional storage volume $Q_0\ \tau$ is conservatively neglected, as well as the storage capacity of the network and the PS.

PS inflow Q is evaluated under the following assumptions: (1) the rainfall-runoff transformation is stationary and deterministic, (2) the initial condition of the drainage catchment may be neglected and (3) Q may be estimated by the rational method:

$$Q = \varphi S\ h\ \tau^{-1} \tag{7}$$

where S is the contributing catchment area, φ is the runoff coefficient, and h and τ are rainfall depth and duration.

Assuming that the SU is full at the end of the first of two consecutive rain events, the risk of overflow for a SSS with PS and above ground SU may be written as a function of four dimensionless groups: k_ζ, k_λ, $k_{\psi,0}$ and $k_{T,a}$ (Table 1).

$$R_a = \frac{k_\lambda}{k_\zeta + k_\lambda} + \frac{k_{\psi,0} \cdot e^{-K_{T,a}(k_\lambda + k_{\psi,0})} - k_\lambda \cdot e^{-(k_\lambda + k_{\psi,0})}}{k_\lambda + k_{\psi,0}} + \frac{k_\lambda \cdot \left[e^{-k_{T,a}(k_\zeta + k_\lambda + k_{\psi,0})} - e^{-(k_\zeta + k_\lambda + k_{\psi,0})}\right]}{k_\zeta + k_\lambda + k_{\psi,0}} \tag{8}$$

Figure 1(b) shows the sequence of components of SSS with below ground SU as follows: (i) the network, which transfers run-off volume $V = \varphi\ S\ h$ to (ii) the below-ground tank with storage volume V_s and (iii) the PS, which draws water to downward drainage, treatment, or a water body at rate $i\ Q_p < n\ Q_p \leq Q_0$ in the inter-arrival time t between two consecutive rain events.

The probability R_b of an overflow may be written as a function of four dimensionless groups: k_ζ, k_λ, $k_{T,b}$ and k_ψ (Table 1).

$$R_b = \frac{k_\psi}{k_\psi + k_\zeta} \cdot e^{-k_{T,b}(k_\psi + k_\zeta)} + \frac{k_\zeta}{k_\psi + k_\zeta} \cdot e^{-(k_\psi + k_\zeta)} \tag{9}$$

Pollutants washed-off from urban catchment surfaces and attached to solid sediments, may be removed by sedimentation, provided that the residence time within the SU is sufficiently long (Guo, 1996). The operating conditions of detention facilities are generally characterized by intermittent and variable rainfall, leading to variable inflows and storage levels. The effective detention time is the ratio between the rain volume detained in the SU and the release rate. Therefore, the effective detention time may be shorter than design detention tine T_d.

The risks of insufficient water treatment of SSS with above and below ground SU are:

$$R_{T_d,a} = e^{-k_{T,a}k_{\psi 0}} - \frac{k_\lambda\ e^{-\left(k_{\lambda,T_d} + k_{\psi 0}\right)} + k_{\psi 0}\ e^{\left[-k_{\lambda,T_d} - k_{T,a}k_{\psi 0} - k_\lambda (k_{T,a} - 1)\right]}}{k_\lambda + k_{\psi 0}} \tag{10}$$

$$R_{T_d,b} = e^{-k_{T,b}k_\psi} - \frac{k_\zeta\ e^{-\left(k_{\zeta,T_d} + k_\psi\right)} + k_\psi\ e^{\left[-k_{\zeta,T_d} + k_{T,b}k_\psi - k_\zeta (k_{T,b} - 1)\right]}}{k_\zeta + k_\psi} \tag{11}$$

where dimensionless groups are define in Table 1.

Assuming that the SU is empty at the beginning of each rain event, the risks of overflow and insufficient detention time (Equations 8–10 and 11) become:

$$R'_a = \frac{k_\lambda}{k_\zeta + k_\lambda} + e^{-k_\lambda} - \frac{k_\lambda}{k_\zeta + k_\lambda} e^{-(k_\zeta + k_\lambda)} \tag{12}$$

$$R'_b = e^{-k_\zeta} \tag{13}$$

$$R'_{T_d,a} = \int_0^{\frac{Q_0 T_d}{i\ Q_p}} f_\tau\ d\tau = 1 - e^{-k_{\lambda,T_d}} \tag{14}$$

$$R'_{T_d,b} = \int_0^{\frac{iQ_p T_d}{n\ \varphi\ S}} f_h\ dh = 1 - e^{-k_{\zeta,T_d}} \tag{15}$$

A more detailed treatment of the risk models, including derivation is reported in Supplementary Material.

