



PONTIFICIA UNIVERSIDAD CATOLICA DE CHILE

ESCUELA DE INGENIERIA

AN INTEGRATED MODEL FOR REPRESENTING HYDROLOGIC PROCESSES AND IRRIGATION AT RESIDENTIAL SCALE IN SEMIARID AND MEDITERRANEAN REGIONS

JOSEFINA BELÉN HERRERA RONDA

Thesis submitted to the Office of Research and Graduate Studies in partial
fulfillment of the requirements for the Degree of Master of Science in Engineering

Advisor:

JORGE GIRONÁS LEÓN

Santiago de Chile, October, 2015

© 2015, Josefina Herrera



PONTIFICIA UNIVERSIDAD CATOLICA DE CHILE
ESCUELA DE INGENIERIA

AN INTEGRATED MODEL FOR REPRESENTING HYDROLOGIC PROCESSES AND IRRIGATION AT RESIDENTIAL SCALE IN SEMIARID AND MEDITERRANEAN REGIONS

JOSEFINA BELÉN HERRERA RONDA

Members of the Committee:

JORGE GIRONÁS LEÓN

CARLOS BONILLA MELÉNDEZ

JOSÉ VARGAS BAECHER

GLORIA ARANCIBIA HERNÁNDEZ

Thesis submitted to the Office of Research and Graduate Studies in partial
fulfillment of the requirements for the Degree of Master of Science in Engineering

Santiago de Chile, October, 2015

To José and my family.

ACKNOWLEDGEMENTS

Firstly I want to thank my husband for his confidence, empathy and steadfast support from the beginning of my studies, and my parents and sisters who always believed in my abilities. I am grateful for their patience and unwavering support. I also want to acknowledge my classmates through my years in the School of Engineering, and my graduate colleagues, for their friendship and the nice lunches during these years.

I would like to express my sincere gratitude to my advisor Dr. Jorge Gironás who has shared his knowledge and advised me with a lot of dedication and patience. His guidance helped me throughout my research and the writing of this thesis. I also want to acknowledge Dr. Carlos Bonilla for his constant interest in this work and his insightful comments and advice. Additionally, I thank the rest of my thesis committee: Dr. José Vargas and Dra. Gloria Arancibia, for their comments and support.

I want to thank CONICYT for funding my master studies through the Magíster Nacional Grant Program (CONICYT-PCHA/MagísterNacional/2014-22140398). I also acknowledge the Arturo Cousiño Lyon scholarship given by the Sociedad del Canal del Maipo.

This study is part of FONDECYT research project under grant N°1131131. Additional support from project INNOVA-CORFO 12IDL2-13630 and CEDEUS-Conicyt/Fondap/15110020 is also appreciated.

GENERAL INDEX

ACKNOWLEDGEMENTS.....	iii
GENERAL INDEX	iv
INDEX OF TABLES.....	vi
INDEX OF FIGURES	vii
RESUMEN	ix
ABSTRACT	xi
1. INTRODUCTION	1
1.1. Hypothesis.....	4
1.2. Objective	4
2. METHODOLOGY.....	6
2.1. Hydrological Processes	8
2.1.1. Evapotranspiration	8
2.1.2. Interception	9
2.1.3. Infiltration	10
2.1.4. Bare soil evaporation.....	11
2.1.5. Percolation.....	12
2.1.6. Redistribution.....	13
2.1.7. Irrigation.....	14
2.2. Outputs of the Model	15
2.2.1. Soil water content.....	15
2.2.2. Rainfall excess and surface runoff	15

2.2.3.	Subsuperficial hydrograph	16
3.	MODEL CALIBRATION AND VALIDATION	18
3.1.	Evaporation Calibration and Validation	18
3.2.	Subsurface Runoff Hydrograph Calibration and Validation.....	19
3.3.	Redistribution Validation	21
4.	APPLICATION TO A RAIN GARDENS.....	24
4.1.	Description	24
4.2.	Rain Garden Design	25
4.2.1.	Rain garden geometry	25
4.2.2.	Soil parameters and vegetation	27
4.3.	Meteorological Data.....	27
4.4.	Results and Discussion.....	28
4.4.1.	Sensitivity analysis and impacts on the irrigation needs.....	31
5.	CONCLUSION	39
	REFERENCES	41

INDEX OF TABLES

Table 1: Evaporation parameters for the five soil samples tested.	19
Table 2: Soil parameters used for both laboratory experiments to validate subsurface hydrograph.....	21
Table 3: Vegetation parameters of each rain garden	27
Table 4: Irrigation program P1. Irrigation is applied during 15 minutes.....	35

INDEX OF FIGURES

Figure 1: Conceptual representation of the physical processes at a residential scale simulated in IHMORS.	7
Figure 2: Time evolution of experimental (EXP) and simulated (IHMORS) soil water content under evaporation for the five soil samples described in Table 1....	20
Figure 3: Comparison of the observed (EXP) and simulated (IHMORS) soil moisture dynamic and subsurface hydrograph. (a) and (c) show the results for experiment 1, whereas (b) and (d) show results for experiment 2.....	22
Figure 4: Soil water content simulated by IHMORS (I) and HYDRUS (H). For both models 1 and 2 correspond to layers 1 and 2. The initial water contents considered for layers 1 and 2 were (a) 0.14 and 0.15, (b) both 0.15, (c) 0.16 and 0.15.	23
Figure 5: Rain gardens design for Santiago (a) and Temuco (b) using <i>Sedum</i> and grass respectively.....	26
Figure 6: Precipitation and temporal evolution of the soil water content using continuous simulation during 2012 and 2013 for Santiago (a) and Temuco (b). ...	29
Figure 7: Simulated water balance in the rain gardens located in Santiago and Temuco during 2012 and 2013: (a) Global water balance (b) Distribution of water volumes for soil layer 1 (L1) and layer 2 (L2). P is the water incoming to the rain garden, F is infiltrated water, I is the intercepted water, Pe is the percolated water, ET is the evapotranspired water, and R is the redistributed water during dry weather.....	30

Figure 8: Soil water content duration curve of (a) a rain garden in Santiago with *Sedum* (S), grass (G) and bare soil (B), (b) a rain garden in Temuco with *Sedum*, grass, bare soil and grass without considering summer precipitation (GS).....33

Figure 9: Simulated water balance of rain gardens in Santiago and Temuco with *Sedum* (S), grass (G) and bare soil (B). Water is lost to the atmosphere by percolation (Pe) and evapotranspiration (ET) or evaporation (E).34

Figure 10: Soil water content duration curves for the rain garden in Santiago with *Sedum* and three irrigation schedules: a monthly irrigation program (P1), a constant irrigation program with soil moisture sensor reporting field capacity (P2), and an irrigation plan that replicates the previous day evapotranspiration (P3). The curve associated with no irrigation (WI) is also presented.....36

Figure 11: Soil water content duration curves for the rain garden in Santiago with *Sedum* connected (C) and disconnected (WC) with the contributing impervious area.....38

RESUMEN

La impermeabilización en zonas naturales altera los procesos físicos y biológicos debido a que reduce la tasa de infiltración y evapotranspiración, y aumenta los volúmenes de escorrentía directa y los flujos de descarga. Para reducir estos efectos se han propuesto prácticas de control de escorrentía a escala local, conocidos como sistemas urbanos de drenaje sustentable (SUDS), los cuales son tecnologías que simulan los procesos naturales de captura, retención e infiltración de las aguas lluvias para controlar los flujos de descarga de eventos frecuentes y preservar el ciclo hidrológico. En general los SUDS consideran algún tipo de infraestructura verde, por lo que la aplicación de estas técnicas en regiones semiáridas y mediterráneas requiere la consideración de aspectos relacionados con su mantenimiento, tales como la necesidad de riego y la selección de la vegetación. Este estudio desarrolla el modelo IHMORS (del inglés Integrated Hydrological Model at Residential Scale) el cual es un modelo continuo que simula los procesos hidrológicos más importantes junto con las prácticas de irrigación de las áreas verdes. En el modelo las áreas contribuyentes y las prácticas de control de drenaje son modeladas combinando y conectando diferentes subáreas que están sujetas a procesos superficiales (intercepción, evapotranspiración, infiltración y generación de escorrentía superficial) y procesos subsuperficiales (percolación, redistribución y generación de escorrentía subsuperficial). El modelo considera estos procesos para evaluar la dinámica del contenido de humedad en diferentes horizontes de suelo. Los distintos componentes del modelo primero fueron testeados utilizando experimentos numéricos y de laboratorio, y luego fueron aplicados a un caso de estudio. En esta aplicación se evaluó el desempeño a largo plazo del control de escorrentía y de las necesidades de riego de un jardín infiltrante con diferentes tipos de vegetación, bajo diferentes climas y prácticas de riego. El modelo identificó diferencias significativas en el desempeño de las distintas alternativas y proporcionó una buena perspectiva respecto a la necesidad de mantenimiento de la infraestructura verde para el control de la escorrentía.

Palabras claves: simulación continua; contenido de agua en el suelo; infraestructura verde; modelación hidrológica; riego; escala residencial.

ABSTRACT

Urbanization alters physical and biological processes that take place in natural environments. New impervious areas change the hydrological processes, reducing infiltration and evapotranspiration and increasing direct runoff volumes and flow discharges. To reduce these effects, runoff control practices implemented at local scales have been developed, which are identified with different names such as sustainable urban drainage systems, low impact development and best management practices. These technologies, which typically consider some type of green infrastructure, simulate natural processes of capture, retention and infiltration to control flow discharges from frequent events and preserve the hydrological cycle. Applying these techniques in semiarid and Mediterranean regions requires accounting for aspects related to the maintenance of green areas, such as the irrigation needs and the selection of the vegetation. This study develops the Integrated Hydrological Model at Residential Scale, IHMORS, which is a continuous model that simulates the most relevant hydrological processes together with irrigation processes of green areas. In the model contributing areas and drainage control practices are modeled by combining and connecting different subareas subjected to surface processes (i.e. interception, evapotranspiration, infiltration and surface runoff) and subsurface processes (percolation, redistribution and subsurface runoff). The model simulates these processes and accounts for the dynamics of the water content in different soil layers. The different components of the model were first tested using laboratory and numerical experiments, and then an application to a case study was carried out. In this application I assess the long-term performance in terms of runoff control and irrigation needs of rain gardens with different vegetation, under different climate and irrigation practices. The model identifies significant differences in the performance of the alternatives and provides a good insight for the maintenance needs of green infrastructure for runoff control.

Keywords: continuous simulation; soil water content; green infrastructure; hydrological modeling; irrigation; residential scale.

1. INTRODUCTION

Urban development can produce great impacts on local hydrology and water environment (Alley and Veenhuis, 1983; Lee and Heaney, 2003; Shuster et al., 2005; Lee et al., 2012; Trinh and Chui, 2013). The conversion of landscape from pervious to impervious surfaces reduces the infiltration rates and decreases the surface storage capacity, producing higher direct runoff volumes and peak flow discharges (Lee and Heaney, 2003; Xiao et al., 2007; Freni and Oliveri, 2007). To reduce these effects, runoff control practices implemented at local scales have been developed, which are identified with names such as sustainable urban drainage systems (SUDS), low impact development (LID) and best management practices (BMP) (Fletcher et al., 2014). These practices consist of a range of technologies and techniques, which generally include green infrastructure, that are used to control stormwater runoff in a manner more sustainable than conventional solutions. They correspond to smaller scale stormwater treatment devices (Trinh and Chui, 2013; Fletcher et al., 2014) located at or near the runoff source (Barraud et al., 2004; Fletcher et al., 2014) which simulate natural processes of capture, retention and infiltration of stormwater runoff (Huang et al., 2014; Fletcher et al., 2014; Walsh et al., 2014) to control the direct runoff from frequent events and preserve the hydrological cycle (Elliot and Trowsdale, 2007; Everett et al., 2015). These functions are similar to that of any green area, although they also improve water quality (Everett et al., 2015; Houdeshel et al., 2015) and allow reducing water for maintenance purposes, as they typically correspond to green areas that receive water from impervious areas (Sample and Heaney, 2006; Xiao et al., 2007). Such characteristics can be very relevant in semiarid environments because they can treat urban runoff while simultaneously using stormwater as the primary irrigation source, which ultimately may lead to lower maintenance costs (Sample and Heaney, 2006; Houdeshel and Pomeroy., 2013, Sample et al., 2014).

