Zubelzu, S.; Rodríguez Sinobas, L.; Andrés Doménech, I.; Castillo-Rodríguez, J.; Perales Momparler, S. (2019). Design of water reuse storage facilities in Sustainable Urban Drainage Systems from a volumetric water balance perspective. The Science of The Total Environment. 663:133-143. https://doi.org/10.1016/j.scitotenv.2019.01.342

Design of water reuse storage facilities in Sustainable Urban Drainage Systems from a volumetric water balance perspective

S. Zubelzu[a], L. Rodríguez-Sinobas[b], I. Andrés-Domenech[c], J.T. Castillo-Rodríguez[d], and S. Perales-Momparler[e]

[a], Departamento de Ingeniería Agroforestal, Universidad Politécnica de Madrid. Av Complutense s/n, (28040, Madrid, Spain). Email: sergio.zubelzu@upm.es

[b], Departamento de Ingeniería Agroforestal, Universidad Politécnica de Madrid. Av Complutense s/n, (28040, Madrid, Spain). Email: Leonor.rodriguez.sinobas@upm.es

[c], Research Institute of Water and Environmental Engineering (IIAMA), Universitat Politècnica de València, Camino de Vera s/n, (46022 Valencia, Spain). Email: igando@hma.upv.es

[d], Research Institute of Water and Environmental Engineering (IIAMA), Universitat Politècnica de València, Camino de Vera s/n, (46022 Valencia, Spain). Email: jecasrod@upv.es

[e], Green Blue Management, S.L. Avda. del Puerto, 180 (46023 Valencia, Spain). Email: sara.perales@greenbluemanagement.com

Corresponding author: Sergio Zubelzu.

***Highlights (for review : 3 to 5 bullet points (maximum 85 characters including spaces per bullet point)**

Volumetric water balance is proposed to analyze urban catchments.

The minimum of a cost function based on the water balance is proposed.

The minimum cost determines the optimum design of Sustainable Urban Drainage Systems.

Several urban catchments are studied with the proposed methodology.

Abstract

This paper presents a methodology for designing water reuse storage facilities as part of Sustainable Urban Drainage Systems (SUDS) in urban catchments. The method analyzes the whole water balance of the catchment. The contributions to the balance are irrigation and precipitation; the outlets are evapotranspiration, seepage and discharge to the conventional sewage system. The internal system variations are the volume of water to be locally reutilized and the soil water content variation. A cost function that includes the costs of irrigation, discharge to the conventional sewer system and reuse of water locally is proposed to estimate the optimum volume of water to be reused. This approach for SUDS design goes beyond traditional events-based perspectives oriented to damage prevention. This method conceives stormwater as a resource and seeks its optimal use through the design of SUDS. Several types of urban catchments were studied, and the results show that the proposed methodology can be applied either for simulating SUDS behavior in urban catchments or for estimating the optimum volume of water to be locally reused.

Keywords

Stormwater management; Surface runoff; Water reuse; Low impact development; Urban catchment.

1 Introduction

Urban development results in an increase in impervious zones that influence the hydrology of urban basins. The infiltration and evapotranspiration decrease, and runoff increases (Rodríguez-Sinobas et al., 2018). The runoff peak flow and the risk of pluvial flooding increases, and the runoff volume conveyed to the receiving water bodies also increases (Ahiablame and Shakya, 2016). The concentration time (Lim and Lu, 2016) and the groundwater recharge (Ogden et al., 2011; Ursino, 2015) decrease, and contamination is favored (Morales-Torres et al., 2016). These effects will continue to increase in view of the projections of future climate change (Pike et al., 2011).

Stormwater management in cities has traditionally been based on centralized systems that seek to evacuate runoff as quickly as possible through drainage networks that collect and convey the runoff to the final destination (Kong et al., 2017).

In contrast, in recent years, a different stormwater management approach, the so-called sustainable urban drainage management, has become more common (Sustainable Urban Drainage System, SUDS, by its terminology in the United Kingdom, or Low Impact Development, LID, as they are known in the United States). This paradigm shift advocates for a decentralized management (Wang et al., 2018) as close to the runoff source as possible (Chang et al., 2018). SUDS aim to mimic the hydrology of the predevelopment state (Pappalardo et al., 2017).

SUDS include different infrastructures oriented to decentralized storm water management, such as green roofs, porous pavements, infiltration trenches or infiltration areas (Mguni et al., 2016, Wang et al., 2017).

Some studies have analyzed the effectiveness of SUDS and have tested their feasibility for efficient urban basin management (Ahiablame et al., 2013; Busrzta-Adamiak and Mrowiec, 2013; Dietz, 2007; Gregoire and Claussen, 2011; Hunt et al., 2006; Lee et al., 2013; Trinh and Chui, 2013), identifying barriers to their implementation (Dhakal and Chevalier, 2017; Loperfido et al., 2014; Rodríguez-Rojas et al., 2018; Zhang et al., 2012) or analyzing the future evolution of SUDS (Zischg et al., 2019).

Conversely, few studies have focused on the development of tools or design criteria for SUDS. Some public administrations, as shown in Ballard et al. (2015) or Rossman and Huber (2016), have proposed design criteria, guidelines and recommendations. These references define the characteristics of the design event and set up limitations to the maximum peak runoff flow and runoff volume, among other variables. This type of events-based approach to SUDS design ensures the correct operation of the SUDS for events that do not exceed the magnitudes of the design event. This design proposal agrees with the management principles of conventional drainage systems but is not aligned with the philosophy of SUDS.

The SUDS operating principles go beyond simple runoff management that is oriented to damage prevention and incorporates concepts such as local reutilization and efficient use of resources. SUDS must manage the water resources efficiently for a wide range of situations, and not only for design events. Additionally, as a holistic approach, the design of SUDS must consider all of the variables influencing the hydrological cycle and not only those that are related to the design rainfall event.

Considering the above, the main objective of this paper is to propose a method for SUDS design and analysis from a volumetric water balance perspective. Therefore, we propose: (1) to assess the feasibility of the proposed method to satisfy the existing SUDS design standards, and (2) to analyze the sensitivity of the main water balance variables to the installed SUDS characteristics.

2 Materials and Methods

2.1 General volumetric water balance

A volumetric water balance (eq. 1) is proposed to analyze urban catchments.

$$R + I = ETk + \Delta\theta + SUD + CUD + D \qquad (1)$$

where R is the precipitation, I is the irrigation, ETk is the crop evapotranspiration, CUD is the water volume conveyed to the conventional sewer system, SUD is the water volume managed by the SUDS, D is the seepage and $\Delta\theta$ is the soil water content variation.

The volume of water managed by the SUDS refers to a generic volume of water that is susceptible to be stopped, stored and locally reutilized. It is the result of the implementation of one or several SUDS.

The following criteria were defined to characterize each variable of the water balance:

1) For each type of land use within the catchment, precipitation (R) can be divided into runoff (R_R) and infiltration (R_I) as follows (eqs. 2 and 3).

$$R_R = \Sigma\, R \times c_i \qquad (2)$$

$$R_I = \Sigma\, R \times (1 - c_i) \qquad (3)$$

2) Runoff coefficients (c_i) were estimated with the Soil Conservation System Curve Number Method (Soil Conservation System, 1985).

3) The rainfall infiltrating the pavement (R_{Ipav}) can be locally managed (SUD) or percolate to the phreatic level (D) depending on whether the infiltrated water is being collected or not.

4) The rainfall that infiltrates planting zones (R_{Iplant}) increases the soil water content (θ) to reach saturation. Once the soil is saturated, the additional infiltrated rainfall can be locally managed (SUD) or percolate to the phreatic level (D).

5) Two alternatives were considered for runoff: (a) the runoff from pervious and impervious zones is directly conveyed to the conventional sewer system (CUD) or (b) the runoff from impervious zones is conveyed to the pervious zones to jointly infiltrate with the runoff that was generated in pervious areas.

6) Crop evapotranspiration (ETk) depends on the potential evapotranspiration (ET_0) and the crop coefficient (kc), as indicated in eq. 4.

$$ETk = kc \times ET_0 \tag{4}$$

7) Soil water content variation ($\Delta\theta$) only refers to planting zones. Soil water content varies by rainfall infiltration, irrigation, evapotranspiration and infiltration from the storage element (RI). With c_{RD} being the portion of runoff directed to the pervious zones and c_D being the portion of the incoming water that is stored in the soil, $\Delta\theta$ can be computed as follows (eq. 5).

$$\Delta\theta = \theta_i - \theta_{i-1} = R_R \times c_{RD} \times c_D + R_{Iplant} \times c_D + RI \times c_D + I \times c_D - Etk \tag{5}$$

where θ_i and θ_{i-1} are the soil moisture contents at the current and previous temporal steps.