2.5. Risk of failure of SSS

Probability $P(\theta)$ that the SSS does not perform its task in stationary conditions is obtained by combining the risks of overflow, too short detention times within the SU, and PS failure, as:

$$P(\theta) = \sum_{i=0}^{n} \binom{n+r}{i} a^i \cdot f^{n+r-i} \cdot R(i) \tag{16}$$

where $R(i)$ is the combined risk of overflow and too short detention time.

Equation (16) can estimate the risk of failure of the SSS whenever rain falls, as a function of the constant parameters:

$\theta = [k_\zeta, k_\lambda, k_\psi, k_{T,a}, k_{T,b}, k_{\lambda,T_d}, k_{\zeta,T_d} a, n, r]$.

Equation (16) is a particular application of the "loading resistance interference" concept (Mays and Cullinane, 1986) where the incoming rainfall volume is the load and the resistance is the combined system capacity to detain volume and release it to

downward drainage, treatment or water body. The interaction of the load and resistance probability density functions resembles the interaction of two stochastic processes: rainfall and SSS performance.

The basic steps in the risk assessment by use of equation (16) are: (1) estimate the probability density function of rainfall depth duration and interevent time (statistics were taken here from Adams and Papa (2000)); (2) derive the distribution of inflow volumes by use of proper hydrological model (inflow probability distribution is derived here according to Ursino and Salandin (2014) by use of rational model (7)); (3) estimate the SU detention volume and PS capacity according to a design manual (e.g. CIRIA (2001)); (4) choose the system set-up (possible sequences of SU and PS are shown in Figure 1); (5) estimate the reliability of one pump (failure and repair rates were taken here from Korving et al. (2006)); (6) define SSS's failure as the risk of overflow, or insufficient water quality control, or a weighted average of the two; (7) apply risk interference concepts (equation (16)). Basic assumptions (Equations 1–6) allowed the analytical solution of both: the risk of overflow and the risk of insufficient water quality control (Equations 8–15). Provided a site-specific statistical characterization of the main random variables, other than the one used here, the risk assessment is possible by numerical integration of equation (16).

Equation (16) may be used to evaluate:

(1) the annual risk of SSS failure (not shown here),

$$P_N(\theta) = 1 - \left[1 - P(\theta)\right]^N \tag{17}$$

where N is the average number of rainfall events in one year and $1 - P(\theta)^N$ is the annual reliability of the SSS;

(2) the risk of failure of the SSS over its design life M (not shown here):

$$P_M(\theta) = 1 - \left[1 - P_N(\theta)\right]^M \tag{18}$$

Equation (18) holds for unchanged climate, land use and managing conditions, although it may easily be generalized for non-stationary conditions $(\theta_1, \theta_2, \ldots \theta_M)$, where θ_j is the set of climate and design parameters which accounts for the yearly stage of development and the economical and environmental scenarios at year j, in scenarios of changing climate, land use or management strategy (Read and Vogel, 2015; Salas and Obeysekera, 2014).

The risk of failure $P(\theta)$ depends on climate (through ζ, λ ψ and *IETD*), the three hydraulic parameters Q, Q_0 and V_s, the detention time T_d, the reliability a, and the numbers n and r of the necessary and redundant pumps in the PS. The definition of design parameters of minimal models is complex, site-specific, and should preferably take into account uncertainty and non-stationary states of the urban catchment (not shown here). In the following, the real world complexity is condensed into dimensionless, reasonable effective parameters and Q, Q_0 and V_s, per unit catchment area, are expressed as follows:

$$\frac{V_s}{S} = \frac{C_1}{\zeta} \tag{19}$$

$$\frac{Q}{S} = \frac{C_2\,\lambda}{\zeta}\frac{Q_0}{S} = \frac{C_3\,\lambda}{\zeta} \tag{20}$$

3. Application

Constructed ponds, which provide removal of total suspended solids up to 70%, have detention volumes normalized over catchment area $V_s\,S^{-1} = 2 \div 20$ mm, correspondingly, $C_1 = 0.4 \div 4$ (Papa et al., 1997). Similarly, underground stormwater detention systems, designed to detain and treat, for instance, the first $5 \div 25$ mm of rainfall have $C_1 = 1 \div 5$ (EPA, 2001). For T_d =24 hours and $Q_0 = V_s\,T_d^{-1}$, $C_3 = 0.1 \div 2$. The inflow rate may be up to one order of magnitude higher than the outflow rate, in environments which undergo rapid changes in use, so that restoration or maintenance of pre-development conditions implies $C_2 = 1 \div 10\,C_3$.