Semiarid and Mediterranean ecosystem analysis has drawn widespread attention from a large number of researches as more than 40% of the continents are covered by

drylands (Slaymaker and Spencer, 1998). Hence, the response of these ecosystems has great ecological, climatic, and economic relevance (D'Odorico and Porporato, 2006). However, the performance of LID and SUDS practices has been little studied in these climates. In fact, even when the results of these techniques can vary substantially due to different climate conditions (Huang et al., 2014), their effectiveness has been less tested in arid and semiarid climates (Houdeshel et al., 2015). Moreover the design can change drastically in these climates as compared to humid areas, as there are critical variables that must be considered, such as supplemental irrigation (Ascione et al., 2013) and choosing the correct vegetation to survive through long hot and dry periods (Houdeshel and Pomeroy., 2013; Houdeshel et al., 2015).

Hydrological models are valuable tools when assessing the performance of stormwater facilities in semiarid and Mediterranean regions because they allow evaluating the effects of runoff reduction and the efficient use of water. Some researches have used existing tools to study the behavior of these practices. Huang et al. (2014) investigated the performance of five LID alternatives on water balance and flood control in a semiarid climate in northern China, whereas Walsh et al. (2014) analyzed a residential scale rainwater harvesting program in a semiarid watershed in San Diego, California. Both previous studies used the U.S. Environmental Protection Agency's Stormwater Management Model (SWMM), a comprehensive hydrological model which simulates rainfall-runoff process in urban areas (Gironás et al., 2010). The new version 5.1 has the capability of simulating different types of LID including permeable pavements, rain gardens, green roofs, street planters, rain barrels, infiltration trenches and vegetative swales (Rossman, 2010). Nonetheless, some studies have reported unsatisfactory results when simulating stormwater runoff hydrographs (Burszta-Adamiak and Mrowiec, 2013; Li and Babcock, 2014; Carson et al., 2015), whereas others have reported successful results once the parameters are calibrated using observed data (Palla and Gnecco, 2015; Rosa et al., 2015; Yang et al., 2015). The capabilities of this new version include evaporation of standing surface water, infiltration and percolation (Rossman, 2010). Nevertheless, the evapotranspiration (*ET*) in the SWMM

LID module is calculated on a daily basis based only on temperature data, and thus neither the type of plant nor the available soil moisture control the process (Rossman, 2010, Carson et al. 2015). Moreover, the model does not explicitly identify areas partially covered with vegetation, where especial considerations must be taken to calculate *ET* (Allent et al., 1998; Allen et al., 2005). Furthermore, it is not possible to capture and visualize the dynamic of soil water content in different LIDs, nor in contributing subcatchments. Finally it is neither possible to enter an irrigation schedule as an input nor to design one based on the dynamics of *ET* or the soil moisture. Both *ET* as well as soil moisture dynamic and irrigation are relevant to study SUDS, LID or BMP performance in semiarid regions (Sample and Heaney, 2006; Houdeshel et al., 2015), so other hydrological models and tools incorporating these processes properly are needed.

There are few studies or models that explicitly consider both watering needs and soil moisture behavior together with runoff control performance. Sample and Heaney (2006) compared and integrated different irrigation management options within the context of urban stormwater modeling in order to perform an economic analysis of reducing runoff using LIDs from the consumer perspective (i.e. homeowners) in Boulder, Colorado. Alternatively, Xiao et al. (2007) developed a numerical model on an hourly basis to simulate hydrological processes at residential scales and compared simulated with observed data. They analyzed four LID techniques (i.e. rain gutter, cistern, law retention basin and driveway interceptor) and studied their performance in runoff reduction and efficient use of irrigation water. Despite these studies successfully simulated the dynamics of soil water content, they did not focus on the soil moisture regime so as to determine percentages of time in which soil water content reaches critical levels for vegetation survival or decision making in irrigation. Such characterization would allow for a better quantification of the amount of time involved in irrigation associated with economic costs (i.e. personnel expense, maintenance, etc.). Models and tools that are able to simulate the surface/subsurface processes and the continuous dynamics of the soil water content behavior in detail are essential when studying the performance of Green Infrastructure in semiarid and Mediterranean regions.

These capabilities permit evaluating the possibility of the plant living or withering, and therefore analyzing the sustainability of a given drainage technique.

1.1. Hypothesis

Given the background presented in the previous section, the hypothesis of this study is the following:

Climate, geographical location and connectivity must be explicitly considered when designing runoff control practices, because these properties have a significant effect not only in the performance of the practices, but also in its operation, selection of vegetation and maintenance.

1.2. Objective

The objective of this thesis is to develop a computer model to assess dynamically the performance of variables related to the operation and maintenance of runoff control practices in different climatic conditions. In addition, the following specific objectives will be addressed using this model: (1) to study the influence of the climate on the selection of vegetation and the watering needs, in order to analyze its effect on the maintenance of the runoff control practices, (2) to analyze the role of connectivity among the contributing areas and runoff control practices in maintaining the green areas incorporated in these practices, and (3) to study the hydraulic performance of runoff control practices.

To accomplish these objectives, this study develops the Integrated Hydrological Model at Residential Scale (IHMORS), which allows evaluating in a continuous manner the rainfall-runoff processes and stormwater control at residential scales, together with the irrigation of green areas and the vegetated LID's involved. Thus the model can be applied not only in humid regions but mainly in semiarid and Mediterranean regions, as it includes an irrigation module. In the model contributing areas and drainage control

practices are modeled by combining and connecting different subareas subjected to surface processes (i.e. interception, evaporation, *ET*, infiltration and surface runoff) and subsurface processes (percolation, redistribution and subsurface runoff). The model simulates these processes and accounts for the dynamics of the water content in different soil layers. The different components of the model were first tested using laboratory and numeral experiments, and then an application to a case study was carried out. In this application I assess the long-term performance in terms of runoff control and irrigation needs of rain gardens with different vegetation, under different climates and irrigation practices.

The thesis is organized as follow: Section 2 provides an overview of the model and the variables involved, and describes the equations adopted to simulate the different hydrological processes. Section 3 presents the laboratory and numerical experiments used for validation and calibration of the equations representing the most relevant processes. Then, a long-term application to rain gardens and a sensitivity analysis varying the type of vegetation and the irrigation program is discussed in Section 4. Finally, section 5 provides the main conclusions.

2. METHODOLOGY

The IHMORS is a physically based continuous hydrological model for simulating rainfall-runoff processes in urban areas, which focuses on the performance of stormwater runoff control facilities, as well as irrigation practices at residential scale. The model was developed in MATLAB and considers data input through a MS Excel spreadsheet. Common SUDS techniques like rain gardens, green roofs, surface retention areas, driveway interceptors and others, can be simulated with the model by combining and connecting different subareas, each with different properties. Hence, each subarea is subjected to different hydrological processes according to its properties and the corresponding meteorological data. The model input data include: (1) meteorological information, (2) time step information, (3) subareas' spatial configuration, (4) physical properties of each subarea including vegetation properties if necessary, and (5) an optional irrigation program defined by the user, although IHMORS also can compute irrigation programs based on ET demands or a minimum soil water content.

The model builds on the framework proposed by Xiao et al. (2007) for the representation of both surface and subsurface processes together with watering needs. To simulate the different hydrologic processes involved they used well-known equations and mentioned the necessity of interconnecting subareas to represent interactions among them. Nonetheless, IHMORS implements several changes and improvements which include (1) the explicit and flexible representation of this connectivity, (2) the simulation of water redistribution through one or more soil layers during dry-weather, and (3) the evaporation from bare soil, which is linked to subsurface processes to correctly simulate the soil moisture in each layer. Moreover, IHMORS incorporates a propagation model that can simulate storage and subsurface runoff transport through conduit elements.

IHMORS works with a cascade of subareas which can be permeable or impermeable. These subareas are conceived as rectangular planes interconnected through horizontal runoff flows, which are distributed uniformly over the downstream subareas as an additional form of precipitation. Each subarea can have different soil

layers. Figure 1 shows all of the hydrological processes considered in the model, which are described in detail in the following subsections. Each process involved is updated according to the time step selected by the user. Water enters each subarea in the form of rainfall, run-on and/or irrigation which can be intercepted by vegetation or stored by the surface storage capacity. The water that reaches the surface can infiltrate or return to the atmosphere by evaporation (if the soil is bare) or *ET* (if the soil is covered by vegetation). In the subsurface, water moves through the soil layers by percolation and/or redistribution during dry weather days. Water reaching the last soil layer, can then either move to deep percolation and/or go to the drainage system, depending on type of SUDS, LID or green area represented. In parallel, non-infiltrated water becomes runoff and flows downstream to another subarea defined in the model or the drainage system. Such flow is simulated with a non-linear reservoir.

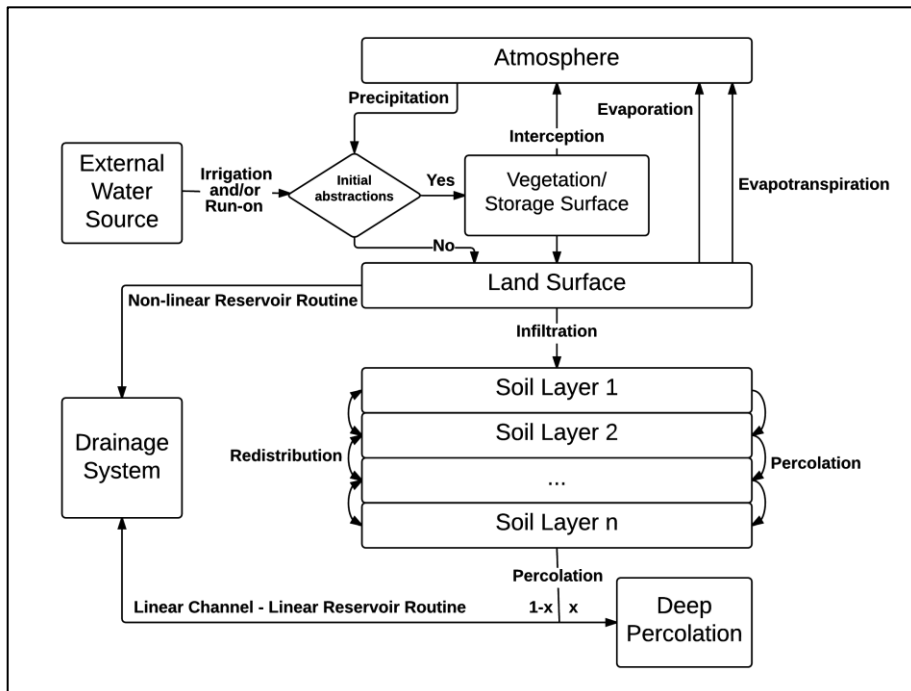


Figure 1: Conceptual representation of the physical processes at a residential scale simulated in IHMORS.

2.1. Hydrological Processes

2.1.1. Evapotranspiration

Evapotranspiration ET is the loss of water that combines the process of evaporation and transpiration (Allen et al., 1998). Evaporation is the process whereby liquid water is converted to water vapor and removed from evaporating surfaces such as lakes, rivers, pavements, soils and wet vegetation (Allen et al., 1998). Transpiration is the vaporization of liquid water contained in plant tissues and the vapor removal to the atmosphere (Allen et al., 1998). When the soil is completely covered with vegetation, evaporation and transpiration occur simultaneously and they are simulated as a single process (Allen et al., 1998). To estimate ET , the model first computes the reference evapotranspiration ET_0 which corresponds to the rate of ET from a reference surface (usually grass) without water restrictions (Allen et al., 1998). ET_0 in mmh^{-1} is estimated using the hourly Penman-Monteith equation (Allen et al., 1998):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{37}{T + 273} u_2 (e^* - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

where R_n is the net radiation ($\text{MJm}^{-2}\text{h}^{-1}$), G is the soil heat flow ($\text{MJm}^{-2}\text{h}^{-1}$), γ psychrometric constant ($\text{kPa}^\circ\text{C}^{-1}$), T is the hourly air temperature at two meters height ($^\circ\text{C}$), u_2 is the wind speed at two meters height (ms^{-1}), e^* is the saturation vapor pressure (kPa), e_a is the actual vapor pressure (kPa) and Δ is the slope vapor pressure curve ($\text{kPa}^\circ\text{C}^{-1}$). Using ET_0 value, the model estimated ET as (Allen et al., 1998):

$$ET = \begin{cases} ET_0 k_c & \theta > \theta_{FC} \\ ET_0 k_c \frac{\theta}{\theta_{FC}} & \theta \leq \theta_{FC} \end{cases} \quad (2)$$

where θ is the average soil water content of the first layer, k_c is the crop coefficient of the plant and θ_{FC} is the soil water content at the field capacity of the first layer (m^3m^{-3}). In the model k_c is considered to be time dependent, and thus the user has to enter the plant date, duration of the different stages of crop growth and the k_c values for the initial, mid-term and late season stage. Note that ET_0 will be also used to calculate interception and the water loss from bare soil (evaporation), as described in the next subsections. If is necessary, ET can be disaggregated into smaller time steps.