To the extent that SUD is considered to be an available resource to be reutilized locally, a storage element can be installed and different alternatives for water reuse can be analyzed. Two alternatives for water reuse are proposed: re-infiltration to the planting zones (RI, eq. 6) or to the phreatic level (RI_{PH}, eq. 7). For infiltration boxes or wells, RI depends on the amount of water stored, the contact area (CS, that is, the area of walls of the box in contact with water) and the soil infiltration properties (it is supposed that, for the steady state, the infiltration rate depends on the saturated hydraulic conductivity of the soil, ks).

$$RI = SUD \times (1 - r_{RIPH}) \times CS \times ks / V_{SUD} \qquad (6)$$

$$RI_{PH} = SUD \times r_{RIPH} \times CS \times ks / V_{SUD} \qquad (7)$$

In which r_{RIPH} represents the portion of the stored water that is infiltrated to the phreatic level (RI_{PH}).

8) The volume of water available for local reuse (SUD) is the portion of infiltrated water that does not store within the soil and/or does not percolate. If c_{DSUD} and c_{IS} represent the fractions of infiltrated water that go to the SUDS in planting and pavement zones, respectively, SUD can be defined as shown in eq. 8.

$$SUD = R_R \times c_{RD} \times (1 - c_D) \times c_{DSUD} + R_{Iplant} \times (1 - c_D) \times c_{DSUD} + R_{Ipav} \times c_{IS} - RI - RI_{PH} \qquad (8)$$

SUD may range from zero to V_{SUD}, which is the planned storage capacity.

9) The volume of water that is conveyed to the conventional sewer system (CUD) is the sum of runoff (from pervious and impervious zones) that is not stored in the pervious zones to infiltrate, plus the volume of water that is directed to the storage tank exceeding V_{SUD} (eq. 9).

$$CUD = R_R \times (1 - c_{RD}) + SUD > V_{SUD} = R_R \times (1 - c_{RD}) +$$

$$[R_R \times c_{RD} \times (1 - c_D) \times c_{DSUD} + R_{Iplant} \times (1 - c_D) \times c_{DSUD} + R_{Ipav} \times c_{IS} - RI - RI_{PH} - V_{SUD}]_{SUD > V_{SUD}}$$

$$(9)$$

10) Seepage (D) proceeds from both the infiltrated water that is not stored in the soil and/or is not collected in the SUDS and proceeds from RI_{PH} as well (eq. 10).

$$D = R_R \times c_{RD} \times (1 - c_D) \times (1 - c_{DSUD}) + R_{Iplant} \times (1 - c_D) \times (1 - c_{DSUD}) + R_{Ipav} \times (1 - c_{IS}) + RI_{PH} +$$

$$RI \times (1 - c_D) + I \times (1 - c_D) \qquad (10)$$

11) Irrigation (I) is the variable that closes the water balance. The application of water as a daily basis fulfills the difference between the ETk and the water that reaches the soil (represented by

the values within the parenthesis in eq. 11). Irrigation is applied only within the period in which the aggregated monthly difference between R and ETk is negative.

$$I = ETk_{daily} – (R_R \times c_{RD} \times c_D + R_{Iplant} \times c_D + RI \times c_D) \qquad (11)$$

12) Finally, it is assumed that water infiltrates to the planting areas following the general 1D soil water flux governing equation (eq. 12).

$$u = - k(\theta) \times dH/dz \qquad (12)$$

where u is the effective velocity, H is the hydraulic potential and k(θ) is the soil hydraulic conductivity, which has been estimated by the van Genutchen (1987) and Mualem´s (1976) equations, while the parameters were retrieved from Carsel and Parrish (1988).

In summary, Figure 1 illustrates the scheme that was proposed for the whole water balance and depicts all of the aforementioned variables. The proposed method is considered to be an ideal uniform profile for the soil water distribution process that is described above.

-Figure 1 near here-

Figure 1. Scheme of the proposed water balance.

2.2 Design criteria for water reuse storage facilities

The optimum volume of water to be reutilized is deduced from the described water balance. An optimization problem can be proposed for the optimum volume of water (V^*_{SUD}) for different optimization functions according to the pursued objective. In this paper, we propose a minimization problem that considers the costs of managing water (eq. 13).

$$\text{Min } C = C(V_{SUD}) = V_{SUD} \times UC_{SUD} + UC_{CUD} \times CUD + UC_I \times I$$

$$\text{st: } V_{SUD} > 0; \qquad (13)$$

$$I \geq 0$$

in which UC_{SUD}, UC_{CUD} and UC_I are the unitary costs (€/m^3) of water reuse (drain systems, storage capacity, etc.), conveying water to the municipal sewer system and irrigation, respectively. V_{SUD}, CUD and I are the corresponding volumes described in section 2.1.

An average runoff coefficient was considered (eq. 14) to characterize the different types of land use with regard to its hydrological properties.

$$c^* = \Sigma\, c_i \times S_i/S_T \tag{14}$$

where S_i represents each land use area and S_T represents the total area.

2.3 SUDS characterization

The present paper considers SUDS to encompass a set of infrastructures aimed at collecting, storing and reutilizing water locally. The resulting effect of the installed SUDS is the process of SUD generation (see eq. 8). On this basis, the proposed methodology allows different typologies of SUDS to be incorporated as follows:

a) Porous pavements: c* represents the average runoff coefficient defined by the means of the specific runoff coefficient of each land use category. Permeable pavements can be incorporated, including their specific c_i and S_i values, as shown in eq. 14.

b) Swales, rain gardens or infiltration areas: these facilities can be included in the water balance through c_{RD}. The entire runoff is directed to pervious zones if $c_{RD} = 1$, while $c_{RD} = 0$ implies that no infiltration area or its equivalent is included.

c) Drain systems: c_{IS} and c_{DSUD} allow the inclusion of drain systems for planting and paved zones, respectively. A value of 1 represents an entire zone that is waterproofed and drained, and 0 means that drains have not been installed.

d) Stored water: r_{RIPH} refers to the destination of stored water. Values of $r_{RIPH} = 0$ or 1 correspond to cases in which the water is used for irrigation or groundwater recharge, respectively.

e) Green roofs: these roofs can be included, which modify c* and kc. Depending on the specific green roof design, c_{DSUD} or c_{IS} might also be affected.

3 Results and discussion

The methodology has been applied to four generic urban catchments with different characteristics (called design alternatives, see Table 1), depending on whether the runoff is directed (section 3.1) or not (section 3.2) to the pervious zones to infiltrate. A section that analyzes the feasibility of the SUDS designed with the proposed method to satisfy the existing design standards is also presented (section 3.3). Finally, section 3.4 presents a comparative analysis.

-Table 1 near here-

Climatological data (daily rainfall and potential evapotranspiration) have been collected from the weather station located at Barajas Airport in Madrid (Spain). Records from 2000 to 2016 were averaged on a daily basis.

Concerning the unitary costs of the system, the following values have been considered for the cost function proposed in section 2.2: $UC_I = 1.68$ €/m^3, $UC_{SUD} = 0.315$ €/m^3, and $UC_{CUD} = 1.99$ €/m^3.

3.1 Design alternatives that convey runoff to permeable zones

3.1.1 Optimum water volume and minimum cost

The first set of analyzed catchments include infiltration zones to receive and infiltrate runoff (c_{RD}=1). A drain infrastructure underlying the entire catchment collects the infiltrated water and stores it in a tank (c_{IS}=c_{DSUD}=1). Figure 2 shows both the optimum volume of water to be reutilized (V^*_{SUD}, which corresponds with the optimum storage capacity) and the cost of the optimum solution for different design alternatives.

-Figure 2 near here-

Figure 2. Optimum solutions, alternatives that convey the runoff to infiltrate. Optimum volumes (Figure 2a) and the cost of the optimum solution of each analyzed alternative (Figure 2b).

The optimum water volume to be reused (Figure 2a) mainly depends on the final use of the stored water (r_{RIPH}) and the average runoff coefficient (c*). The smaller V^*_{SUD} values correspond to $r_{RIPH} = 0$. Unlike the planting soil, no capacity limit for water infiltration is observed for the phreatic level, so the required storage capacity is not as important for $r_{RIPH} = 1$ as it is for $r_{RIPH} = 0$.

No runoff goes to CUD ($c_{RD} = 1$), and the potential discharge from the storage tank is the only source of CUD. Consequently, the cost of conveying water to the conventional sewer system will be negligible compared with irrigation or SUDS costs.

As Figure 2a shows, V^*_{SUD} increases in c* increments when $r_{RIPH} = 0$. The stored water can infiltrate into a great volume of planting soil if c* is small, whereas the same amount of water ($c_{RD} = 1$ so that the runoff and the infiltration go to the storage element in any case) has to be infiltrated in a smaller volume of planting soil if c* increases. As a consequence, discharges to CUD reduce if V^*_{SUD} increases to store the water that cannot infiltrate into soil at planting zones.