Derivation of rain events from continuum records with a separation time equal to design detention time T_d, may tend to overestimate detention volumes (Guo, 1996), thus, $IETD = 0.5\,T_d = 12$ hours. Climatic parameters for Canada and the United states are $\zeta = 0.08 \div 0.3$ mm^{-1}, $\lambda = 0.06 \div 0.15$ hr^{-1} and $\psi = 0.008 \div 0.017$ hr^{-1} (Adams and Papa, 2000; Zhang and Guo, 2014, 2013). In the hypothetical examples discussed in this section $\zeta = 0.2$ mm^{-1}; $\lambda = 0.1$ hr^{-1}; $\psi = 0.01$ hr^{-1}.

The analysis of 5 years failure records of two sewer PS in the Netherlands showed that: (1) the failure rate is erratic with inter-arrival times between 8 and 100 days; (2) clusters of dependent failures may occur; (3) the average repair time is between 1 hour and several days, emphasizing the importance of proper maintenance and management policies (Korving et al., 2006). Pump reliability may be therefore $a = 0.99 \div 0.5$.

Figure (2) shows the combined risk of failure of SSS with above-ground (continuous line) and below-ground SU (dashed line) for various PS set-ups (different n and r) and reliability a of the pumps. In the case of above-ground tanks, the risk of failure of the SSS, $P(\theta)$ (equation 16) is evaluated for $R(i) = 0.5 \cdot (R_a + R_{T_d,a})$ (Equations 8 and 10), whereas for below-ground SU it is $R(i) = 0.5 \cdot (R_b + R_{T_d,b})$ (Equations 9 and 11). In a real case, $R(i)$ may be defined according to the design storm water management standard, whether it is pollutant removal, detention or both. Thus different weights may be given to the risk of overflow and to the risk of insufficient water quality control.

$P(\theta)$ increases with C_1 up to a certain maximum and then decreases. This is particularly evident in SSS with below ground SC. Partitioning of total PS capacity into a larger number of components n without redundancy does not substantially affect the risk of failure. Below-ground tanks are more reliable than above-ground ones over a restricted range of relatively small C_1, and both are less prone to failure as the number r of redundant pumps increases. The setup influences the load density function, and thus the load-resistance interference, because below ground SU can store small rain event avoiding overflow even though the PS is on failure. The risk of SSS failure with back-up capacity ($r > 0$) is more sensitive to changes in a, and thus to changes in management strategy.

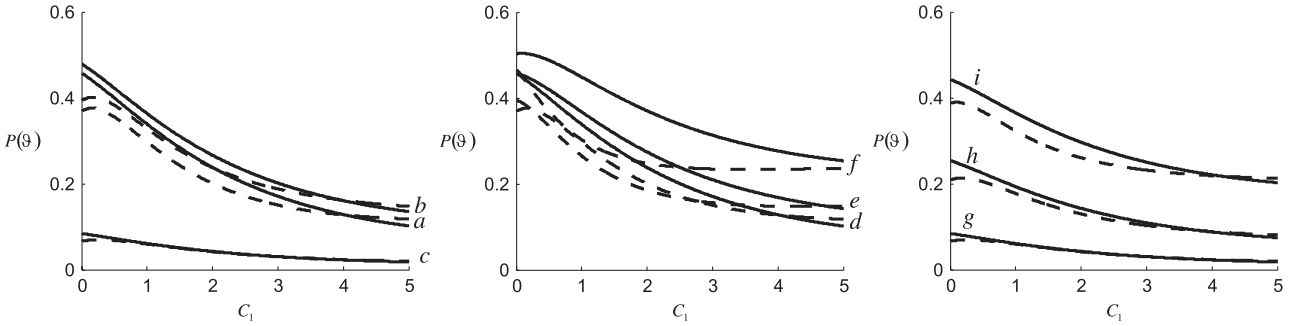

Figure 2. Combined risk of failure of SSS vs $C1$, for various set-ups and management strategies of PS. Continuous line: above ground SC; dashed line: below ground SC. a: PS is equipped with $n = 4$ pumps; reliability of each pump: $a = 0.8$; no redundant pump in stand-by $r = 0$; b: PS has $n = 2$ pumps, $a = 0.8$ and $r = 0$; c: PS has $n = 2$ pumps; $r = 2$ pumps redundant in stand by, and $a = 0.8$; d, e and f: $n = 4$, $r = 0$ and $a = 0.8$, 0.6 and 0.4 respectively; g, h and i: $n = 2$, $r = 2$ and $a = 0.8$, 0.6 and 0.4 respectively; Climatic parameters: $\zeta = 0.2\ \text{mm}^{-1}$; $\lambda = 0.1\ \text{hr}^{-1}$; $\psi = 0.01\ \text{hr}^{-1}$; design parameters: $C_3 = 0.1$;$C_2 = 10$.