2.1.2. Interception

Part of the rainfall is intercepted by vegetation or surface storage and then returned to the atmosphere through evaporation (Viessman and Lewis, 1995). The model can intercept both irrigation and rainfall (Figure 1). The interception I (mm) is estimated for each time interval using a modified Merriam equation (Merriam, 1960):

$$I = S \left(1 - e^{-\frac{P}{S}} \right) + E_S \quad (3)$$

where S is the maximum interception capacity, or depression, for the vegetation (mm), P is cumulative precipitation and/or irrigation (mm) and E_S is the amount of water lost by evaporation and/or absorption during the storm (mm), estimated as:

$$E_S = kET_0t \quad (4)$$

where k is the ratio of surface area of intercepting leaves to the horizontal projection of this area and t is the time from the beginning of the storm (h). The beginning of a new storm is identified by defining a minimum dry inter-event time to separate different precipitation events.

During dry periods the intercepted water evaporates, freeing up storage from the canopy and/or the surface storage for future precipitation events.

2.1.3. Infiltration

Infiltration is the process where water is absorbed by the permeable soil. The model considers Hortonian or infiltration excess overland flow as the process to generate surface runoff (Horton, 1933). This mechanism considers that once the rainfall intensity exceeds infiltration capacity, surface runoff occurs (van de Giesen et al., 2000). Nonetheless, the infiltration rate computed by the model is reduced in case the soil reaches saturation, and thus the so called saturation excess overland flow mechanism (Beven, 2012) is also incorporated to some extent. To estimate the infiltration rates f for each time interval, the Green and Ampt equation is used (Green and Ampt, 1911):

$$f = K_s \left(\frac{\psi \Delta \theta}{F} + 1 \right) \quad (5)$$

where K_s is the saturated hydraulic conductivity (mmh^{-1}), F is the cumulative infiltration (mm), $\Delta \theta$ is the moisture content variation at the wetting front ($\text{m}^3 \text{m}^{-3}$) and ψ is the suction head at wetting front (mm). Note that F is reset to zero before irrigation or a precipitation event begins. ψ varies with to the moisture content (Corradini et. al, 1997; Lee et al., 2013) and is calculated using the van Genuchten equation (van Genuchten, 1980):

$$\psi = \psi_b \left(S_e^{-\left(\frac{n}{n-1}\right)} - 1 \right)^{n-1} \quad (6)$$

where ψ_b is the bubbling pressure (mm), n is the curve shape parameter and S_e is the relative saturation given by:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad (7)$$

where θ is the average soil water content (m^3m^{-3}), θ_s is the saturated soil water content or total porosity (m^3m^{-3}) and θ_r is the residual soil water content (m^3m^{-3}) or soil moisture after completely drained (Chow, 1988).

2.1.4. Bare soil evaporation

Evaporation E from bare soil is the transformation of liquid water to vapor water. Evaporation can be conceptualized as a two stage-process (Allen et al., 2005). In the first stage the soil surface remains wet and the evaporation rate is predicted to occur at the maximum rate, limited only by energy availability at the soil surface. After that, the second stage begins, in which the evaporation rate decreases and depends on the amount of water remaining in the soil surface and the soil hydraulic properties (Snyder et al., 2000). IHMORS models E by combining the equation proposed by Allen et al. (1998) for the first stage and the equation proposed by Snyder et al. (2000) for the second stage. Hence E is given by:

$$E = \begin{cases} K_r K_{cmax} E T_0 & K_r = 1 \\ \beta K_r K_{cmax} E T_0 & K_r < 1 \end{cases} \quad (8)$$

where K_{cmax} is the maximum value of the crop coefficient representing an upper limit on evaporation, which is introduced to reflect the natural constraints on available energy (Allen et al., 2005), β is a constant which defines the point of change from stage 1 to stage 2 (Snyder et al., 2000) and K_r is the daily evaporation reduction coefficient which can be estimated as follows:

$$K_r = \begin{cases} 1 & \theta_d \geq \theta_{REW} \\ \frac{0.5\theta_{WP} - \theta_d}{0.5\theta_{WP} - \theta_{REW}} & \theta_{REW} > \theta_d > 0.5\theta_{WP} \\ 0 & \theta_d < 0.5\theta_{WP} \end{cases} \quad (9)$$

where θ_d is the soil water content at the end of the previous day (m^3m^{-3}), θ_{WP} (m^3m^{-3}) is the wilting point at which the plants can no longer extract water from the soil (Briggs and Shantz, 1912), and θ_{REW} is the soil water content corresponding to the readily evaporated water level (m^3m^{-3}). This value can be estimated as (Allen et al., 2005):

$$\theta_{REW} = \theta_{FC} - \frac{d_{REW}}{z_e} \quad (10)$$

where d_{REW} is the maximum depth of water that can be evaporated without restrictions from the soil surface during the first stage (mm) and z_e is the depth of the soil subjected to drying through evaporation, with values ranging typically between 0.10 – 0.15 m (Allen et al., 2005). Some values of β and d_{REW} obtained from an experimental set-up will be shown in section 3.1.

2.1.5. Percolation

Percolation corresponds to the flow through each soil layer in the root zone (Savabi and Williams, 1995). In each layer, water content exceeding θ_{FC} is subjected to percolation to the next layer. The amount of water available to percolate is attenuated by a delay factor which depends on the depth and properties of the layer, as proposed by Savabi and Williams (1995):

$$p_{ej} = \begin{cases} (\theta_j - \theta_{FCj}) \left(1 - e^{-\frac{\Delta t}{t_j}}\right) \frac{d_j}{\Delta t} & \theta_j > FC_j \\ 0 & \theta_j \leq FC_j \end{cases} \quad (11)$$

where p_{ej} is the percolation rate from layer j (mm h^{-1}), d_j is the thickness of layer j (mm), Δt is the time interval (h) and t_j is the travel time through layer j (h) which is computed with the linear storage equation:

$$t_j = \frac{\theta_j - \theta_{FCj}}{K_j} d_j \quad (12)$$

where K_j is the unsaturated hydraulic conductivity of layer j (mmh^{-1}), which is calculated as follows (van Genuchten, 1980; Mualem, 1976):

$$K(S_{ej}) = K_s S_{ej}^L \left(1 - \left(1 - S_{ej}^{n/(n-1)} \right)^{(n-1)/n} \right)^2 \quad (13)$$

where L is the pore tortuosity, an empirical parameter with a typical value of 0.5 (Mualem, 1976).

2.1.6. Redistribution

Redistribution is the vertical water movement through unsaturated soils that takes place when rainfall ceases or is significantly reduced within a storm period, i.e. when infiltration is null (Smith et al., 2002). The forces that govern this process are capillarity and the gravitational gradient (Leconte and Brissette, 2001; Smith et al., 2002), and can be estimated using the vertical component of the Darcy's law (Corradini et al., 2000; Guo and Luu, 2015):

$$r_j = K_j \left(\frac{d\psi}{dz} + \cos\alpha \right) \quad (14)$$

where r_j is the redistribution rate of water flowing from layer j (mmh^{-1}), $d\psi$ is the suction head difference between layer j and layer $j \pm 1$ (i.e. the layer above or below) depending on the flow direction (mm), dz is the distance between the midpoints of the layers involved in the redistribution (mm), and α is the angle between the flow direction and the vertical axis. In this case, the flux is positive upward, therefore $\cos\alpha = -1$.

IHMORS considers that water flows from the layer with the lower absolute suction head to the adjacent one. If the soil is composed of three layers or more and the

flow is established both upward and downward, the total redistribution flow obtained using Equation (14) is split according to a factor p_r . This factor is given by the difference between the suction head of adjacent layers and that from where water is flowing due to redistribution. Thus, more redistribution flow is established between layers for which the difference in their suction heads is larger.

2.1.7. Irrigation

Irrigation is essential to maintain green areas and green infrastructure vegetation in semiarid climates. The traditional and simplest irrigation method is to supply fixed volumes of water at certain times during the day. Eventually the volume or the frequency may change through the year. This approach typically does not consider the occurrence of rainfall and thus the efficiency can be low (Stewart and Musick, 1982). Thus, predicting optimal timing and amounts of irrigation to improve efficiency becomes very relevant. IHMORS considers the three irrigation plans proposed by Sample and Heaney (2006) to achieve this purpose. The first one is a unique irrigation plan provided by the user to IHMORS as an irrigation depth vs the time table. The second is an irrigation plan that uses the previous schedule as long as the field capacity is not exceeded (i.e. the plan simulates the availability of a soil moisture sensor). Finally, the third plan corresponds to a daily variable schedule defined as a certain percentage of the previous 24 hours of ET_0 . This percentage can vary for different time steps. To use this plan, the user must enter an external file containing the percentages for the same time intervals used to define the original irrigation program. Alternatively, IHMORS can compute the irrigation needs so that the soil water content in the top layer never reaches a value smaller than a desirable water content value. Following traditional practices, this value is defined as the average between θ_{FC} and θ_{WP} (Allen et al., 1998).

2.2. Outputs of the Model

2.2.1. Soil water content

A single but time variant soil water content is assumed for each layer j . The rate of change in time of the soil water content of layer j , ϑ_j (mm) is estimated using the following mass balance equation:

$$\frac{d\vartheta_j}{dt} = \begin{cases} f - ET - E - p_{e1} + r_1 & j = 1 \text{ (top layer)} \\ p_{e_{j-1}} - p_{ej} + r_j - r_{j-1} & j > 1 \end{cases} \quad (15)$$

Then, soil water content in each layer j , at each time step can be estimated as:

$$\theta_j = \theta_{i,j} + \frac{d\vartheta_j}{dt} \frac{\Delta t}{d_j} \quad (16)$$

where $\theta_{i,j}$ is the soil water content at the beginning of the time step of layer j (m^3m^{-3}).

IHMORS first solves the mass balance without considering the redistribution. The soil water content is lower and upper limited by θ_r and θ_s respectively. Thus, the infiltration rate is reduced if the soil water content exceeds θ_s , whereas if the soil water content is less than θ_r , then IHMORS decreases the evaporation and/or the percolation rate. Only after these adjustments can the redistribution be calculated for the same time step.

2.2.2. Rainfall excess and surface runoff

IHMORS calculates in each time step the rainfall excess e (ms^{-1}) as:

$$e = p - f \quad (17)$$

where p includes precipitation, irrigation and run-on from other upstream subareas during the time step and f is the infiltration rate. If the subarea considers a surface storage depth h_p , then surface runoff is generated only once the storage capacity is full. The surface runoff hydrograph is calculated using the non-linear reservoir approach in which the Manning equation and the continuity equation are combined for a rectangular plane (Huber et al., 2005):

$$\frac{dh}{dt} = e - \frac{Q_{sp}}{A} \quad (18)$$

$$Q_{sp} = \frac{w}{n} (h - h_p)^{\frac{5}{3}} s^{\frac{1}{2}} \quad (19)$$

where h is the flow depth (m), t is time (s), w is the subarea width (m^2), n is the Manning coefficient, s is the catchment slope (mm^{-1}) and Q_{sp} is the surface runoff discharge (m^3s^{-1}).