Considering that the cost of conveying water to the conventional sewer systems is not a major asset to the total cost, the results are mainly influenced by the irrigation cost: $UC_I > UC_{SUD}$, and usually $I > V_{SUD}$. This fact explains the alternatives in which $r_{RIPH} = 0$ show lower costs than that of the others (Figure 2b).

3.1.2 Effect of the planned SUD on the main water balance variables

Figure 3 shows the variations of I (Figure 3a), RI (Figure 3b), D (Figure 3c), CUD (Figure 3d), and V_{SUDav} (Figure 3e) as the planned V_{SUD} varies.

-Figure 3 near here-

Figure 3. Influence of V_{SUD} on the water balance. Variations of I (Figure 3a), RI (Figure 3b), D (Figure 3c), CUD (Figure 3d), and V_{SUDav} (Figure 3e) as the planned V_{SUD} varies. Points represent V^*_{SUD}. Continuous lines: c*=0.5, dotted lines: c*=0.1 and c*=0.9.

As Figures 3a and 3b show, irrigation is partially covered by re-infiltration. Therefore, I reduces as V_{SUD} increases for $r_{RIPH} = 0$. Otherwise, RI=0 and, consequently, I is constant. RI increases as V_{SUD} increases to the maximum re-infiltration capacity, which depends on the soil porosity and precipitation patterns. A reduction in irrigation is not proportional to the RI increase since RI depends on the soil capacity to receive the water and not on the plant water requirements that determine the irrigation scheduling.

Seepage (D) does not vary if $r_{RIPH}=0$ (Figure 3c). Conversely, the increase in V_{SUD} clearly influences D if $r_{RIPH} = 1$. In this case, the storage element becomes the unique groundwater feeding source. D is limited by precipitation patterns if $r_{RIPH} = 1$, and there is a threshold V_{SUD} value that stores all the infiltrated water. This V_{SUD} value ensures that no flow is discharged to the conventional sewer system.

CUD is only caused by the excess of incoming water beyond V_{SUD}. Consequently, CUD decreases as V_{SUD} increases and approaches zero in the case the storage capacity holds all the incoming water volume (Figure 3d). CUD reduction as V_{SUD} increases is more pronounced as $r_{RIPH} = 1$, since the infiltration of the stored water is not limited by the soil water content.

V_{SUDav} is higher if the stored water is used for irrigation ($r_{RIPH} = 0$) as a result of the greater resistance of the planting soil to receive water (see Figure 3e).

As the location of V^*_{SUD} in the graphics included in Figure 3 shows, the optimum solution for $r_{RIPH} = 1$ is found for CUD = 0. In these cases, irrigation does not depend on V^*_{SUD}, and the SUDS cost is lower than the cost of conveying the water to the conventional sewer system, so the total cost is mainly determined by the latter. Conversely, the optimum solution for $r_{RIPH} = 0$ depends on the I and CUD costs, and their relative weight is determined by c*. As a consequence, the optimum solution varies between the following extreme cases: CUD = 0 and I ≈ 0.65 m^3/m^2 if c* = 0.1 and I = 0 and CUD ≈ 0.28 m^3/m^2 if c* = 0.9.

3.2 Design alternatives that do not convey runoff to permeable zones

3.2.1 Optimum water volume and minimum cost

The runoff goes directly to CUD in this group of design alternatives (c_{RD} = 0). A drain infrastructure underlying the entire catchment collects the infiltrated water and stores it in a tank (c_{IS} = c_{DSUD} = 1). Figure 4 shows the minimum cost (Figure 4a) and the storage capacity that yields the minimum cost (Figure 4b) for each design alternative.

-Figure 4 near here-

Figure 4. Optimum solutions, alternatives not conveying the runoff to infiltrate. Optimum volumes (Figure 4a) and the cost of the optimum solution of each analyzed alternative (Figure 4b).

The runoff is directed to the conventional sewage system so V^*_{SUD} minimally influences CUD. In general, the volume of reutilized water decreases compared with the alternatives explained in section 3.1, since runoff is not collected by SUDS. Unlike the previous design alternatives, V^*_{SUD} decreases as c* increases. No runoff is directed to permeable zones, and the unique feeding source of V_{SUD} is R_I, which reduces as c* increases, so a smaller V^*_{SUD} is required as c* increases. The greatest V^*_{SUD} corresponds to the case in which water is reutilized for irrigation (r_{RIPH} = 0).

3.2.2 Effect of the planned SUD on the main water balance variables

Figure 5 shows I (Figure 5a), RI (Figure 5b), D (Figure 5c), CUD (Figure 5d), and V_{SUDav} (Figure 5e) variations as the planned V_{SUD} varies.

-Figure 5 near here-

Figure 5. Influence of V_{SUD} on the water balance. Variation of I (Figure 5a), RI (Figure 5b), D (Figure 5c), CUD (Figure 5d), and V_{SUDav} (Figure 5e) as the planned V_{SUD} varies. Points represent V^*_{SUD}. Continuous lines: c*=0.5, dotted lines: c*=0.1 and c*=0.9.

The relationship between I and RI (Figures 5a and 5b) does not differ from that observed for the previous design alternatives (Figures 3a and 3b).

Seepage (Figure 5c) is smaller than in the previous design alternatives (sect. 3.1) because of the different runoff destination. However, the trend with V_{SUD} does not differ substantially; D increases to a maximum value that coincides with the V_{SUD} value that stores all the infiltrated water. This V_{SUD} value also defines a threshold beyond which no discharge is conveyed from the storage tank to CUD (Figure 5d). Unlike in the previous section, CUD does not reach zero because the runoff is still discharged to CUD.

The irrigation cost is more sensitive to V^*_{SUD} than is the cost of conveying water to the conventional sewer system, which is almost independent of V^*_{SUD}. Moreover, the amount of infiltrated water is small, because runoff is not collected. All of these facts emphasize that, for $r_{RIPH} = 0$, the optimum solutions are similar to the points of maximum re-infiltration, minimum irrigation and CUD (Figures 5a, 5b and 5d). Conversely, since I does not depend on V^*_{SUD}, if $r_{RIPH} = 1$, the optimum solution in these cases are similar to the V_{SUD} value that minimizes CUD.

3.3 Case study: Comparison with event-based design criteria

The method presented in this paper is based on a water balance that uses climatological data on a daily basis. Unlike the traditional design models, this method seeks to achieve optimum stormwater management for the widest range of hydrological conditions and not only for specific rainfall events. Therefore, SUDS performance designed with the exposed criteria was analyzed for typical rainfall extreme events. With this purpose, we adapted the requirements that were defined in Ballard et al. (2015), which establishes that SUDS must be designed to constrain the runoff volume and the peak runoff flow to the predevelopment green field rates. Following this reference, the volume requirements have to be complied for a rainfall event of a

100 year return period of 6 hour duration, while a 100 year return period critical duration event has to be considered for the runoff flow rate. We considered these durations, but we chose a 25 year return period event, since it adapted better to the local Spanish design criteria.

The alternatives presented in Table 1, with an additional alternative that considers the classical catchment design without SUDS, were studied. For each design alternative, the distributions among land uses (impermeable pavements with c=0.9, irrigated planting zones with c=0.01 and porous pavements with c=0.6) presented in Table 2 were considered.

-Table 2 near here-

The total theoretical yearly irrigation requirement, which was calculated as the difference between the precipitation and evapotranspiration, is approximately 5,287.23 m^3, thus resulting in a maximum daily irrigation depth of 5.48 mm.

3.3.1 Runoff volume

Table 3 shows the calculated runoff volumes for the alternatives and the pavements combinations that are presented in Tables 1 and 2, for a 25 year return period event of 6 hour duration.

-Table 3 near here-

Table 3 shows that the alternatives of collecting and conveying the runoff to infiltrate in permeable zones (alternatives 1 and 2) remove runoff and satisfy the volume requirements.

In the absence of installations to collect runoff (alternatives 3 and 4), the fulfillment of the requirements depends on the porous pavement area. A minimum of 1,500 m^2 porous pavements (with 5,000 m^2 planting zones and 3,500 m^2 impermeable pavements) has to be provided to reduce the runoff volume to a level that is below the predevelopment level.

Figure 6 shows the hydrographs that were calculated with the dimensionless hydrograph method that was proposed by Haan et al. (1994), for the alternatives and pavement combinations that consider the rainfall event of 6 hour duration with a 25 year return period.

-Figure 6 near here-

Figure 6. Hydrographs for an event of 6 hour duration with a 25 year return period. Infiltration and runoff hydrographs of the analyzed alternatives and pavement combinations for a rainfall event of 6 hour duration and 25 year return period (Q = runoff flow rate; Q_{inf} = infiltrated flow; Q_{SUDin} = incoming flow to the storage element; Q_{SUDout} = outcoming flow from the storage element to CUD).