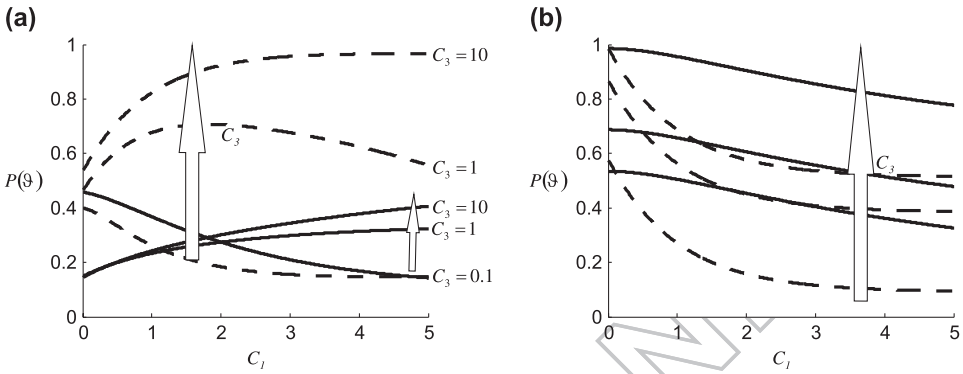

Figure 3. Combined risk of failure of SSS vs $C1$ for various C_3, i.e.: $C_3 = 0.1, 1, 10$ and design detention time $T_d = 2a$ hours. Continuous line: above-ground SU; dashed line: below-ground SU. Left (a): SU full at end of first of two rain events; right (b): SU empty at beginning of each flow event. Design parameters: $C_2 = 10$; $n = 4$, $r = 0$, $a = 0.6$; climatic parameters: $\zeta = 0.2\ \text{mm}^{-1}$; $\lambda = 0.1\ \text{hr}^{-1}$; $\psi = 0.01\ \text{hr}^{-1}$.

Figure 3(a) shows the combined risk of overflow and insufficient detention for various storage volumes (C_1) and outflow rates (C_3).

Large outflow rates lessen the risk of overflow by reducing tank draw-down time and increase that of too short detention. Figure 3(a) shows that the risk of failure of SSS with above-ground SU decreases with increasing C_3 when C_1 is below a certain threshold, whereas it increases with increasing C_3 when C_1 is above that threshold. Extended SUs have a very high probability of not achieving the established water quality objective, and the low risk of overflow does not counterbalance the loss of reliability regarding water quality. The value of threshold C_1 corresponding to switching between 'small' and 'extended' SUs, in this case study is $C_1 \approx 2$.

Figure 3(b) shows the risk of failure $P(\theta)$ of SSS with above-ground SU, evaluated for $R(i) = 0.5 \cdot (R_{1_a} + R'_{2a} + R'_{Td,a})$ (Equations 12 and 14), whereas for below-ground tanks it is: $R(i) = 0.5 \cdot (R'_b + R'_{Td,b})$ (Equations 13 and 15). Thus, Figure 3(b) shows the risk of SSS failure evaluated under the assumption that the tank is empty at the onset of each flow event. The risk of overflow is underestimated and the risk of insufficient detention time is overestimated. In the case study presented here, this modeling assumption is conservative only for SSS with 'small' below-ground SU and above-ground SU.

4. Discussion

Conventional stormwater models (Elliott and Trowsdale, 2007) do not take into due consideration the interplay of human and technical systems, even though technical socio-economic and ecological issues need consideration and integration (Rauch et al., 2005). A new probability model links risk assessment to complexity, non-stationarity and socio-hydrology.

In previous risk models uncertainty is restricted to climate parameters (Guo, 2001; Guo and Baetz, 2007; Guo et al., 2012; Zhang and Guo, 2013, 2014), or to stormwater effluent concentration and BMP removal rate (Park et al., 2015; Park and Roesner, 2012). Risk models of PS components (Hahn et al., 2006; Jin and Mukherjee, 2010; Ermolin et al., 2002) do not take into due account the stochastic nature of run-off flow, neither the hydraulic functioning of SU. Combining socio-economic aspects affecting the risk of failure of PS and technical issues concerning the BMP performance represents a first step toward the quantitative evaluation of socio-hydrological systems, which is a new topic, currently under debate (Montanari, 2015; Sivapalan, 2015). This step is taken here within the framework of reliability interference theory. Systematic SSS's failure records could be used to validate risk models and give advice to the involved parties. Thus systematic data collection and circulation among

meteorological station holders, infrastructure managers, socio and demographic observatories and engineers which are aware of uncertainty in problem solving should become part of standard operation (Hlavinek et al., 2009).

Further study of the two-way interaction between hydrology and water management may advance the comprehension of feedback and non stationary dynamics of the co-evolution of land and society. The need to evaluate positive and negative feedback between societal and environmental changes and determine the appropriate complexity for models of socio-hydrological systems has been repeatedly emphasized in recent times (Montanari, 2015; Montanari et al., 2013; Sivapalan et al., 2012).

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