2.2.3. Subsuperficial hydrograph

The output of percolated water is modeled by combining a linear channel and a linear reservoir, which results in a lag and route model whose instantaneous unit hydrograph is expressed as (Bras, 1990):

$$h(t) = U(t) = \frac{1}{\kappa} e^{-\frac{(t-\tau)}{\kappa}} \quad (20)$$

where τ is a lag time of the linear channel (h) and κ is a linear reservoir parameter. Parameters τ and κ are defined to represent a variety of situations that are typical of LID and SUDS such as contribution to base flow and subsurface drainage through perforated pipes or other drainage layers. The convolution between $U(t)$ and the percolated water

p_e is solved numerically utilizing a small time step finer than that used to simulate other processes in the model. Thus, the subsurface outflow Q_{sb} (m^3s^{-1}) is computed as

$$Q_{sb} = p_e U \quad (21)$$

3. MODEL CALIBRATION AND VALIDATION

Three tests were performed to validate critical components of the model: bare soil evaporation, subsurface runoff hydrograph and soil moisture redistribution. None of these three processes are often explicitly considered by rainfall-runoff models for urban settings. In particular, bare soil evaporation and redistribution required a novel approach for their implementation in the model, whereas the analysis of subsurface runoff allows validating the model to simulate the downstream contribution of percolated flows, as expected from different SUDS technique such as green roofs. Moreover, this testing process was also used to identify some unknown parameter values that are relevant for the model. Simulated results of evaporation and subsurface runoff hydrograph were compared to observed data collected in experiments. Furthermore, results from the redistribution component were compared to those from a numerical model that solves flow in porous media.

To evaluate the quality of the calibrations and/or validations, I used the Modified Coefficient of Efficiency (MCE) given by (Legates and McCabe, 1999):

$$MCE = 1 - \frac{\sum_i |O_i - P_i|}{\sum_i |O_i - \bar{O}|} \quad (22)$$

where O_i is the observed data, P_i is the predicted data, \bar{O} is the observed mean and i indicates each time step. MCE ranges between $-\infty$ to 1. A value of 1 indicates an exact match with the observations, and a value of 0 implies that the simulation predicts the observed data with the same efficiency as \bar{O} .

3.1. Evaporation Calibration and Validation

To test and calibrate evaporative parameters, five different soil samples used as substrates in green roofs were dried under ambient conditions. The samples were

weighed on a daily basis to measure evaporative water loss. θ_{WP} (Equation (9)) was measured in the laboratory, whereas d_{REW} (Equation (10)) was defined so that the extension of the first stage in evaporation was 2-3 days (Allen et al., 1998). During the experiments all the meteorological variables needed in Equation (1) were recorded. IHMORS was used to calculate ET and then bare soil evaporation parameters from Equations (8) to (10) were calibrated (Table 1). IHMORS was then used to estimate the dynamics of soil moisture content of the samples (Figure 2), which is closely compared to experimental data (MCE values larger than 0.8).

Table 1: Evaporation parameters for the five soil samples tested.

	Unit	Sample				
		a	b	c	d	e
θ_{WP}	m^3m^{-3}	0.026	0.120	0.004	0.110	0.170
d_{REW}	mm	22	27	16	16	6
K_{cmax}		2.368	2.658	1.627	1.489	0.428
β		0.208	0.462	0.523	0.800	1.934

3.2. Subsurface Runoff Hydrograph Calibration and Validation

I performed two experiments to validate the capability of the model to simulate subsurface flow and the corresponding hydrograph. In both experiments I applied a constant rain pulse of 2.31 mm min^{-1} and 2.14 mm min^{-1} during 15 minutes over a sample of 6.3 cm of soil in a square box 50 cm wide draining from underneath through an orifice. Initial soil water contents were 0.321 and $0.33 \text{ m}^3\text{m}^{-3}$. Both water content in the mind point at 3 cm depth and the flow discharge drained from the box were measured every 5 min since the beginning of the rain pulse application. The soil used in these experiments was the same as that reported as sample a in Table 1. Percolation parameters used in Equations (11) to (13) determined in the laboratory (Table 2), and the

parameters used to calculate the subsurface hydrograph (Equations (20) and (21)) were calibrated with the first experiment and validated with the second experiment. Figure 3a and Figure 3b show the time evolution of soil water content for both experiments. Observed data were very constant over time and thus the average of the observations becomes a better estimate than the simulation (i.e. MCE values in both cases are near 0). Nonetheless, subsurface flow is well simulated, and both the calibration and validation hydrographs produced by IHMORS match the observations well (Figure 3c and Figure 3d).

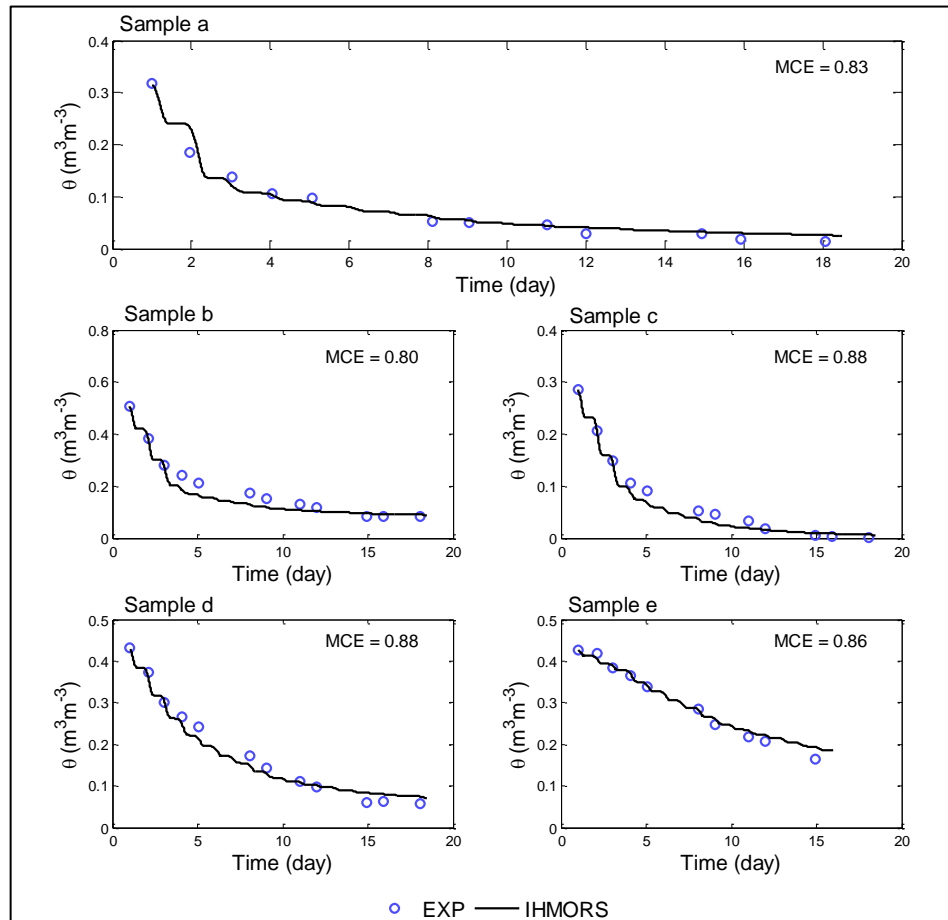


Figure 2: Time evolution of experimental (EXP) and simulated (IHMORS) soil water content under evaporation for the five soil samples described in Table 1.

Table 2: Soil parameters used for both laboratory experiments to validate subsurface hydrograph.

	Unit	Value
Percolation parameters		
θ_r	m^3m^{-3}	0.01
θ_s	m^3m^{-3}	0.540
n		1.8
K_s	mmh^{-1}	1250
θ_{FC}	m^3m^{-3}	0.230
L		0.5
Hydrograph parameters		
τ	h	10^{-7}
κ		$6 \cdot 10^{-6}$

3.3. Redistribution Validation

HYDRUS-1D (Simunek et al., 2013) was used to validate the water redistribution flux through the soil layers. HYDRUS-1D is a widely used computer software package which simulates water flow and solute transport in a vertical, horizontal or inclined direction into non-uniform soils (Simunek et al., 2013). HYDRUS-1D solves the Richards's equation to simulate the variably-saturated water flow, and has been widely and succesfully used to simulate unsaturated flow in porus media, such as the substrate of green roofs (Hiltner et al., 2008), and a large layered soil column (Ma et al., 2010).

To validate the redistribution component of IHMORS, I simulated a 0.6 m depth soil composed of a 0.2 depth top layer (layer 1) over a second layer of 0.4 m depth (layer 2). The soil parameters of both layers were the same as those shown in Table 2, but I defined different initial water contents to study the performance of the model under 3 different cases. The initial water contents of layers 1 and 2 were 0.14 and 0.15 for case 1, both 0.15 for case 2, and 0.16 and 0.15 for case 3. Figure 4 compares the evolution of the soil water content in both layers due to distribution calculated with HYDRUS-1D

(H) and IHMORS (I). In the 3 cases, obtained MCE coefficients larger than 0.5 demonstrated that the evolution of soil water contents simulated by both models are mostly in agreement, despite the simpler approach adopted in IHMORS.

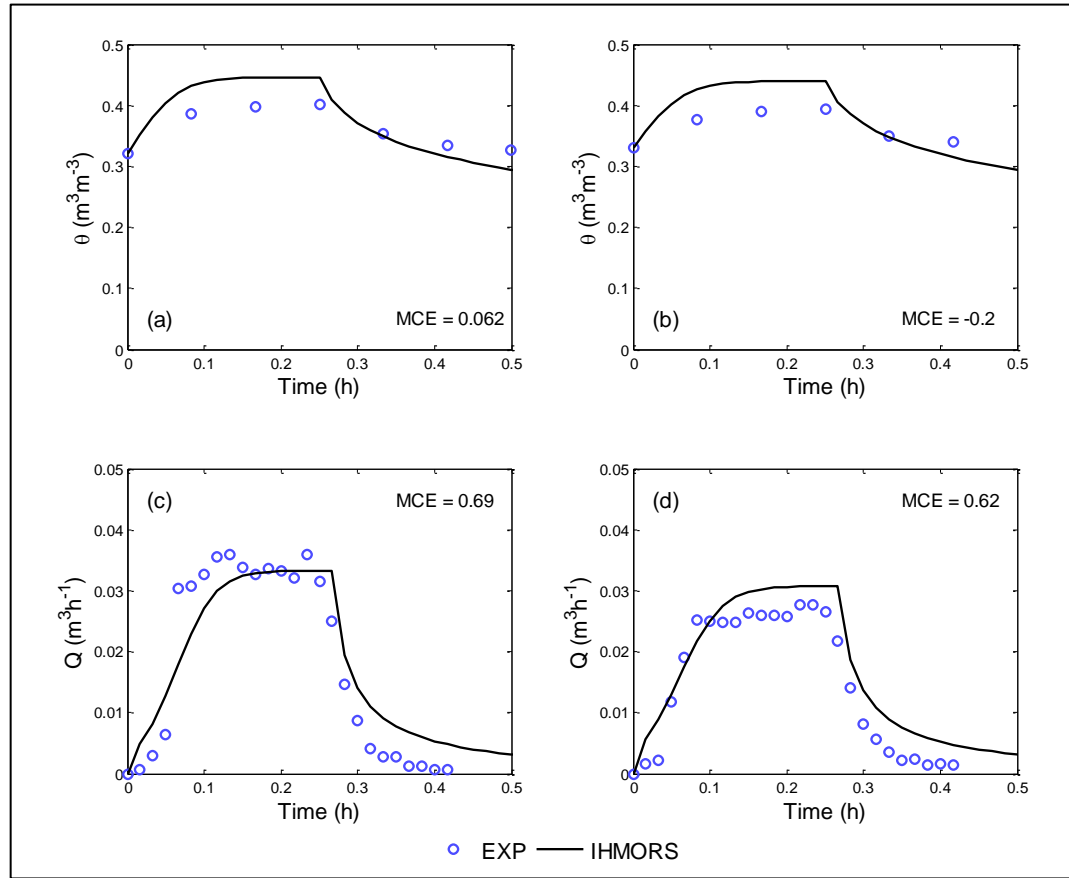


Figure 3: Comparison of the observed (EXP) and simulated (IHMORS) soil moisture dynamic and subsurface hydrograph. (a) and (c) show the results for experiment 1, whereas (b) and (d) show results for experiment 2.