No differences were observed among the runoff hydrographs of alternatives 0, 3 and 4. The infiltration hydrographs present different behavior depending on the runoff management. Alternatives 3 and 4 do not harvest runoff, so the infiltrated volumes are smaller than the ones for alternatives 1 and 2. The peak infiltrated flow of alternatives 1 and 2 is higher than that of alternatives 0, 3 or 4. The infiltrated flow of the predevelopment state is always smaller than the infiltrated flow of alternatives 3 and 4, whereas in alternatives 1 and 2, the infiltrated flow depends on the porous pavement area.

When the initial soil water content is 0.25 m^3/m^3, the storage tank will start to fill after the peak runoff flow. The start of filling, and then the probability of discharging to CUD, strongly depends on the soil water storage capacity, which, in turn, depends on the soil type and initial soil water content.

No discharge from the storage element to the conventional sewer system (Q_{SUDout}) was produced because the incoming volume was smaller than V^*_{SUD} in any case. It has to be noted that RI is supposed to be zero during the rainfall event. This explains why V_{SUD} curves become horizontal for alternatives 2 and 4. Conversely, $RI_{PH} \neq 0$ if $r_{RIPH} = 1$ since the phreatic level can receive water during the rainfall event. As a result, V_{SUD} curves reduce after reaching a maximum point for alternatives 1 and 3.

3.3.2 Peak runoff

Figure 7 presents the hydrographs for the alternatives and pavement combinations considering the rainfall event of critical duration and the 25 year return period.

-Figure 7 near here-

Figure 7. Hydrographs for a 25 year return period critical duration event. Infiltration and runoff hydrographs of the analyzed alternatives and pavement combinations for a rainfall event of critical duration and a 25 year return period (Q = runoff flow rate; Q_{inf} = infiltrated flow; Q_{SUDin} = incoming flow to the storage element; Q_{SUDout} = outcoming flow from the storage element to CUD).

The tendency of the runoff hydrographs does not differ between this rainfall event and the previous event. The compliance of the requirement depends on the porous pavement area for alternatives 0, 3 and 4 (the requirements are satisfied if $S_{pavpor} > 1{,}500\ m^2$), while it is guaranteed in any case if runoff is conveyed to permeable zones for infiltration (alternatives 1 and 2).

Results differ from the hydrographs that are presented in Figure 6 for the infiltrated flow. As Figure 7 shows, the maximum soil infiltration capacity limits the peak infiltrated flow for any alternative, including the predevelopment situation. V_{SUD} filling curves look similar to the same curves of the previous rainfall event, and the differences among the design alternatives are also caused by the destination of the stored water. There is also a relevant time lag between the start of infiltration and the tank filling due to the soil storage capacity. No discharge is observed in the conventional sewer system for this rainfall event either.

Finally, Table 4 shows that the aggregated volume reduces compared with volumes shown in Table 3.

-Table 4 near here-

3.4 Comparative analysis

The design alternative that conveys the surface runoff to pervious zones within the catchment and that uses the stored water for irrigation is the optimum choice in terms of irrigation and water conveyed to the conventional sewer system. Moreover, it is this alternative that yields the minimum cost.

Design alternatives that harvest surface runoff fulfill the classical design standards, while the compliance for the other design alternatives depends on the surface of porous pavements. This relationship between the area of pervious zones and the effectiveness of the SUDS was also stated by other authors, for example, Palla and Gnecco (2017) or Yang and Chui (2018). The complementarity among different SUDS that are observed in the present paper was also highlighted by other authors, for example, Duan et al. (2016). Similar to the results presented in the present paper, Mei et al. (2018) found that the combination of porous pavements plus bioretention cells and vegetated swales was the optimum solution according to a cost/benefit criterion.

The literature does not agree with respect to the ability of SUDS to reduce flood risk, and results are highly conditioned by the location and the analyzed combination of SUDS. For example, Ahiablame and Shakia (2016) found that combining porous pavements, rain gardens and rain barrels would lead to a 47 % reduction in the average annual runoff. Kong et al. (2017) observed that the hydrological response did not mimic the predevelopment situation despite the installed SUDS. In contrast, Bortolini and Zanin (2018) observed that rain gardens were able to practically eliminate surface runoff for most of the analyzed rainfall events. In this research, we have found that in harvesting surface runoff, using rain gardens and storing the infiltrated water, neither flood nor discharge to the conventional sewer system from the catchment should be expected.

In contrast, we have not found relevant differences in the SUD performance depending on the storm duration as, for example, Her et al. (2016) observed. The main differences in our study were caused by the soil storage capacity. The relevance of the soil water content to the runoff control and the volume reduction was also highlighted by Batalini de Macedo et al. (2019).

4 Conclusions

A methodology based on a comprehensive volumetric water balance was proposed to analyze urban catchments, including SUDS, using climatological data on a daily basis. The contributions to the balance are irrigation and precipitation; the outlets are evapotranspiration, seepage and discharge to the conventional sewage system. The internal system variations are the volume of water to be locally reutilized and the soil water content variation.

A cost function including the costs of irrigating, discharging to the conventional sewer system and reusing water locally was proposed to estimate the optimum volume of water to be managed.

The methodology was applied not only to simulate the behavior of the main water balance hydrological variables but also to estimate the optimum amount of water to be managed locally.

Regarding the study of different urban catchments, the catchments that conveys runoff to the pervious areas and uses the stored water for irrigation provides the optimum solution. This design ensures the minimum cost and the most efficient management of resources (the greatest amount of water available to be reused and the smallest discharge to the conventional sewer system). Additionally, alternatives conveying runoff to permeable zones satisfy the traditional SUDS design criteria regarding the reduction of volume and peak runoff flow to the predevelopment situation.

Further investigations should be conducted to evaluate the infrastructure operating conditions during the season to focus on irrigation management. Moreover, field experiments should help to monitor the variables that are studied in the present paper, such as the soil water content or the storage filling level. In the field experiments, particular attention should also be paid to the operating conditions under extreme rainfall events.

5 Acknowledgements

This research was partially developed within the LIFE CERSUDS project and was financed by the LIFE Programme 2014-2020 of the European Union for the Environment and Climate Action [LIFE15 CCA/ES/000091].

6 References

Ahiablame, L.M., Engel, B.A., Chaubey, I. 2013. Effectiveness of low impact development practices: literature review and suggestion for future research. Water, Air and Soil Pollution, 223(7), 4253-4273.

Ahiablame, L.M., Shakya, R. 2016. Modelling flood reduction effects of Low Impact development at a watershed scale. Journal of Environmental Modelling, 171, 81-91.

Ballard, B.W., Wilson, S., Udale-Clarke, H., Illman, S., Scott, T., Ashley, R., Kellaguer, R. 2015. The SuDS Manual. Construction industry research and information association. London: Department for Environment, Food & Rural Affairs.

Batalini de Macedo, M., Ferreira do Lago, C.A., Mendiondo, E.M. 2019. Stormwater volume reduction and water quality improvement by bioretention: Potentials and challenges for water security in a subtropical catchment. Science of the total environment, 647, 923-931.

Bortollini, L., Zanin, G. 2018. Hydrological behavior of rain gardens and plant suitability: A study in the Veneto plain (north-eastern Italy) conditions. Urban forestry & urban greening, 34, 121-133.

Busrzta-Adamiak, E., Mrowiec, M. 2013. Modelling of green roofs´ hydrologic performance using EPA´s SWMM. Water science technology, 61(1), 36-42.

Carsel, R.F., Parrish, R.S. 1988. Developing joint probability distributions of soil water retention characteristics. Water Resources Research, 24, 755-769.

Chang, N., Lu, J., May Chui, T.F., Hartshon, N. 2018. Global Policy of low impact development for storm water management in urban regions. Land Use Policy, 70, 368-383.

Dhakal, K.P., Chevalier, L.R. 2017. Managing urban storm water for urban sustainability: barriers and policy solutions for green infrastructure application. Journal of Environmental Management, 203, 171-181.

Dietz, M.E. 2007. Low impact development practices: a review of current research and recommendations for future directions. Water, air and soil pollutants, 186(1-4), 351-363.

Duan, H.F., Li, F., Yan, H. 2016. Multi-objective optimal design of detention tanks in the urban stormwater drainage systems: LID implementation and analysis. Water resources management, 30, 4635-4648.

Gregoire, B.G., Clausen, J.C. 2011. Effect of a modular extensive green roof on storm water runoff and water quality. Ecological engineering, 37(6), 963-969.

Haan, C.T., Barfield, B.J., Hayes, J.C. 1994. Design Hydrology and Sedimentology for Small Catchments. New York: Academic Press.