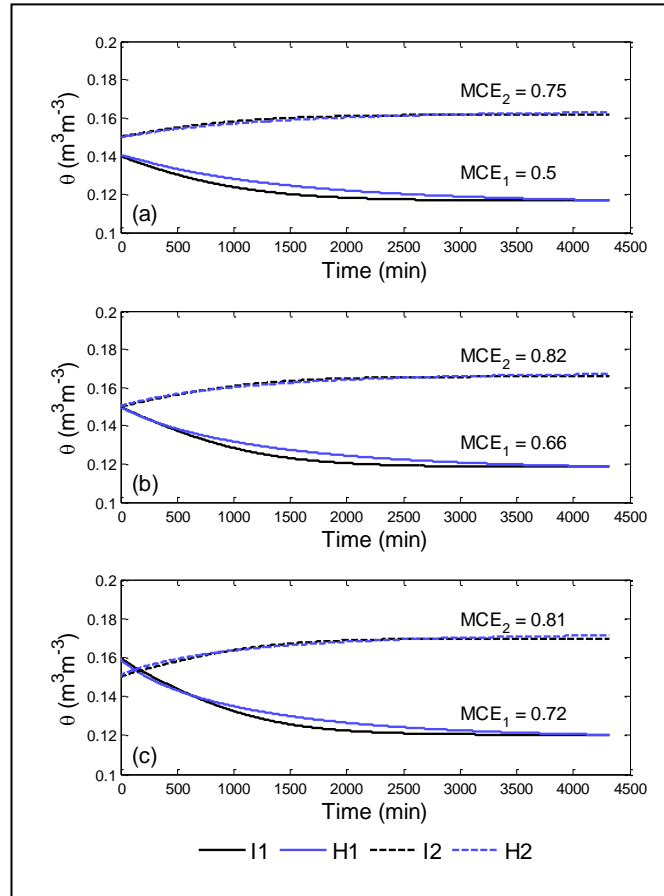


Figure 4: Soil water content simulated by IHMORS (I) and HYDRUS (H). For both models 1 and 2 correspond to layers 1 and 2. The initial water contents considered for layers 1 and 2 were (a) 0.14 and 0.15, (b) both 0.15, (c) 0.16 and 0.15.

4. APPLICATION TO A RAIN GARDENS

4.1. Description

After validating its properties, the IHMORS model is used to simulate and assess the behavior of a green infrastructure that reduces runoff volume. In particular, I model the long-term performance of rain gardens in terms of runoff control, dynamics of the soil water content and irrigation needs. In this analysis different vegetation types under different climates and irrigation practices were considered. A rain garden is a depression in the ground filled with plants and a surface mulch layer, which allows storing and infiltrating relatively small volumes of stormwater runoff (Cahill, 2012). Moreover, these techniques also utilize the *ET* capacity of the vegetation for runoff volume reduction (Cahill, 2012).

Two rain gardens located in Chile were modeled in this case. These rain gardens are designed as if they were going to be implemented in the cities of Santiago (33°26'S 70°39'W) and Temuco (38°46'S 72°38'W), which differ in their climates. Santiago has a warm temperate climate with dry summers (Peel et al., 2007), with mean annual precipitation of 313 mm, and 25-30 rainy days in an average year (DGAC, 2015). On the other hand, Temuco has a warm temperate humid climate with warm summers (Peel et al., 2007) with a mean annual precipitation of 1157 mm and 161 rainy days in an average year (DGAC, 2015). Thus, the selected cities can be assumed to be representative of the dry and wet extremes of the Mediterranean climate typical of central Chile. In both cases, the rain gardens are designed to control the runoff from a 100% impervious area of 10 m².

IHMORS was used to continuously model the performance of these rain gardens over a 2-year period, using a simulation time step of 15 min and a minimum dry weather time of 6 h to separate the rainfall events. The proposed time step is needed because of the small spatial scale involved and the necessity to capture the dynamics of the percolation, redistribution and infiltration processes, which control the soil water

content. In the following subsections, the rain gardens' design and the description of input data and parameters needed by the model are described.

4.2. Rain Garden Design

Both rain gardens were designed according to traditional standards (UDFCD, 2010; Cahill, 2012), which consider a geometric design as well as the definition of substrate and vegetation based on the local conditions.

4.2.1. Rain garden geometry

The rain gardens were designed to retain the so-called water quality capture volume (WQCV), i.e. the volume representative of runoff from frequent storm events such as the 80th percentile storm (UDFCD, 2010). The Chilean regulations define the WQCV as the runoff volume produced by a representative frequent precipitation P_r falling over the contributing impervious area A_{imp} (m²). Respectively, values of $P_r = 10$ mm and 12 mm for Santiago and Temuco are defined by the Chilean regulations (MOP, 2013). Thus the WQCV (m³) is calculated as

$$WQCV = \frac{P_r A_{imp}}{1000} \quad (23)$$

In both cases it was considered a contributing rectangular surface with area $A_{imp} = 10$ m², roughness coefficient of $n_{imp} = 0.011$, slope $s_{imp} = 2\%$ and width $w_{imp} = 5$ m. Basic considerations defined in the literature were adopted in the design regarding the rain garden area where infiltration takes place A (m²). Cahill (2012) suggests a maximum A_{imp}/A ratio of 5. On the other hand A must satisfy the following relationship (UDFCD, 2010):

$$A \geq \frac{2}{3} \frac{WQCV}{D} \quad (24)$$

where D is the ponding depth (m). A maximum value of $D = 300$ mm is recommended by the UDFCD (2010) to maintain vegetation properly, while the soil depth should generally range between 600 - 900 mm (Cahill, 2012). Thus, I defined for the top layer, or layer 1, a depth $d_1 = 0.2$ m in both cases, which is representative of the depth of the root zone (Shorten and Pleasants, 2007). Similarly the bottom layer, or layer 2, in both cases has a depth $d_2 = 0.4$ m. Furthermore, both rain gardens have the same area ($A = 2$ m²), slope ($s_{\text{garden}} = 0.1\%$) and width ($w_{\text{garden}} = 2$ m). Only D differs for both locations ($D = 50$ mm for Santiago and $D = 60$ mm for Temuco), as this design variable depends on the local WQCV (Figure 5a and Figure 5b).

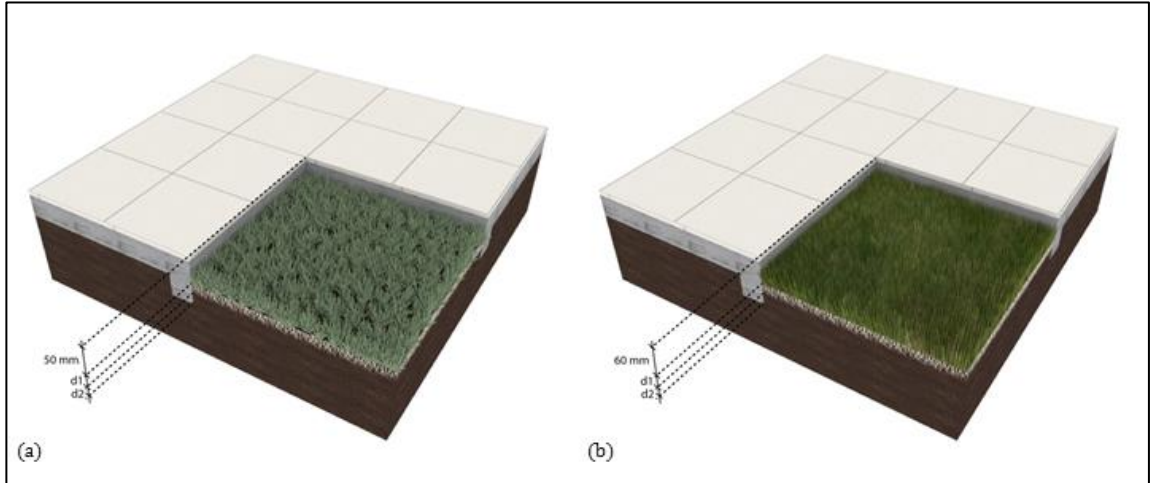


Figure 5: Rain gardens design for Santiago (a) and Temuco (b) using *Sedum* and grass respectively.

4.2.2. Soil parameters and vegetation

The same substrate used in the validation experiments, whose parameters were presented in Table 2, was considered for both rain gardens. Following the suggestion from UDFCD (2010) vegetation fully covering the rain garden is considered. Nonetheless, different vegetation for each city was chosen according to the local climate. Hence, species of *Sedum* (*Sedum rupestre*, *Sedum spurium*, *Sedum kamtschaticum*, and *Sedum rubrotinctum*) and grass, whose corresponding parameters according to Equations (2) and (3) are presented in Table 3, were adopted for Santiago and Temuco respectively. An initial water content of $0.15 \text{ m}^3\text{m}^{-3}$ in both layers was assumed for each garden.

Table 3: Vegetation parameters of each rain garden

	Unit	Vegetation	
		Sedum	Grass
k		3	2.8
S	mm	1.27	0.254
k_c^1		0.53^2	0.95^3

¹ Constant value for the year.

² Sherrard, (2012).

³ Allen et al. (1998).

4.3. Meteorological Data

Two years (i.e. 2012 and 2013) of hourly local meteorological data (i.e. precipitation, temperature, wind velocity, relative humidity and net radiation) were used in this example (INIA, 2012). Annual precipitation values in Santiago during 2012 and 2013 were 295 mm and 156 mm respectively, while in Temuco these were 582 mm and 623 mm respectively.

4.4. Results and Discussion

IHMORS was used to analyze the performance of the rain gardens in both locations. In particular, I focus on the dynamics of the soil water content and the overall long-term water balance. Furthermore a sensitivity analysis is provided, which explores the impacts of rain garden irrigation schedules and design practices (i.e. the selection of the vegetation and connection or disconnection of upstream contributing areas) on its maintenance needs.

Figure 6 shows the temporal dynamics of soil water content for both locations. As expected, the soil water content of Santiago is less variable, very responsive to the seasonal precipitation in the middle of each year (winter), and decreases at very constant rates during the dry months of fall and summer (Figure 6a). In contrast, the soil moisture in Temuco is much more variable throughout the year as precipitation occurs throughout the season. For both cities, soil water content increases with precipitation events and decreases quickly after each peak, as it has been reported in previous studies (Xiao et al., 2007; Houdeshel and Pomeroy, 2013). Because layer 2 is deeper, the variability in this layer is much less significant than for layer 1 in both cities. Indeed, in Temuco the soil moisture in layer 2 tends to be quite constant (around 0.23), except for the driest days in summer.

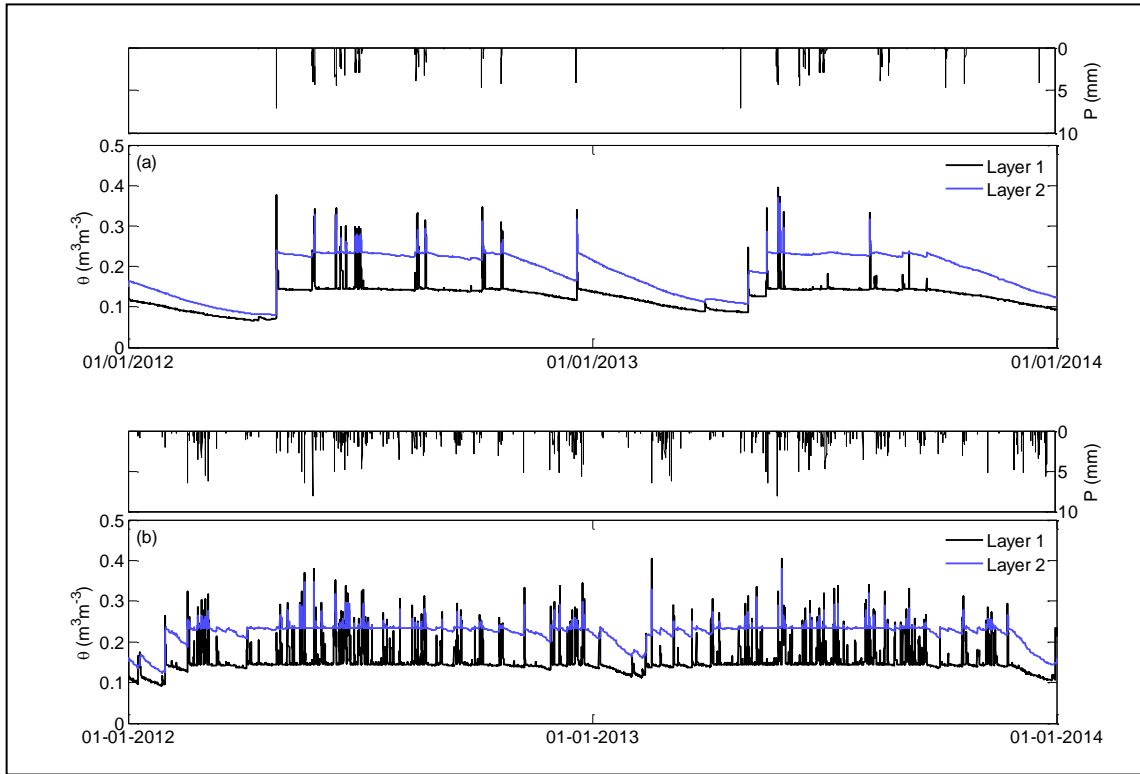


Figure 6: Precipitation and temporal evolution of the soil water content using continuous simulation during 2012 and 2013 for Santiago (a) and Temuco (b).