Her, Y., Jeong, J., Arnold, J., Gosselink, L., Glick, R., Jaber, F. 2017. A new framework for modelling decentralized low impact developments using soil and water assessment tool. Environmental modelling & software, 96, 305-322.

Hunt, W.F., Jarret, A.R., Smith, J.T., Sharkey, L.J. 2006. Evaluating bioretention hydrology and nutrient removal at three field sites in North Carolina. Journal of Irrigation and Drainage Engineering, 132(6), 600-608.

Kong, F., Ban, Y., Yin, H., James, P., Dronova, I. 2017. Modeling storm water management at the city district level in response to changes in land use and low impact development. Environmental Modelling & Software, 95, 132-142.

Lee, J., Hyun, K., Choi, J. 2013. Analysis of the impact of low impact development on runoff from a new district in Korea. Water Science technology, 68(6), 1315-1321.

Lim, H.S., Lu, X.X. 2016. Sustainable urban storm water management in the tropics: an evaluation of Singapore´s ABC waters program. Journal of Hydrology, 538, 842-862.

Loperfido, J.V., Noe, G.B., Garnagin, S.T., Hogan, D.M. 2014. Effects of distributed and centralized storm water best management practices and land cover on urban stream hydrology at the catchment scale. Journal of hydrology, 519, 2584-2595.

Mei, C., Liu, J., Wang, H., Yang, Z., Ding, X., Shao, W. 2018. Integrated assessment of green infrastructure for flood mitigation to support robust decision-making for sponge city construction in an urbanized watershed. Science of the total environment, 639, 1394-1407.

Mguni, P., Herslund, L., Bergen Jensen, M. 2016. Sustainable urban drainage systems: examining the potential for green infrastructure-based storm water management for siubsaharian cities. Natural Hazars, 82, S241-S257.

Morales-Torres, A., Escuder-Bueno, I., Andrés-Domenech, I., Perales-Momparler, S. 2016. Decission support system tool for energy-eficiency, sustainable and integrated urban storm water management. Environmental Modelling and Software, 84, 518-528.

Mualem, Y. 1976. A new model for predicting the hydraulic of unsaturated porous media. Water Resources Research, 12, 513-522.

Ogden, F.L., Pradhan, N.R., Downer, C.W., Zahner, J.A. 2011. Relative importance of impervious area, drainage density, width function, and sub storm drainage on flood runoff from an urbanized catchment. Water resources research, 47, W12503

Palla, A., Gnecco, I. 2015. Hydrologic modelling of Low Impact Development systems at the urban catchment scale. Journal of Hydrology, 528, 361-368.

Pappalardo, V., La Rosa, D., Campisano, A., La Greca, P. 2017. The potential of Green infrastructure application in urban runoff control for land use planning: a preliminary evaluation from a southern Italy case study. Ecosystem services, 26, 345-354.

Pyke, C., Warren, M.P., Johnson, T., Lagro, Jr. J., Scharfenberg, J., Groth, P., Freed, R., Schroeer, W., Main, E. 2011. Assessment of low impact development for managing storm water with changing precipitation due to climate change. Landscape and Urban Planning, 103, 166-173.

Rodríguez-Rojas, M.I., Huertas-Fernández, F., Moreno, B., Martínez, G., Grindlay, A.L. 2018. A study of the application of permeable pavements as a sustainable technique for the mitigation of soil sealing in cities: a base study in the south of Spain. Journal of Environmental Management, 205, 151-162.

Rodríguez-Sinobas, L., Zubelzu, S., Perales-Momparler, S., Canogar, S. 2018. Techniques and criteria for sustainable urban storm water management. The case study of Valdbebas (Madrid, Spain). Journal of Cleaner Production, 172, 402-416.

Rossman, L.A., Huber, W.C. 2016. Storm Water Management Model. Reference Manual. Volume I – Hydrology (Revised). Cincinnati, Oh: Environmental Protection Agency.

Soil Conservation System 1985. National engineering handbook. Washington, DC: Soil Conservation System.

Trinh, D.H., Chui, T.F.M. 2013. Assessing the hydrologic restoration of an urbanized area via an integrated distributed hydrological model. Hydrology and Earth System Sciences, 17, 4789-4801.

Ursino, N. 2015. Risk analysis of sustainable urban drainage system and irrigation. Advances in water resources, 83, 277-284.

Van Genuchten, M.T. 1987. A numerical model for water and solute movement in and below the root zone. Res. Rep. 121. Riverside, Ca: U.S. Salinity Laboratory Agricultural Research Service, U.S. Department of Agriculture.

Wang, M., Swettapple, C., Fu, G., Farmani, R. 2017. A framework to support decision making in the selection of sustainable urban drainage system design alternatives. Journal of Environmental modelling, 201, 145-152.

Wang, M., Zhang, D.Q., Su, J., Dong, J.W., Tan, S.K. 2018. Assessing hydrological effects and performance of low impact development practices based on future scenarios modelling. Journal of Cleaner Production, 179, 12-23.

Yang, Y., Chui, T.F.M. 2018. Integrated hydro-environmental impact assessment and alternative selection of low impact development practices in small urban catchments. Journal of Environmental modelling, 223, 324-337.

Zhang, X., Shen, L., Tam, V.W.Y., Lee, W.W.Y. 2012. Barriers to implement extensive green roof systems: a Hong Kong study. Renewable and Sustainable Energy Reviews, 16, 314-139.

Zischg, J., Rogers, B., Gunn, A., Rauch, W., Sitzenfrei, R. 2019. Future trajectories of urban drainage systems: A simple exploratory modeling approach for assessing socio-technical transitions. Science of the total environment, 615(2), 1709-1719.

Table 1. Analyzed design alternatives.

Design Alternative	Draining and storing	Irrigation reutilization	Phreatic level reutilization	Infiltration area	Coefficients	Section
Alt. 1	Yes	No	Yes	Yes	$r_{RIPH}=1$ $c_{IS}=c_{DSUD}=1$ $c_{RD}=1$	3.1
Alt. 2	Yes	Yes	No	Yes	$r_{RIPH}=0$ $c_{IS}=c_{DSUD}=1$ $c_{RD}=1$	3.1
Alt. 3	Yes	No	Yes	No	$r_{RIPH}=1$ $c_{IS}=c_{DSUD}=1$ $c_{RD}=0$	3.2
Alt. 4	Yes	Yes	No	No	$r_{RIPH}=0$ $c_{IS}=c_{DSUD}=1$ $c_{RD}=0$	3.2

Table 2. Land uses distribution for each design alternative

Scenario	Impermeable pavement (m^2)	Porous pavement (m^2)	Planting zone (m^2)
S1	5,000	0	5,000
S2	4,500	500	5,000
S3	4,000	1,000	5,000
S4	3,500	1,500	5,000
S5	3,000	2,000	5,000
S6	2,500	2,500	5,000
S7	2,000	3,000	5,000

Table 3. Runoff volume (m^3) for the studied alternatives and pavements combinations

Scenario	Alt. 0	Alt. 1	Alt. 2	Alt. 3	Alt. 4
S1	45.3	0.0	0.0	45.3	45.3
S2	43.5	0.0	0.0	43.5	43.5
S3	41.7	0.0	0.0	41.7	41.7
S4	39.9	0.0	0.0	39.9	39.9
S5	38.1	0.0	0.0	38.1	38.1
S6	36.3	0.0	0.0	36.3	36.3
S7	34.5	0.0	0.0	34.5	34.5
Pre-development S (m^2)=10,000; c=0.45			40.3		

Table 4

Table 4. Runoff volume for the studied alternatives and pavements combinations

Scenario	Alt. 0	Alt. 1	Alt. 2	Alt. 3	Alt. 4
S1	21.4	0.0	0.0	21.4	21.4
S2	20.6	0.0	0.0	20.6	20.6
S3	19.7	0.0	0.0	19.7	19.7
S4	18.9	0.0	0.0	18.9	18.9
S5	18.0	0.0	0.0	18.0	18.0
S6	17.2	0.0	0.0	17.2	17.2
S7	16.4	0.0	0.0	16.4	16.4
Pre-development S (m^2)=10,000; c=0.45			19.1		