Annual water volumes in percentages associated with each hydrological process in the rain garden are summarized in Figure 7. For each location Figure 7a shows two bars. The left one presents the fate of the water incoming to the rain garden (P), which includes both the rainfall falling directly over the garden and the run-on coming from the contributing area. For both cities, most of this water becomes infiltration (F) whereas a very minor portion is intercepted (I). Despite the maximum intercept capacity of the *Sedum* used in Santiago, which is greater than that of the grass in Temuco, more water is intercepted in Temuco as the annual rainfall is larger. Because the infiltration rates were not exceeded by precipitation during both years of simulation, surface runoff downstream did not occur.

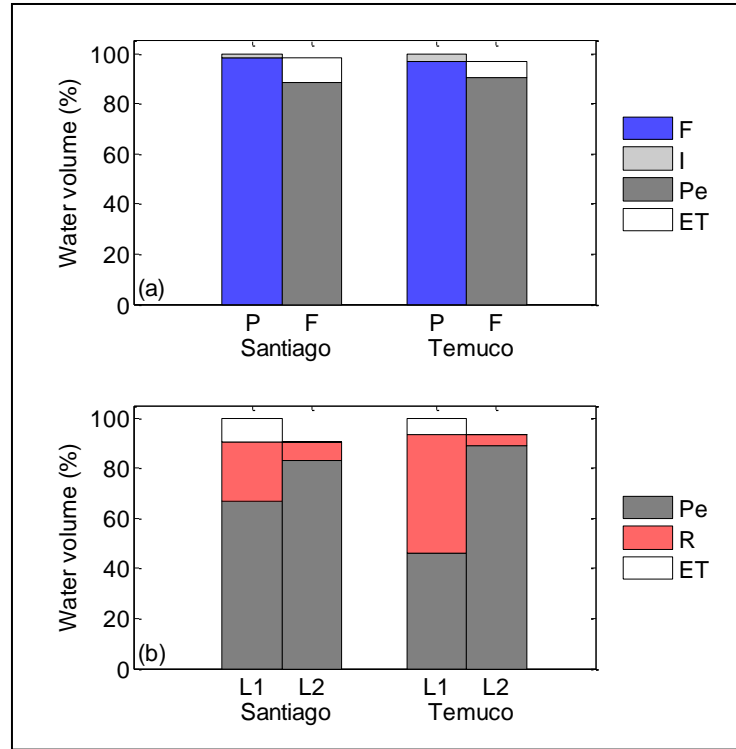


Figure 7: Simulated water balance in the rain gardens located in Santiago and Temuco during 2012 and 2013: (a) Global water balance (b) Distribution of water volumes for soil layer 1 (L1) and layer 2 (L2). P is the water incoming to the rain garden, F is infiltrated water, I is the intercepted water, Pe is the percolated water, ET is the evapotranspired water, and R is the redistributed water during dry weather.

The second bar in Figure 7a shows the fate of the water volume infiltrated into the soil considered as the combination of layer 1 and 2. Part of this water is lost to the atmosphere by evapotranspiration (ET) and the other percolates out of layer 2 (Pe). Proportionally, water loss through ET was greater in Santiago than in Temuco although the crop coefficient of grass (Temuco) is greater than that of the *Sedum* used in Santiago.

This result is supported by DehghaniSanij et al., (2004) who measured higher values of ET_0 for soils in semiarid regions.

Figure 7b shows the final distribution of water volumes separately for soil layer 1 (L1) and layer 2 (L2). In Santiago, most of the water volume incoming to L1 percolates to L2 (~67%). Approximately 24% of the remaining volume redistributes to L2 during dry-weather and the rest (~9%) is lost to the atmosphere through ET. In contrast, in Temuco redistribution to L2 during dry season is the most relevant flow acting over the water incoming to L1 (i.e. ~47%). This occurs because the high rates of rainfall raise the soil water content in L1 more often, which in turn increases the suction head gradient and enhances the redistribution. This phenomenon also increases the soil water content of L2 above θ_{FC} , which explains why the percolation from L2 in Temuco is larger than in Santiago. Finally, note that redistribution from L2 to L1 is minor in both cities, although larger in Santiago. Overall these results demonstrate that redistribution during dry-weather days can be a relevant process and should be simulated by models describing water flows in LID's and green areas in general.

4.4.1. Sensitivity analysis and impacts on the irrigation needs

The model is used to evaluate the performance of the rain garden under different vegetation types and irrigation schedules, although one could also vary the type of substrate. In this analysis I consider both grass and *Sedum* for each location in addition to a bare soil given by the substrate a (Table 1), whose wilting point measured in the laboratory is $\theta_{WP} = 0.15 \text{ m}^3\text{m}^{-3}$. Moreover, the rain garden in Temuco was tested after removing the summer precipitation in order to analyze the impact of a dry summer in the soil water content behavior. Such a situation did indeed take place during the 2014-2015 summer.

The analysis is focused on assessing the temporal dynamics of the soil water content by means of what I call the soil water content duration (SWCD) curve. This curve represents the percentage of time that a given soil water content is equaled or

exceeded. The SWCD curve is equivalent to the well-known flow duration curve, used to characterize the streamflow regime by defining the percentage of time a given flow is equaled or exceeded over a historical period (Cigizoglu and Bayazit, 2000). By using the SWCD curve I can characterize the overall soil moisture dynamics and detect the number of days in which the soil moisture is larger or less than a particular value (i.e. θ_{FC} , θ_{WP} , etc.), or the number of days in which irrigation becomes essential. Thus, this curve could potentially be used to estimate irrigation costs not only associated with the extra amount of water needed, but also the extra amount of time involved in the process (i.e. personnel expense, maintenance, transportation, contracts, etc.).

Figure 8 shows the SWCD curves for Santiago (Figure 8a) and Temuco (Figure 8b) as well as two critical soil water contents associated with the substrate: θ_{FC} and θ_{WP} . Soil water content between these two values is desirable as water is being efficiently used in irrigation without compromising the plants, whereas if the soil moisture is less than θ_{WP} the plant will wither permanently (Allen et al., 1998). These figures compare the SWCD curves for three cases in which either *Sedum* (S), grass (G) or bare soil (B) is considered for the rain garden. Furthermore, an additional SWCD curve is plotted for Temuco, which is obtained if summer precipitation in this location is removed.

Results show that planting *Sedum* instead of grass is better in terms of having larger soil moisture content overall. This is much more noticeable in Santiago, where for approximately 50% of the time the differences in soil water content exceed $0.01 \text{ m}^3 \text{ m}^{-3}$. On the other hand the difference is minor in Temuco, and is more noticeable only for the driest 10% of the time. Taking into consider a minor margin for the estimation of the minimum soil content to ensure vegetation maintenance, irrigation is essential for at least 60% of the time in Santiago, although different volumes would be needed depending on the type of vegetation. In Temuco, irrigation becomes necessary for approximately 25% of the time, and the water volume involved is pretty much the same despite the vegetation type.

Another interesting result is that in Santiago, not using vegetation at all allows having during certain periods of time soil moisture contents larger than those simulated when using vegetation. This condition occurs for ~35% (grass) and ~10% (*Sedum*) of the time (around the end of summer and beginning of fall). This does not occur in Temuco, as using any of the two vegetation types allows having soil water contents exceeding the ones associated with a bare soil. Finally, if Temuco had no summer precipitation, the soil water dynamics of a rain garden with grass would be more similar to that of semiarid regions with negligible precipitation in summer like Santiago. Indeed Figure 8b shows that soil moisture would reach values lower than those to be obtained with bare soil for approximately the 60 driest days in the year (i.e. 20% of the time).

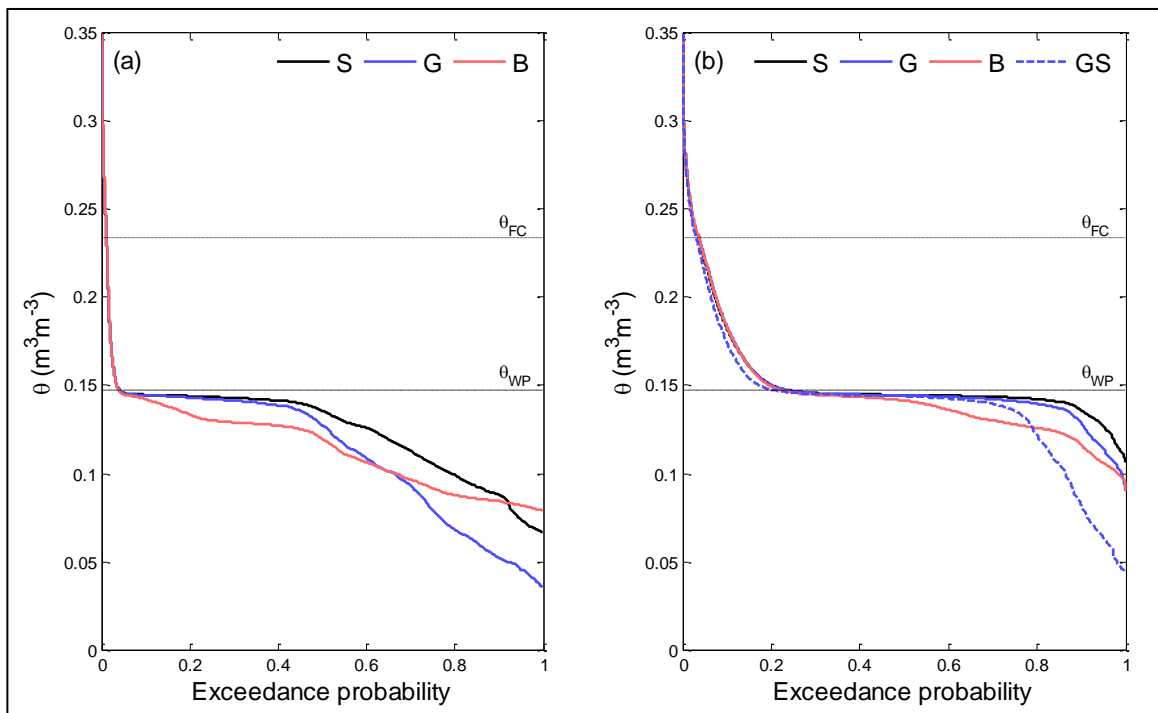


Figure 8: Soil water content duration curve of (a) a rain garden in Santiago with *Sedum* (S), grass (G) and bare soil (B), (b) a rain garden in Temuco with *Sedum*, grass, bare soil and grass without considering summer precipitation (GS).

Figure 9 compares the simulated water balance of the rain gardens with and without vegetation in Santiago and Temuco. Percolation is the lowest in both cities (and thus evaporation is the largest) when no vegetation is used. Figure 9 also shows that, as expected, the water lost by evaporation (E) from soil is proportionately higher in drier rather than humid areas. Finally, note that the extra amount of water evapotranspired by the grass as compared to the *Sedum* is more significant in Santiago. Thus it becomes clear that the selection of vegetation in semiarid regions is relevant and should be carefully considered in the design of rain gardens and green infrastructure.

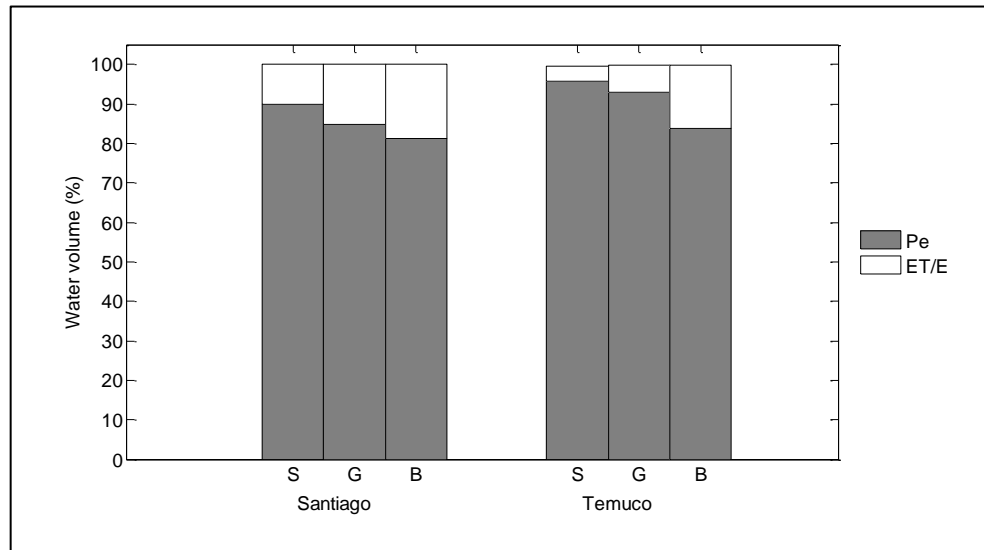


Figure 9: Simulated water balance of rain gardens in Santiago and Temuco with *Sedum* (S), grass (G) and bare soil (B). Water is lost to the atmosphere by percolation (Pe) and evapotranspiration (ET) or evaporation (E).

When soil water content is lower than θ_{WP} (Figure 8a), an irrigation plan becomes key. To explore this issue I test the following three irrigation plans for the rain garden with *Sedum* implemented in Santiago: (1) a base user-defined irrigation program shown in Table 4 (P1) based on the irrigation schedule used in an experimental green roof with

Sedum in Santiago (Reyes et al., 2015), (2) a constant irrigation of 8.6 mm (i.e. the daily average of P1) during 15 minutes, which is applied every day at 8:00 am only if the soil water content is under θ_{FC} (i.e. the plan simulates the existence of a soil moisture sensor) (P2), and (3) a variable irrigation program equal to the previous 24 hours of ET_0 , which is applied every day starting at 8:00 a.m. (P3). In IHMORS P1 and P2 are entered by the user, although for the last case the model determines when the irrigation takes places based on the actual soil moisture content. On the other hand P3 is automatically computed by the model.

Table 4: Irrigation program P1. Irrigation is applied during 15 minutes

Month	Time of application	Depth (mm)
January	6:00 - 14:00 - 22:00	10
February	6:00 - 14:00 - 22:00	6
March	6:00 - 14:00 - 22:00	5
April	6:00 - 14:00 - 22:00	2.5
May	6:00 - 14:00 - 22:00	2
June	8:00	2
July	8:00	2
August	8:00	2
September	8:00	2
October	8:00	2
November	8:00 – 18:00	2.5
December	8:00 – 13:00 – 18:00	4

SWCD curves associated with each plan are shown in Figure 10, which also presents the curve when no irrigation is implemented. For the three irrigation programs, the soil water content remains close to the wilting point, although different water volumes are involved. P1 and P2 imply using pretty much the same amount of water (i.e. 12.59 m³ and 12.52 m³), although P2 reduces by 7 the number of days in which irrigation is provided during the 2 years under analysis. In fact this result demonstrates

one of the advantages of using the SWCD curve as a means to understand the impacts of irrigation programs beyond the volumes involved. P3 consumes a significant less amount of water (84% less than P1) but vegetation may still wilt during the driest month of the year (i.e. ~10% of the time) when the soil moisture is lower than θ_{WP} , and thus irrigation must be intensified. For the sake of comparison, the amount of irrigation needed to preserve the soil water content always above the average between θ_{FC} and θ_{WP} (i.e. $\theta = 0.19$) is 13.6 m^3 .

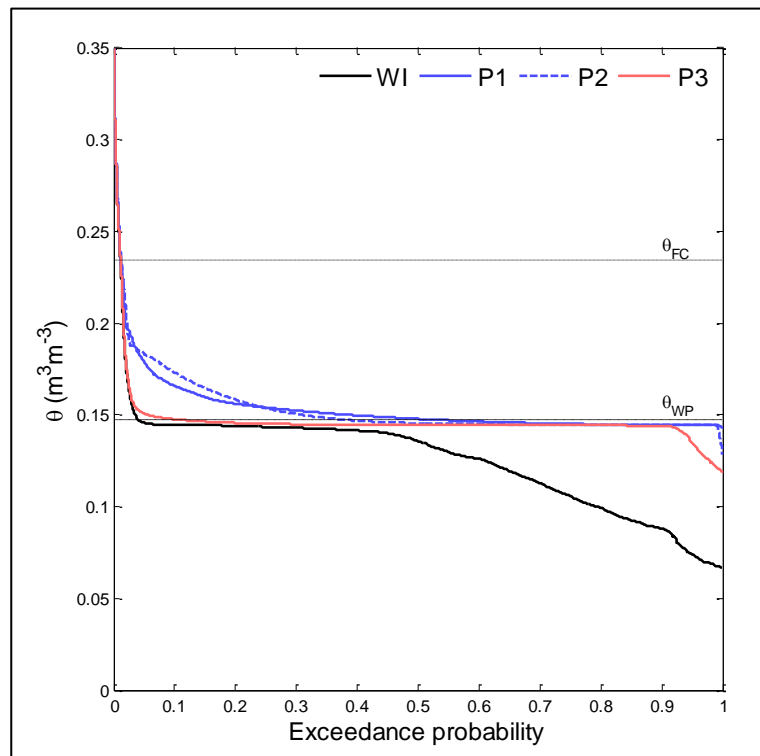


Figure 10: Soil water content duration curves for the rain garden in Santiago with *Sedum* and three irrigation schedules: a monthly irrigation program (P1), a constant irrigation program with soil moisture sensor reporting field capacity (P2), and an irrigation plan that replicates the previous day evapotranspiration (P3). The curve associated with no irrigation (WI) is also presented.

Finally, Figure 11 compares the SWCD curves for Santiago simulated when the rain garden is both connected and disconnected from its contributing impervious area. In the last case the garden only receives water from the precipitation falling on it. The SWCD curve of the disconnected rain garden falls below the curve of the connected rain garden, and thus it becomes clear that green infrastructure capturing runoff from contributing impervious areas can have more water available for the vegetation (Houdeshel et al., 2012). Interestingly, Figure 11 shows that despite the reduced number of days with precipitation in a year in Santiago (25-30 days), a $0.01 \text{ m}^3\text{m}^{-3}$ difference in the soil water content between the connected and disconnected rain garden is simulated for ~180 days. Overall, results show that capturing rainwater and using it for landscape watering needs is a reasonable and realistic way to reduce the use of potable water for landscape irrigation (Seymour, 2005), particularly in regions where precipitation and the hot season are concurrent.

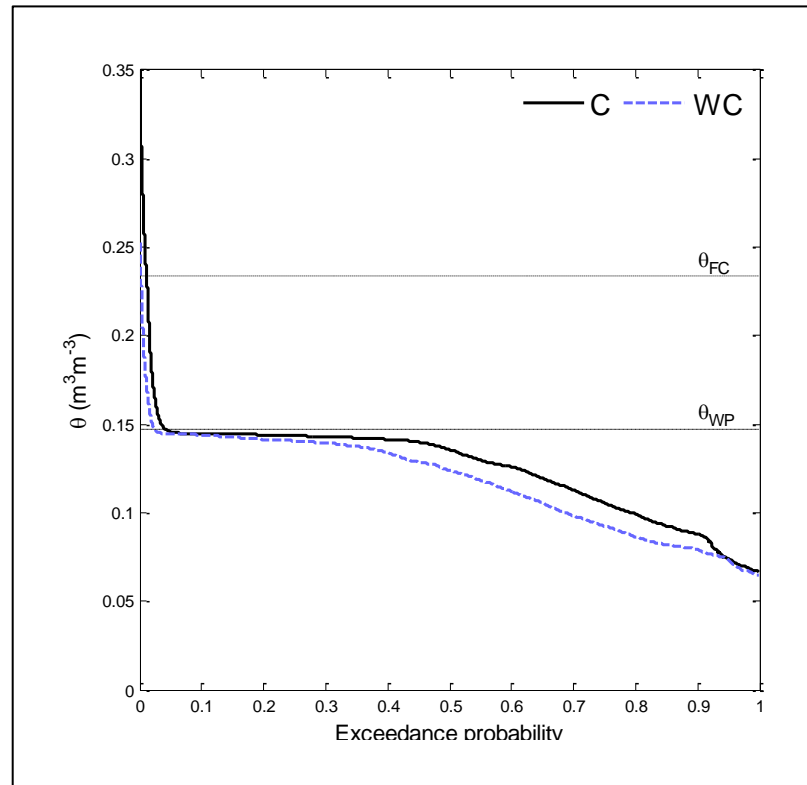


Figure 11: Soil water content duration curves for the rain garden in Santiago with *Sedum* connected (C) and disconnected (WC) with the contributing impervious area.

5. CONCLUSION

This study developed and tested a new hydrological model denoted IHMORS (Integrated Hydrological Model at Residential Scale), which considers the most important surface and subsurface processes to analyse the performance of stormwater facilities at a residential scale. The model also contains an irrigation module to evaluate the maintenance of green areas and green infrastructure, both widely used in sustainable urban drainage systems. Laboratory and numerical experiments allowed validating the bare soil evaporation, subsurface runoff hydrograph and soil moisture redistribution routines, which are critical components of the model rarely considered in an explicit manner in rainfall-runoff modeling for urban settings. The main capabilities of the model include the following: (1) It can evaluate the dynamics of the soil water content and runoff hydrographs through continuous simulation, (2) It can simulate a wide range of spatial configurations, as contributing areas and drainage control practices are modeled by combining and connecting different subareas subjected to surface and subsurface hydrologic processes, (3) Each subarea can contain different layers of soil which are interconnected through vertical flows representing percolation and redistribution.

The model was used to simulate a 2 m² rain garden for two years controlling an impervious area of 10 m², under different warm temperate climates (Santiago, with dry summer, and Temuco, fully humid climate), vegetation types and irrigation practices. Based on this analysis I make the following conclusions:

1. The exercise provided a comprehensive understanding of the performance of this type of drainage practice in terms of both runoff control and the irrigation needs for maintenance. Indeed, surface runoff was not generated in any of the rain gardens tested, but significant differences in terms of irrigation needs were simulated.
2. Irrigation became crucial approximately 25% of the time, regardless the type of vegetation. On the other hand, less water was evapotranspired from the rain

garden with *Sedum* in Santiago, and differences larger than $0.01 \text{ m}^3\text{m}^{-3}$ in soil water content between rain gardens with *Sedum* and grass were simulated during ~50% of the time. Nonetheless, irrigation is essential for at least 60% of the time in Santiago, regardless of the vegetation.

3. For the semiarid climate, using the previous day simulated evapotranspiration as the daily irrigation program reduces in more than 80% the volume of water employed by other irrigation programs based on pulses of water applied through the day. Nonetheless irrigation is still essential during the driest days. Interestingly, two irrigation programs implied the same annual water volume, but 7 more days of irrigation were required with one of them within the study period.
4. In a semiarid climate city like Santiago, run-on water entering the rain gardens from the contributing area can decrease its irrigation needs. Despite rainfall occurring on average 25-30 days per year in the city, the run-on from impervious areas is associated with significant differences in the soil water content for approximately 180 days as compared to those simulated without the run-on contribution.

Potential directions for future research include: 1) improving the model by incorporating processes such as subsurface horizontal flow, pollutant transport and removal, and evapotranspiration from partially vegetated surfaces, 2) expanding the use of the model to evaluate different real stormwater facilities in several climate regions, and 3) linking the capabilities of the model with a cost analysis to formally estimate irrigation and maintenance costs -and savings- associated with both water volumes and durations of irrigation involved.