Figure 1

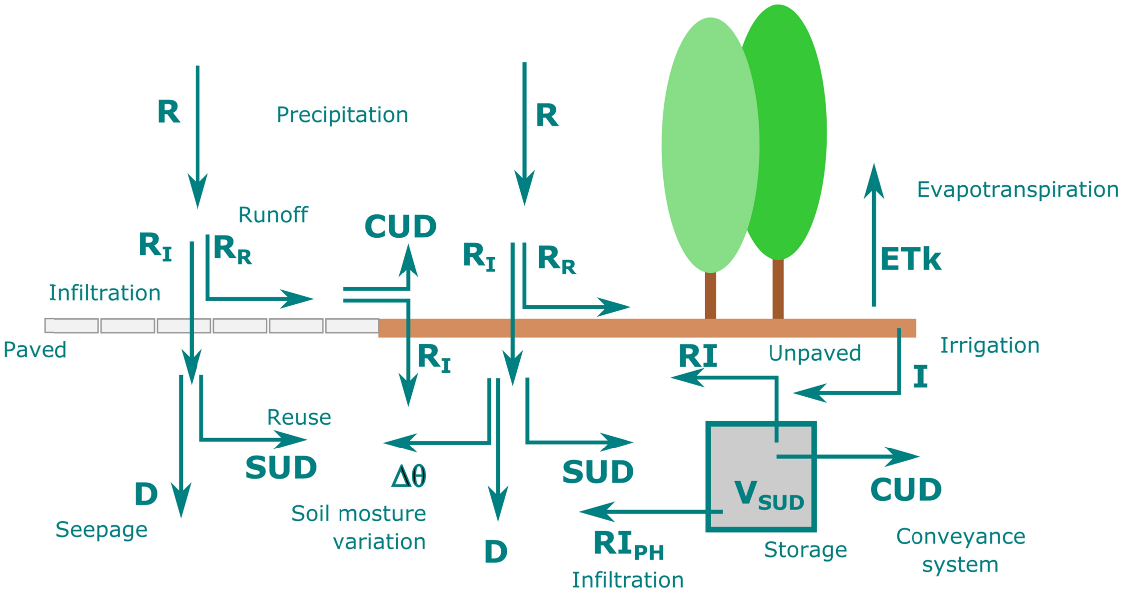

R
Precipitation
R
Evapotranspiration
Runoff
CUD
R_I
R_R
R_I
R_R
ETk
Infiltration
Paved
R_I
RI
Unpaved
Irrigation
I
Reuse
SUD
Δθ
SUD
V_{SUD}
CUD
D
Seepage
Soil mosture
variation
D
RI_{PH}
Infiltration
Storage
Conveyance
system

Figure 2

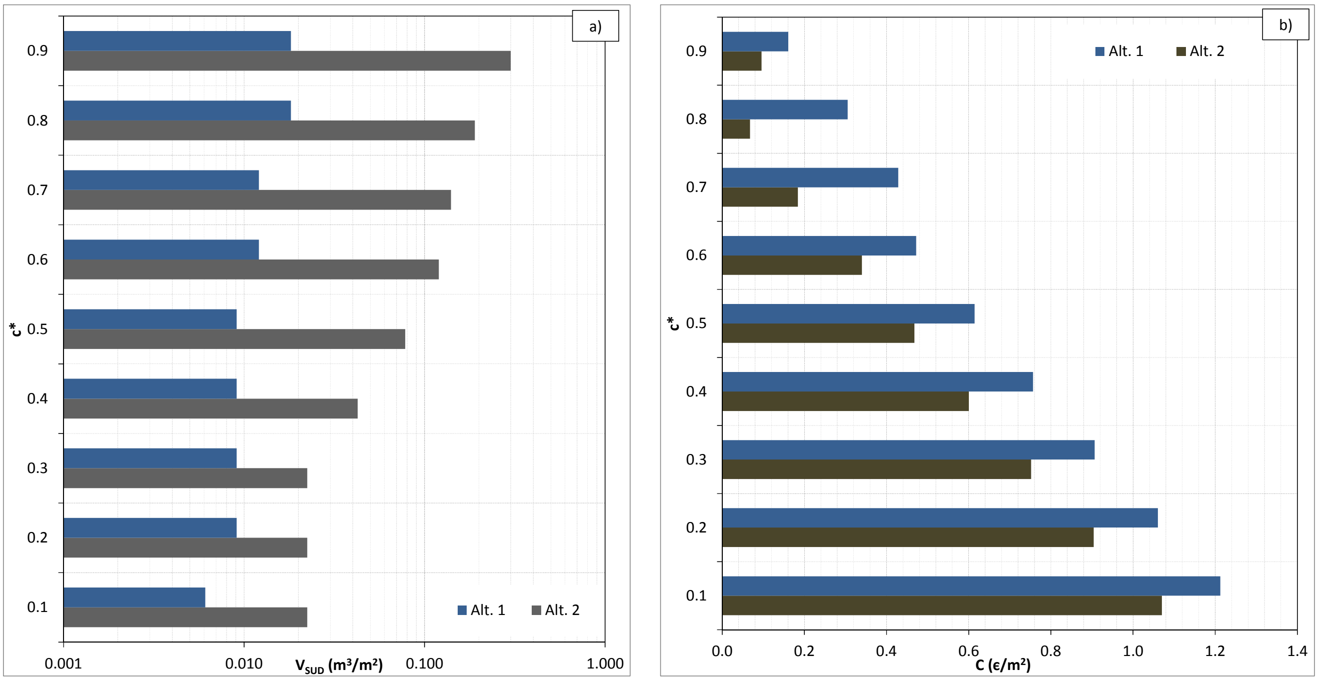

a)
0.9
0.8
0.7
0.6
c* 0.5
0.4
0.3
0.2
0.1
Alt. 1
Alt. 2
0.001
0.010
V_{SUD} (m³/m²)
0.100
1.000
b)
Alt. 1
Alt. 2
0.9
0.8
0.7
0.6
c* 0.5
0.4
0.3
0.2
0.1
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
C (€/m²)

Figure 3

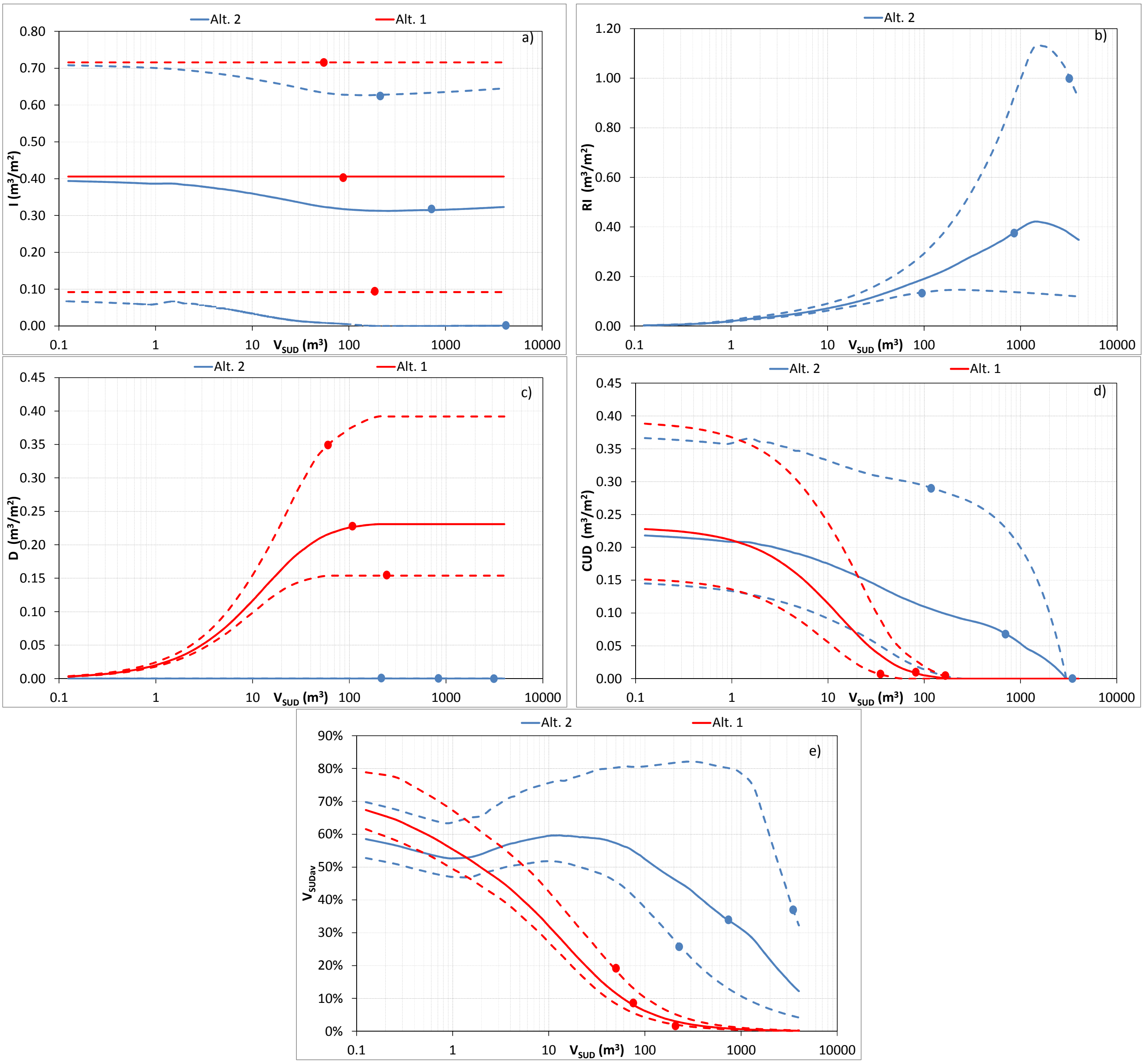

Alt. 2
Alt. 1
a)
I (m³/m²)
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0.1
1
10
V_SUD (m³)
100
1000
10000
b)
RI (m³/m²)
1.20
1.00
0.80
0.60
0.40
0.20
0.00
c)
D (m³/m²)
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
d)
CUD (m³/m²)
e)
V_SUDav
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%