REFERENCES

- Allen, R. G., Pereira, L. S., Raes, D., Smith, M. (1998). *Crop evapotranspiration: Guidelines for computing crop water requirements*. Rome: FAO: Irrigation and Drainage paper.
- Allen, R. G., Pereira, L. S., Smith, M., Raes, D., Wright, J. L. (2005). FAO-56 Dual crop coefficient method for estimating evaporation from soil and application extensions. *Journal of Irrigation and Drainage Engineering*, 131(1), 2-13.
- Alley, W. M., Veenhuis, J. E. (1983). Effective impervious area in urban runoff modeling. *Journal of Hydraulic Engineering*, 109(2), 313-319.
- Ascione, F., Bianco, N., de' Rossi, F., Turni, G., Vanoli, G. P. (2013). Green roofs in European climates. Are effective solutions for the energy savings in air-conditioning? *Applied Energy*, 104, 845-859.
- Barraud, S., Miramond, M., Le Gauffre, P. (2004). A-posteriori analysis of the relevance of a multicriteria decision-aid method for best management practice choice in urban storm drainage. *Urban Water Journal*, 1(3), 209-2016.
- Beven, K.J. (2012). *Rainfall-Runoff Modelling: The Primer*, 2nd Edition, Wiley-Blackwell.
- Bras, R. L. (1990). *Hydrology: An introduction to hydrologic science* (1 ed.). Boston: Adisson-Wesley.
- Briggs, L. J., Shantz, H. L. (1912). The wilting coefficient and its indirect determination. *Botanical Gazette*, 53(1), 20-37.
- Burszta-Adamiak, E., Mrowiec, M. (2013). Modelling of green roofs' hydrologic performance using EPA's SWMM. *Water Science & Technology*, 68(1), 36-42.
- Cahill, T. H. (2012). *Low impact development and sustainable stormwater management*. (1 ed.). New Jersey: Wiley.
- Carson, T., Keeley, M., Marasco, D. E., McGillis, W., Culligan, P. (2015). Assessing methods for predicting green roof rainfall capture: A comparison between full-scale observations and four hydrologic models. *Urban Water Journal*, (in press), doi: 10.1080/1573062X.2015.1056742.
- Chow, V. T., Maidment D. R., Mays, L. W. (1988). *Applied hydrology*. New York: McGraw-Hill.
- Cigizoglu, H. K., Bayazit, M. (2000). A generalized seasonal model for flow duration curve. *Hydrological Processes*, 14(6), 1053-1067.

- Corradini, C., Melone, F., Smith, R. E. (1997). A unified model for infiltration and redistribution during complex rainfall patterns. *Journal of Hydrology*, 192(1), 104-124.
- Corradini, C., Melone, F., Smith, R. E. (2000). Modeling local infiltration for a two-layered soil under complex rainfall patterns. *Journal of Hydrology*, 237(1), 58-73.
- DehghaniSanij, H., Yamamoto, T., Rasiah, V. (2004). Assessment of evapotranspiration estimation models for use in semi-arid environments. *Agricultural Water Management*, 64(2), 91-106.
- Dirección General de Aeronáutica Civil (DGAC). *Dirección Meteorológica de Chile*. <http://www.meteochile.cl> (acceded 23/07/2015)
- D'Odorico, P., Porporato, A. (2006). Ecohydrology of arid and semiarid ecosystems: An introduction. In P. D'Odorico, A. Porporato (1 ed), *Dryland ecohydrology* (pp. 1-10). Netherlands: Springer.
- Elliot, A. H., Trowsdale, S. A. (2007). A review of models for low impact urban stormwater drainage. *Environmental Modelling & Software*, 22(3), 394-405.
- Everett, G., Lamond, J., Morzillo, A. T., Chan, F. K., Matsler, A. M. (2015). Sustainable drainage systems: Helping people live with water. *Water Management*, 1-10.
- Fletcher, T. D., Shuster, W., Hunt, W., Ashley, R., Butler, D., Arthur, S., Viklander, M. (2014). SUDS, LID, BMPs, WSUD and more - The evolution and application of terminology surrounding urban drainage. *Urban Water Journal*, 12(7), 525-542.
- Freni, G., Oliveri, E. (2007). Mitigation of urban flooding: A simplified approach for distributed stormwater management practices selection and planning. *Urban Water Journal*, 2(4), 215-226.
- Gironás, J., Roesner, L. A., Rossman, L. A., Davis, J. (2010). A new applications manual for the Storm Water Management Model (SWMM). *Environmental Modelling & Software*, 25(6), 813-814.
- Green, W. H., Ampt, G. A. (1911). Studies on soil physics, 1. The flow of air and water through soils. *Journal of Agricultural Science*, 4(1), 1-24.
- Guo, J. C., Luu, T. M. (2015). Hydrologic model developed for stormwater infiltration practices. *Journal of Hydrologic Engineering*, 20(9), 1-8.
- Hilten, R. N., Lawrence, T. M., Tollner, E. W. (2008). Modeling stormwater runoff from green roofs with HYDRUS-1D. *Journal of Hydrology*, 358(3), 288-293.
- Horton, R. E. (1933). The role of infiltration in the hydrologic cycle. *Eos, Transactions American Geophysical Union*, 14(1), 446-460.

- Houdeshel, C. D., Pomeroy, C. A., Hultine, K. R. (2012). Bioretention design for xeric climates based on ecological principles. *Journal of the American Water Resources Association*, 48(6), 1178-1190.
- Houdeshel, C. D., Pomeroy, C. A. (2013). Storm-water bioinfiltration as no-irrigation landscaping alternative in semiarid climate. *Journal of Irrigation and Drainage Engineering*, 142(2), 1-6.
- Houdeshel, C. D., Hultine, K. R., Johnson, N. C., Pomeroy, C. A. (2015). Evaluation of three vegetation treatments in bioretention gardens in a semi-arid climate. *Landscape and Urban Planning*, 135, 62-72.
- Huang, J. J., Li, Y., Niu, S., Zhou, S. H. (2014). Assessing the performances of low impact development alternatives by long-term simulation for a semi-arid area in Tianjin, Northern China. *Water Science & Technology*, 70(11), 1740-1745.
- Huber, W. C., Rossman, L. A., Dickinson, R. E. (2010). EPA Storm Water Management Model, SWMM5. In Singh, V. P., Frevert, D. K., *Watershed models* (pp. 343-346). Boca Raton: Taylor & Francis.
- Instituto de Investigaciones Agropecuarias. (2012). *Estaciones*. Agromet. Red agrometeorológica de Inia.
www.agromet.inia.cl (accessed 2015)
- Leconte, R., Brissette, F. P. (2001). Soil moisture profile model for two-layered soil based on sharp wetting front approach. *Journal of Hydrologic Engineering*, 6(2), 141-149.
- Lee, J. G., Heaney, J. P. (2003). Estimation of urban imperviousness and its impacts on storm water systems. *Journal of Water Resources Planning and Management*, 129(5), 419-426.
- Lee, J. G., Selvakumar, A., Alvi, K., Riverson, J., Zhen, J. X., Shoemaker, L., Lai, F. (2012). A watershed-scale design optimization model for stormwater best management practices. *Environmental Modelling & Software*, 37, 6-18.
- Lee, R. S., Traver, R. G., Welker, A. L. (2013). Continuous modeling of bioinfiltration storm-water control measures using Green and Ampt. *Journal of Irrigation and Drainage Engineering*, 139(12), 1004-1010.
- Legates, D. R., McCabe, G. J. (1999). Evaluating the use of "goodness-of-fit" measures in hydrologic and hydroclimatic model validation. *Water Resources Research*, 35(1), 233-241.
- Li, Y., Babcock, R. W. (2014). Green roof hydrologic performance and modelling: A review. *Water Science & Technology*, 69(4), 727-738.

- Ma, Y., Feng, S., Su, D., Gao, G., Huo, Z. (2010). Modeling water infiltration in a large layered soil column with a modified Green–Ampt model and HYDRUS-1D. *Computers and Electronics in Agriculture*, 71S(1), S40-S47.
- Merriam, R. A. (1960). A note on the interception loss equation. *Journal of Geophysical Research*, 65(11), 3850-3851.
- Ministerio de Obras Públicas (MOP). (2013). Aspectos generales del drenaje Urbano. In *Manual de drenaje urbano* (pp. 142-146). Santiago.
- Mualem, Y. (1976). A new model for predicting the hydraulic conductivity of unsaturated porous media. *Water Resources Research*, 12(3), 513-522.
- Palla, A., Gnecco, I. (2015). Hydrologic modeling of Low Impact Development systems at the urban catchment scale. *Journal of Hydrology*, 528, 361-368.
- Peel, M. C., Finlayson, B. L., McMahon, T. A. (2007). Updated world map of the Köppen-Geiger climate classification. *Hydrology and Earth System Sciences*, 11, 1633-1644.
- Reyes, R., Bustamante, W., Gironás, J., Pastén, P. A., Rojas, V., Suarez, F., Vera, S., Victorero, F., Bonilla, C. A. (2015). *Effect of substrate depth and roof layers on green roof temperature and water requirements in semi-arid climate*. Submitted to Ecological Engineering.
- Rosa, D. J., Clausen, J. C., Dietz, M. E. (2015). Calibration and verification of SWMM for Low Impact Development. *Journal of the American Water Resources Association*, 51(3), 746-757.
- Rossman, L. A. (2010). *Storm water management model user's manual. Version 5.0*. Cincinnati: National Risk Management Research Laboratory, Office of Research and Development, US Environmental Protection Agency.
- Sample, D. J., Heaney, J. P. (2006). Integrated management of irrigation and urban stormwater infiltration. *Journal of Water Resources Planning and Management*, 132(5), 362-373.
- Sample, D., Lucas, W., Janeski, T., Roseen, R., Powers, D., Freeborn, J., Fox, L. (2014). Greening Richmond, USA: A sustainable urban drainage demonstrations project. *Proceedings of the ICE-Civil Engineering*, 167(2), 88-95.
- Savabi, M. R., Williams, J. R. (1995). Evaporation and environment, WEPP model documentation. *USDA-ARS National Soil Erosion Research Laboratory Publication*.

- Seymour, R. S. (2005). Capturing rainwater to replace irrigation water for landscapes: Rain harvesting and rain gardens. Proceedings of the 2005 Georgia water resources conference; 25–27 Apr. 2005; Athens, GA.
- Sherrard, J. A., Jacobs, J. M. (2005). Vegetated roof water-balance model: Experimental and model results. *Journal of Hydrologic Engineering*, 17(8), 858-868.
- Shorten, P. R., Pleasants, A. B. (2007). A stochastic model of urinary nitrogen and water flow in grassland soil in New Zealand. *Agriculture, Ecosystems and Environment*, 120(2), 145-152.
- Shuster, W. D., Bonta, J., Thurston, H., Warnemuende, E., Smith, D. R. (2005). Impacts of impervious surface on watershed hydrology: A review. *Urban Water Journal*, 2(4), 263-275.
- Simunek, J., Sejna, M., Saito, H., Sakai, M., van Genuchten, M. T. (2013). The HYDRUS-1D software package for simulating the one-dimensional movement of water, heat, and multiple solutes in variably-saturated media, version 4.17, HYDRUS software series 3, *Department of Environmental Sciences, University of California Riverside, Riverside, California, USA*.
- Slaymaker, O., Spencer, T. (1998). *Physical geography and global environmental change*. UK: Harlow: Longman.
- Smith, R. E., Smettem, K. R., Broadbridge, P., Woolhiser, D. A. (2002). *Infiltration theory for hydrologic applications*. Washington DC: American Geophysical Union.
- Snyder, R. L., Bali, K., Ventura, F., Gomez-MacPherson, H. (2000). Estimating evaporation from bare or nearly bare soil. *Journal of Irrigation and Drainage Engineering*, 126(6), 399-403.
- Stewart, B. A., Musick, J. T. (1982). Conjunctive use of rainfall and irrigation in semiarid regions. In D. Hillel, *Advances in irrigation* (pp. 1-24).
- Trinh, D. H., Chui, T. F. (2013). Assessing the hydrologic restoration of an urbanized area via an integrated distributed hydrological model. *Hydrology and Earth System Sciences*, 17(12), 4789-4801.
- Urban Drainage and Flood Control District (UDFCD). (2010). Stormwater Best Management Practices. In *Urban storm drainage, Criteria manual*. Denver, Colorado: Water resources publications.
- van de Giesen, N. C., Stomph, T. J., de Ridder, N. (2000). Scale effects of Hortonian overland flow and rainfall-runoff dynamics in a West African catena landscape. *Hydrological Processes*, 14(1), 165-175.

van Genuchten, M. T. (1980). A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal*, 44(5), 892-898.

Viessman, W., Lewis, G. L. (1995). *Introduction to hydrology* (4 ed.). New York: Addison Wesley Longman.

Walsh, T. C., Pomeroy, C. A., Burian, S. J. (2014). Hydrologic modeling analysis of a passive, residential rainwater harvesting program in an urbanized, semi-arid watershed. *Journal of Hydrologic*, 508, 240-253.

Xiao, Q., McPherson, E. G., Simpson, J. R., Ustin, S. L. (2007). Hydrologic processes at the urban residential scale. *Hydrological Processes*, 21(16), 2174-2188.

Yang, W., Li, D., Sun, T., Ni, G. (2015). Saturation-excess and infiltration-excess runoff on green roofs. *Ecological Engineering*, 74, 327-336.