Figure 4

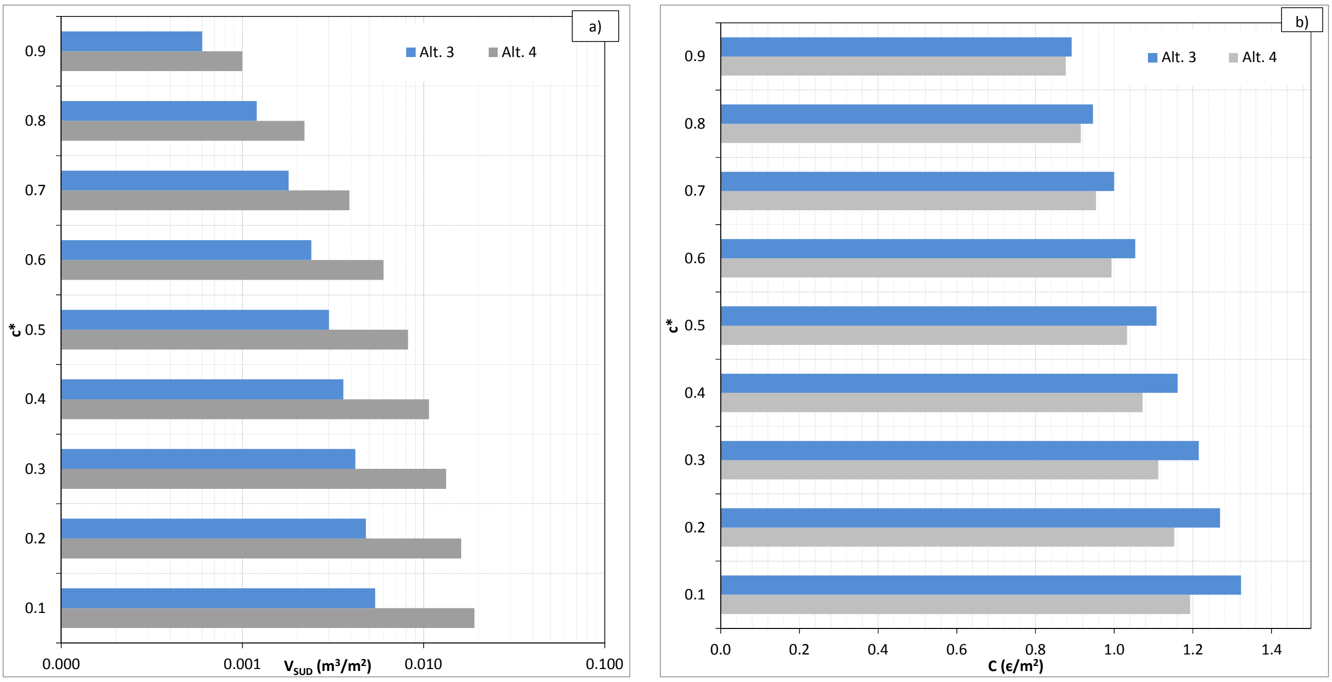

a)
Alt. 3
Alt. 4
c*
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.000
0.001
0.010
0.100
V_{SUD} (m³/m²)
b)
Alt. 3
Alt. 4
c*
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
C (€/m²)

Figure 5

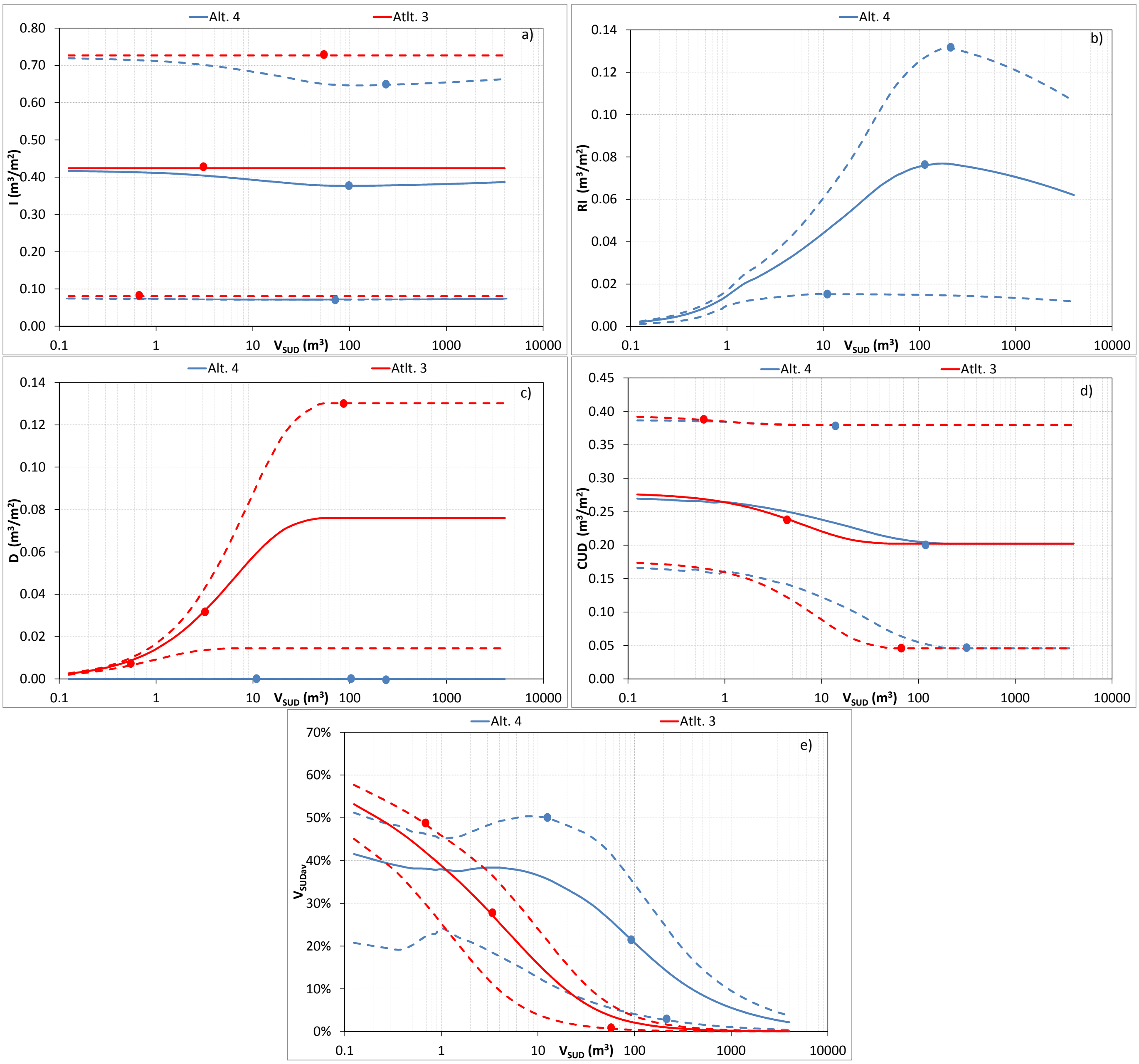

Alt. 4
Atlt. 3
a)
I (m³/m²)
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0.1
1
10
V_SUD (m³)
100
1000
10000
b)
RI (m³/m²)
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
c)
D (m³/m²)
d)
CUD (m³/m²)
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
e)
V_SUDav
70%
60%
50%
40%
30%
20%
10%
0%

Figure 6

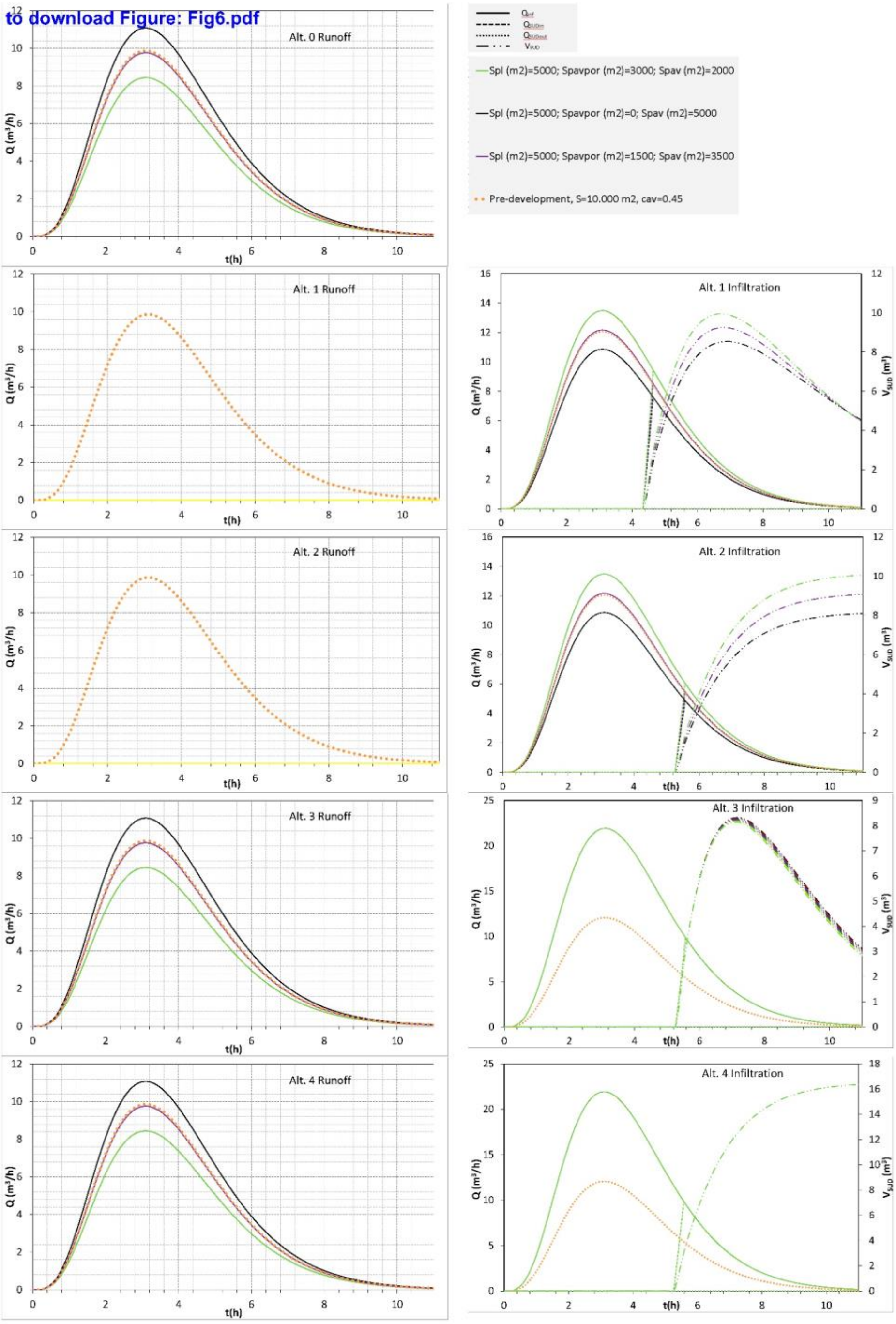
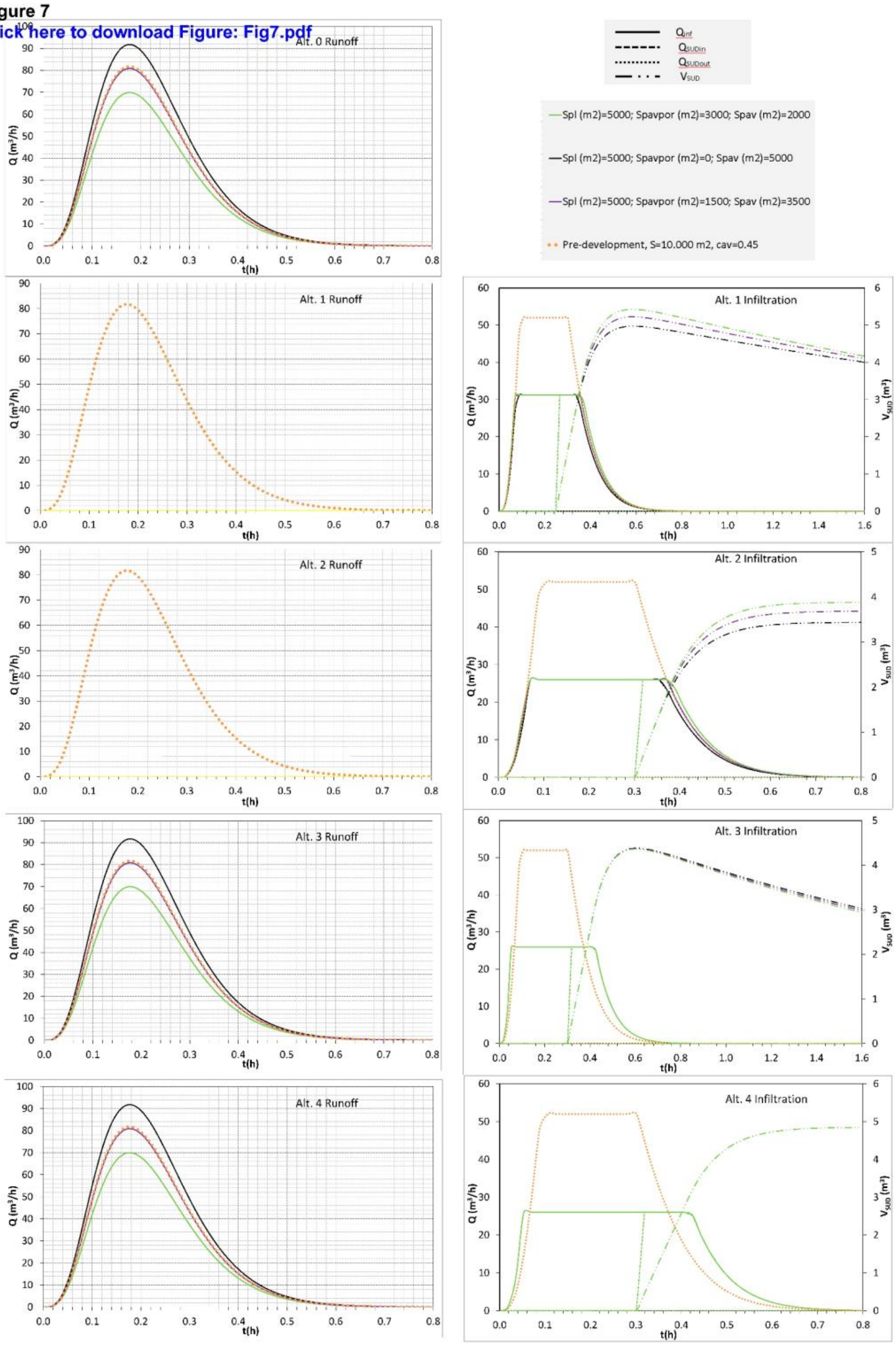

Qinf
QSUDSin
QSUDSout
VSUD
Spl (m2)=5000; Spavpor (m2)=3000; Spav (m2)=2000
Spl (m2)=5000; Spavpor (m2)=0; Spav (m2)=5000
Spl (m2)=5000; Spavpor (m2)=1500; Spav (m2)=3500
Pre-development, S=10.000 m2, cav=0.45
Alt. 0 Runoff
Alt. 1 Runoff
Alt. 1 Infiltration
Alt. 2 Runoff
Alt. 2 Infiltration
Alt. 3 Runoff
Alt. 3 Infiltration
Alt. 4 Runoff
Alt. 4 Infiltration
Q (m³/h)
VSUD (m³)
t(h)
0
2
4
6
8
10
12
14
16
18
20
25

Figure 7


Q_{inf}
Q_{SUDin}
Q_{SUDout}
V_{SUD}
Spl (m2)=5000; Spavpor (m2)=3000; Spav (m2)=2000
Spl (m2)=5000; Spavpor (m2)=0; Spav (m2)=5000
Spl (m2)=5000; Spavpor (m2)=1500; Spav (m2)=3500
Pre-development, S=10.000 m2, cav=0.45
Alt. 0 Runoff
Alt. 1 Runoff
Alt. 1 Infiltration
Alt. 2 Runoff
Alt. 2 Infiltration
Alt. 3 Runoff
Alt. 3 Infiltration
Alt. 4 Runoff
Alt. 4 Infiltration
Q (m³/h)
V_{SUD} (m³)
t(h)
0
10
20
30
40
50
60
70
80
90
100
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
1.0
1.2
1.4
1.6
1
2
3
4
5
6